A Systematic Analysis of the Effect of Air Humidification to Gas Turbine Systems*

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This paper shows the thermodynamic performance of gas turbine systems with air humidification. We make sure that humidifying the air increases the power output and thermal efficiency although air humidification method does not influence to the thermal efficiency greatly under the same calculating conditions. Moreover, humidifying the air is more effective in regenerative cycle, such as AHAT, TOPHAT, REVAP, and HAT cycle. They all show high thermal efficiency near 50%HHV. This is because the exhaust heat can be recovered enough by humidifying and the compressor power is decreased by each method in these systems. Moreover, the result of parameter studies show that the best efficiency of each system is comparable and each system has optimum point of moisture amount to the thermal efficiency.

Key Words: Gas Turbine, Thermal Efficiency, Moist Air, Entropy, Humidification, Power Output, Regenerative Cycle

1. Introduction

The combined cycle power generation has greatly contributed to the rapid improvement of the power generation efficiency and the economy by raising gas turbine combustion temperature. However it is forecast that it is technically difficult to raise the combustor temperature any further because the amount of the NO_x generation increases rapidly and the efficiency improvement reach the ceiling because of increasing of the amount of the cooling air.

Then, many kinds of gas turbine systems with air humidification are proposed to increase the power output and the thermal efficiency with comparatively simple equipments. Though the main purpose of humidifying the air is to increase mass flow and specific heat of working fluid in turbine, the way of humidifying the air is various. Some systems use hot exhaust gas to preheat compressed air and/or feed water. For example, CHENG cycle adapts steam injection to combustor, which produced by heat recovery steam generator⁽¹⁾. HAT (Humid Air Turbine) and AHAT (Advanced HAT) adapt regenerative cycle, in which compressed air is humidified through

the saturator and then preheated through the recuperator⁽²⁾⁻⁽⁴⁾.

However, it is difficult to understand where the difference of the thermal efficiencies and the features of these proposed gas turbine systems come from. Because the conditions to calculate heat and mass balance, such as turbine inlet temperature, the efficiencies of each machines and atmospheric conditions, are different depending on the papers. It is necessary to evaluate the effect that configuration of system itself influence to the thermal efficiency.

Therefore, we studied thermodynamic effect of air humidification to gas turbine system. First, we investigated 8 proposed gas turbine systems, how the components, the configuration of systems and air humidification method (steam injection, water injection and saturator using) influence to the characteristics of these systems by calculating heat and mass balance under the same calculating conditions. Moreover, to clarify the performance of these systems, some parameter studies were carried out.

2. Classification of Systems and Conditions for Calculation

2.1 Classification of gas turbine systems with air humidification

We consider the proposed 8 type gas turbine systems with air humidification. These are CHENG, FLECS, SPRINT, CT-HAI, REVAP, TOPHAT,

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Table 1 Classification of gas turbine with humidifying air

	(a) Steam injection type	(b) Water injection type	(c) Saturator using type
System form	(i) Simple gas Turbine type	SPRINT	
	(ii) Heat recovery type	CHENG FLECS	CT-HAI
	(iii) Regenerative Cycle type		REVAP TOPHAT AHAT HAT

HAT and AHAT^{(5)–(10)}. We classified these systems by system forms and air humidification methods to understand systematically the difference of thermal efficiencies. The classification is shown in Table 1.

System form classification

(i)	Simple gas turbine type	SPRINT

- (ii) Heat recovery type

- (iii) Regenerative cycle type
REVAP, TOPHAT, HAT, AHAT

Air humidification method classification

- (a) Steam injection type CHENG, FLECS

- (b) Water injection type
SPRINT, REVAP, TOPHAT

- (c) Saturator using type CT-HAI, HAT, AHAT

(AHAT has water injection to compressor inlet too. However we classified it to Saturator using type because the amount of injected water is very little.)

2.2 Conditions for calculation of heat and mass balance

To analysis the effect of air humidification to gas turbine systems systematically, it is necessary to calculate the heat mass balance of these systems under the common conditions. The conditions for calculation are shown in Table 2. We use common adiabatic efficiencies of turbine and compressor, atmospheric conditions and heat value of methane as fuel. Moreover, turbine inlet temperature, moisture amount and exhaust temperature are same value shown in Table 3. (however, in case of SPRINT and CT-HAI, the data on references is used because these are the improved systems of the existing gas turbines).

We use the general-purpose software to analyze the steady state of power generation system, which developed by CRIEPI⁽¹¹⁾.

3. Results and Discussion

3.1 Basic performance of each type system

- (i) Simple gas turbine type (SPRINT)

The calculation result of SPRINT is shown in Fig. 1. And Table 4 shows specific output and thermal efficiency of SPRINT with and without humidifi-

Table 2 Common condition for calculation

Turbine	Adiabatic efficiency	92 %
Compressor	Adiabatic efficiency	88 %
Pump	Adiabatic efficiency	80 %
Combustor	Combustor efficiency	100 %
	Pressure drop (fuel side)	15 %
	Pressure drop (air side)	5 %
Mechanical efficiency		99 %
Generator efficiency		98.5 %
Atmosphere conditions		
Temperature		15 °C
Pressure		0.1 MPa
Relative humidity		60 %
Fuel		
Methane	HHV	55380 kJ/kg
	LHV	50940 kJ/kg

Table 3 Condition for calculation of each type

		(i) Simple gas turbine type	(ii) Heat recovery type		
	Unit	SPRINT	CHENG	FLECS	CT-HAI
TIT (ISO standard)	°C	1200	1200	1200	1200
Pressure ratio		2.5/12	15	15	15
Moisture amount*	wt%	0.4	14.0	14.0	8.4
Exhaust temp	°C	-	105	105	

		(iii) Regenerative cycle type			
	Unit	TOPHAT	REVAP	HAT	AHAT
TIT (ISO standard)	°C	1200	1200	1200	1200
Pressure ratio		15	5/5	5/5	15
Moisture amount*	wt%	14.0	14.0	14.0	14.0
Exhaust temp	°C	105	105	105	105

* Weight ratio of moisture amount at combustor inlet

cation. Specific output increases because power for compressor decreases and output power of gas turbine increases by water injection. But thermal efficiency is little improved. This is because the temperature at combustor inlet falls and amount of fuel increases though output power increase.

- (ii) Heat recovery type

(CHENG, FLECS, CT-HAI)

Table 5 shows specific output and thermal efficiency of Heat recovery type systems and the calculation result of CHENG is shown in Fig.2 as representation of this type systems. As steam to inject to combustor is produced by exhaust heat, all systems have near 40%HHV. Compared CHENG and FLECS, as the super heater is deleted to simplify the

equipment in FLECS, more steam is produced but the temperature is lower than that of CHENG under the same exhaust temperature. Therefore, when produced steam is injected to combustor as same amount as that of CHENG, thermal efficiency of FLECS is 3% (absolute value) lower than that of CHENG. But when all processed steam is injected, thermal efficiency of these systems is almost same value.

In the case of CT-HAI, because a part of gas turbine output is need to compress air to saturator and exhaust gas temperature is higher than CHENG and FLECS, thermal efficiency is lower than that of the others. However it increase 5% (absolute value) from the gas turbine without humidifying the air by using exhaust gas to heat water for saturator and humidified air.

(iii) Regenerative cycle type

(REVAP, TOPHAT, HAT, AHAT)

Table 6 shows specific output and thermal efficiency of Regenerative cycle type systems, and the calculation results of AHAT, HAT, TOPHAT and REVAP are shown in Figs. 3 – 6 respectively. Though thermal efficiency of TOPHAT is a little lower than that of other systems under these calculating conditions, Regenerative cycle systems achieve high thermal efficiency near 50% HHV. However, there is little difference of thermal efficiency by air humidification method.

3.2 Mechanism of improving thermal efficiency by humidifying air

Figure 7 shows all results of the calculated 8 systems and simple gas turbine and regenerative cycle gas turbine as reference (calculated under common conditions). By humidifying air, out put increases in all systems and thermal efficiency increases in the systems using exhaust heat to humidification. And humidifying the air is more effective in Regenerative type systems.

Temperature-entropy (T-S) diagram of CHENG and the simple gas turbine as reference is shown in Fig. 8. Entropy is enlarged by injecting steam heated by exhaust gas and output increases, in spite of the almost same amount of input heat as simple gas turbine. Consequently thermal efficiency increases. Other Heat recovery type systems, FLECS and CT-HAI have similar T-S performance with CHENG.

Figure 9 shows T-S diagram of AHAT and regenerative cycle as reference. In case of AHAT as well as CHENG, entropy is enlarged by humidifying. Moreover, as temperature of compressed air falls during the process of humidifying, it becomes possible to recovery the exhaust heat further more. Therefore, humidifying air is more effective to the performance

Table 4 Specific output and thermal efficiency of Simple gas turbine type systems

	unit	SPRINT
Without humidification		
Specific output	kJ/kg	344
Thermal efficiency	%	36.2
With humidification		
Specific output	kW/kg/s	358
Thermal efficiency (HHV)	%	36.5

Table 5 Specific output and thermal efficiency of Heat recovery type systems

	Unit	CHENG	FLECS	CT-HAI
Process steam	kg/s	0	1.7	-
Specific output	kW/kg/s	596	600	499
Thermal efficiency (HHV)	%	39.8	36.9 (39.5*)	38.1

* In the case of all produced steam injection

Table 6 Specific output and thermal efficiency of Regenerative cycle type systems

	unit	TOPHAT	REVAP	HAT	AHAT
Specific output	kW/kg/s	626	684	673	610
Thermal efficiency (HHV)	%	49.4	50.8	50.8	50.5

Fig. 1 Heat and mass balance of SPRINT

Fig. 2 Heat and mass balance of CHENG

Fig. 3 Heat and mass balance of AHAT

Fig. 4 Heat and mass balance of HAT

Fig. 5 Heat and mass balance of TOPHAT

Fig. 6 Heat and mass balance of REVAP

and exhibits higher thermal efficiency of Regenerative cycle type systems. Figures 10, 11 show T-S diagram

Fig. 7 Comparison of thermal efficiencies of gas turbine systems with air humidification under the conditions in Tables 2 and 3

Fig. 8 T-S diagram of CHENG

of other Regenerative type systems, HAT and REVAP respectively. These Regenerative type systems exhibit similar T-S performance with AHAT during the process where humidified air is heated in the recuperator and exhausted to atmosphere (⑤~⑩ in AHAT, ⑦~⑫ in HAT and REVAP). And, the compressor power is decreased by each method in these four systems, in a word, by the water injection to suction in AHAT, by the water injection to the inside of compressor in TOPHAT, and by inter cooling in HAT and REVAP. It is thought that thermal efficiency of these systems is improved by the above-mentioned factors.

Compared AHAT (or TOPHAT) whose pressure ratio is 15 and HAT (or REVAP) whose pressure ratio is 25, the heat head in the turbine of the former is smaller than that of the later because pressure ratio

Fig. 9 T-S diagram of AHAT

Fig. 11 T-S diagram of REVAP

Fig. 10 T-S diagram of HAT

of the former is smaller than that of the later. Therefore specific output of the former is smaller than that of the later. However, because the temperature of exhaust gas from turbine of the former is higher than that of the later thus more heat can be collected in the recuperator, the input heat as the fuel can be reduced. Therefore the former exhibits the thermal efficiency that equals the later in spite of lower pressure ratio.

Next, we compare HAT and REVAP to consider the difference of performance by air humidification

methods in Regenerative cycle type systems. Though these two systems have a common feature that they have inter cooling and high pressure ratio, HAT uses saturator but REVAP has water injection to humidify the fluid air. In HAT, water for humidifying is heated at economizer and inter cooler before humidifying the fluid air at the saturator. On the other hand, in REVAP, water is injected to the fluid air at the atmospheric temperature and then the humidified air is heated at heat exchangers and inter cooler. Thus, there is a little difference in T-S performance on the part of humidifying and heating the fluid air ((5)~(7) in HAT, (4)~(7) in REVAP).

However T-S performance of these systems is very similar as a whole, therefore thermal efficiency becomes very close value.

3.3 Effect of moisture amount

The effect of moisture amount to thermal efficiency is evaluated about Regenerative type systems, REVAP, TOPHAT, HAT and AHAT, which have high thermal efficiency. As restriction conditions for calculation, when moisture amount is changed, the temperature of exhaust gas is restricted over 105 degree C and the temperature difference between air and exhaust gas from turbine at recuperator is restricted over 20 degree C.

The result is shown in Fig. 12. From the result, we can understand that each system has optimum point to thermal efficiency for restriction conditions and the best thermal efficiencies of each system are comparable. When moisture amount is more than optimum point, thermal efficiency decreases with the

Fig. 12 Thermal efficiency changes with moisture amount

increase in the amount of moisture. This is because amount of heat for heating water increases in economizer and then amount of regenerated heat in recuperator decreases. On the other hand when moisture amount is less than optimum point, thermal efficiency decreases with the decrease in the amount of moisture. It is because the exhaust heat increases for decreasing the effect of humidification as mentioned above.

Compared AHAT (or TOPHAT) and HAT (or REVAP), AHAT has the optimum point at relatively less moisture amount region, and HAT has it at relatively more moisture amount region. As HAT uses the heat from inter-cooler as well as exhaust gas to heat water for humidifying, the heat is too much at relatively less moisture amount region although pressure ratio of HAT is higher consequently the temperature at outlet of gas turbine is lower than that of AHAT.

4. Conclusion

We can get some conclusions by comparing gas turbine systems with air humidification under the common conditions.

- The power outputs of gas turbine systems are increased by air humidification. And humidifying the fluid air is more effective to regenerative cycle, thermal efficiencies of Recuperative cycle systems such as AHAT, REVAPHAT and TOPHAT, exhibit near 50%HHV by air humidification.

- This is because the exhaust heat can be recovered enough by humidifying and the compressor power is decreased by each method in Recuperative cycle systems.

- Humidification method influence to the feather of cycle, but not influence to the generation efficiency

seriously.

- From the sensitivity analysis for moisture amount about Recuperative cycle systems, each system has optimum point and the low pressure ratio systems have it at less moisture amount region and the high pressure ratio systems have it at more moisture amount region. However the best thermal efficiencies of these systems are comparable.

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