Gas Turbine Inlet Air Cooling System with Liquid Air

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Gas turbine performance, including power and heat rate, is strongly dependent on environmental conditions, especially air temperature. Gas turbine inlet air cooling (GTIAC) has the effect of enhancing the performance including power. We tested the new GTIAC system with injecting liquid air at an existing 150 MW class gas turbine, and it was successfully performed.

1. Introduction

In order to meet the recent sharp increase in demand for electric power, electric power companies have been striving to enhance power output by installing additional power plants as well as improving the efficiency of existing plants. In particular, work is in progress to install additional gas turbine and gas turbine combined cycle power plants as a means to secure the power supply required during the daytime in summer when the demand for power peaks. However, gas turbines are characterized by a decrease in power output due to a reduction in air density at the inlet of the air compressor when the atmospheric temperature rises. As a result, the generating power output drops during the daytime in summer when the demand for electric power peaks. **Fig. 1** shows an example of this phenomenon.

It can be seen in this example that the power ratio of a gas turbine which operates at 100% load at an atmospheric temperature of 5°C and relative humidity of 60% becomes 83% when the atmospheric temperature rises to 30°C, a drop in the power ratio of 17%.

The gas turbine inlet air cooling (GTIAC) system using liquid air is being researched and developed as a system for improving the power ratio. This system, shown in **Fig. 2**, is designed to increase gas turbine power output by cooling the inlet air with liquid air which is directly injected into the air inlet of the gas turbine during the peak hours of power production in the daytime. The liquid air is produced at lower cost at night and is stored in a tank for use during the day. One major characteristic of this system is that the inlet air cooling capacity can be flexibly adjusted by controlling the injection flow of the liquid air.

This system is under joint research with the Chubu Electric Power Co., Inc. since 1994. Studies were conducted on the realization, economy, and other aspects of this system as a whole, and it was found that it was possible to recover the gas turbine power output to the rated power output during summer (recovery operation).

The prospect that an inlet air cooling system having a high power output and flexibility could be configured was obtained by the recovery operation.

This paper describes the gas turbine inlet air cooling system using liquid air, the results of inlet air cooling tests using a small size gas turbine (4 MW class), and the operation of an actual power generation gas turbine (150 MW class).

2. Outline of the system

2.1 Characteristics of inlet air cooling using injected liquid air

Table 1 shows a comparison between liquid air and ice-based thermal energy storage or LNG thermal energy which is the thermal energy of other inlet air cooling systems. Liquid air has a boiling point of −190°C and a density of 860 kg/m³. The difference in enthalpy between liquid air and common air at atmospheric pressure and 0°C is about 400 kJ/kg which, when converted to the difference in enthalpy in unit volume becomes

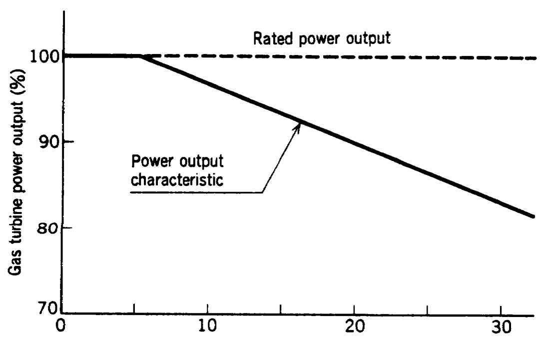

Fig. 1 Gas turbine performance
This figure shows an example of the inlet air temperature characteristic of a gas turbine.

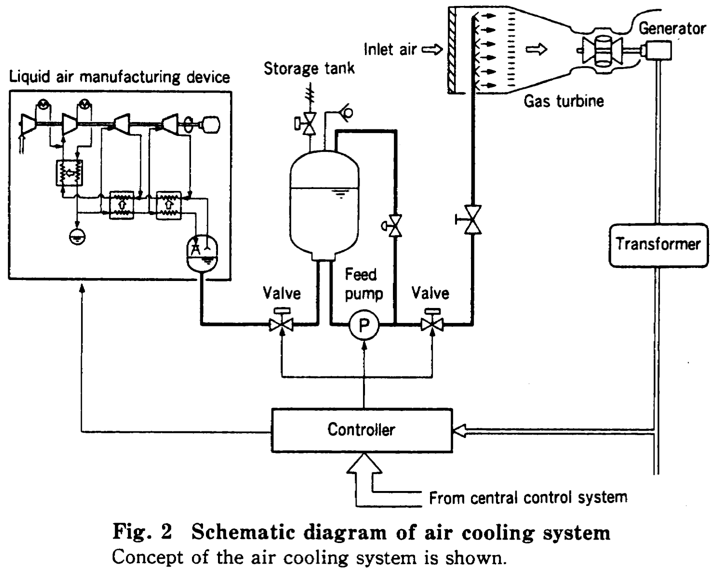

Fig. 2 Schematic diagram of air cooling system
Concept of the air cooling system is shown.

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Table 1 Characteristics of air cooling system

Coolant	Ice	Liquid air	LNG
Kind of thermal energy storage	Heat of fusion	Heat of vaporization	Heat of vaporization
Heat exchange system	Indirect heat exchange	Direct injection	Indirect heat exchange
Coolant temp. (°C)	0	−190	−120
Enthalpy (kJ/kg)	338	414	810
Density (kg/m³)	917	860	386
Enthalpy (per unit volume) (MJ/m³)	165 (Ice: 50%, water: 50%)	356	313
COP*	1.8	0.28	
Facility scale	Relatively wide land is required.	Installation is possible within the existing facility.	Adjacent to the LNG base

* Coefficient of performance

356 MJ/m³. The thermal energy of liquid air is more than twice that of the coolant used in ice-based thermal energy storage (50% of ice + 50% of water). Therefore, the thermal energy capacity is high and the inlet air temperature can be greatly reduced by adding only several percent of liquid air to the gas turbine inlet air.

From the above, the characteristics of a gas turbine inlet air cooling system using injected liquid air can be summarized as follows.

(1) The thermal energy capacity per unit volume of liquid air is great and storage efficiency is high.
(2) Since the component is air, direct injection is possible and heat exchange effectiveness is high.
(3) Flexible inlet air cooling to accommodate varying circumstances is possible by controlling injecting flow.
(4) The effective power coefficient is low, and power required to manufacture the same quantity of coolant is about six times that needed for ice-based thermal energy storage.

From the above characteristics, the gas turbine inlet air cooling system using injected liquid air is regarded as an appropriate generating system to meet peak demand in summer and is being developed.

2.2 Feature of the system

The inlet air cooling system using injected liquid air, as shown in Fig. 2, is composed of an injection device consisting of a liquid air manufacturing device, a storage tank, a feed pump, injection nozzles, and the like. Air is liquefied by the liquid air manufacturing device at night when the electric rate is lower. The liquid air is then charged into the storage tank, and the pressure of liquid air is raised by the feed pump during the peak of power demand in the daytime. The liquid air is subsequently injected through the injection nozzle group which thus serves to cool the gas turbine inlet air.

Swirl type nozzles are used to inject the liquid air. The characteristics of the liquid air injected from these nozzles are that the liquid air becomes fine grains which vaporize instantaneously in the air after injection and mix with the air. It has been confirmed that even if a bare hand is exposed to the liquid air at a position of about one meter downstream from the nozzles, as the liquid air has the property of self-diffusing rapidly to the temperature (over 0°C) having no influence on human body.

In the liquid air manufacturing device to be used for this system, there is little requirement for purity in terms of the percentage content of impurities of water, dry ice and the like contained in liquid air. Further, since DSS (daily start stop) operation is basically required, a large-sized absorber or a component separator for eliminating water content or carbon dioxide which is usually installed in common air separators is not required. Consequently, simplified water separation only is performed by this device, making it possible to reduce the cost of this device significantly.

3. Advantage of inlet air cooling using injected liquid air

When liquid air is injected into the atmosphere, heat is absorbed by the latent heat of vaporization from the surrounding atmosphere. As a result, inlet air temperature falls roughly in proportion to the injection flow until the air reaches saturation. When the liquid air injection flow rate is increased beyond the above saturation point, part of the aqueous vapor in the air is condensed and becomes condensed water drops. Such condensed water drops are extremely fine water drops on the order of about several μm in size, and even if they enter the gas turbine, have no influence on the hardware.

The power output of a gas turbine inlet air cooling system using injected liquid air increases depending on the following two factors:

(1) an increase in inlet air flow due to a lowering of inlet air temperature; and
(2) a decrease in the driving force of the gas turbine compressor.

When liquid air is injected, the density of the atmosphere increases due to the drop in inlet air temperature. As a result, inlet air flow increases and the power output of the gas turbine rises in accordance with the characteristics of the inlet air temperature.

When the air is cooled to the saturation temperature or less, condensed water drops generated in the super-saturated state are sucked into the compressor. The condensed water drops vaporize in the interstage of the compressor, resulting in a lowering of the air temperature due to the latent heat of vaporization of these water drops and a decrease in the driving force of the compressor. For this reason the power output of the gas turbine is comparatively increased.

4. Inlet air cooling test using small-sized gas turbines

Inlet air cooling tests were carried out using a small-sized gas turbine (4 MW class) in order to demonstrate the characteristics of the inlet air cooling of the inlet air cooling system using liquid air and the characteristics of the gas turbine power output increase. Liquid nitrogen which has roughly same physical properties as those of liquid air and is easily obtainable, was used as a coolant in these tests.

4.1 Testing device

The testing device consisted of a small-sized gas turbine and a liquid nitrogen feed device. An Allison 501 KB 5 type small-sized gas turbine was used. Fuel flow was controlled in this engine so as to maintain constantly 14 200 rpm in order to meet the load on the gas turbine during testing. In these tests liquid nitrogen was supplied by a tank pressure type feed device, and the flow was controlled by adjusting the pressure in the tank. This feed device was capable of freely varying liquid nitrogen flow from 0.14 kg/s to 0.53 kg/s.

4.2 Test results

The tests were conducted three times under varying conditions of injection flow. The performance of the gas turbine was measured before liquid air was injected and during a constant flow of injected liquid air. Variations in power output were then compared between both cases.

Test results showed that the inlet air temperature decreased from 31.1°C to 20.3°C when liquid nitrogen was injected at a maximum flow rate of 0.53 kg/s (4% of inlet air flow) which resulted in gas turbine power output being raised by 11%.

Fig. 3 shows the characteristics of injection flow — power output and of inlet air temperature — power output which were rearranged using standard conditions of atmospheric temperature of 30°C and a relative humidity of 70% based on the results of the tests conducted three times.

As seen from Fig. 3, the decrease ratio of the inlet air temperature against the injection flow becomes slow when the inlet air temperature reaches a supersaturated state, but the power output of the gas turbine is raised according to the estimated curve. This shows that in addition to an increase in the inlet air flow of the compressor due to a decrease in the gas turbine inlet air temperature, a decrease in the driving force of the compressor due to the intermediate stage cooling effect caused by condensed water drops generated in the supersaturated state acts effectively to increase the power output of the gas turbine.

5. Inlet air cooling test using an actual gas turbine for power generation

The inlet air cooling test using a small-sized gas turbine verified the effect of inlet air cooling through the injection of liquid nitrogen. Based on these results, inlet air cooling tests were then conducted by injecting liquid air in order to verify the inlet air cooling effect on actual gas turbine used for power generation.

5.1 Testing device

Fig. 4 shows a system schematic diagram of the testing device. The testing device consists of a storage tank, a feed pump, injecting nozzles, valves, as well as instruments and controllers for monitoring and controlling the above compo-

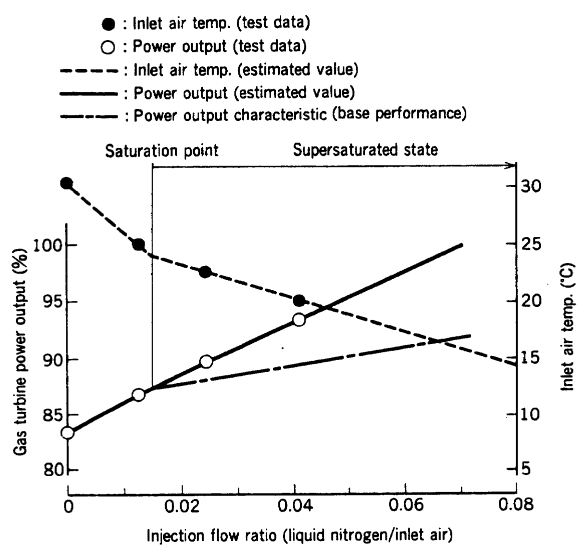

Fig. 3 Power output for 4 MW class gas turbine test
The figure shows the injecting flow — power output characteristics at an atmospheric temperature of 30°C and relative humidity of 70%.

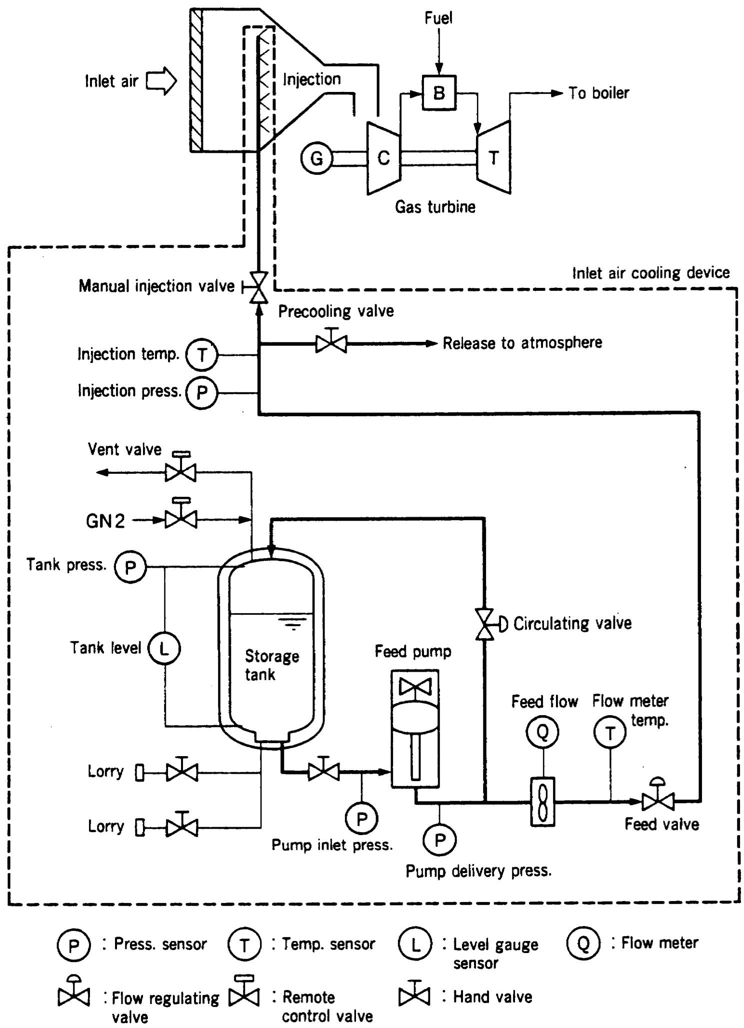

Fig. 4 System schematic diagram for 150 MW class gas turbine

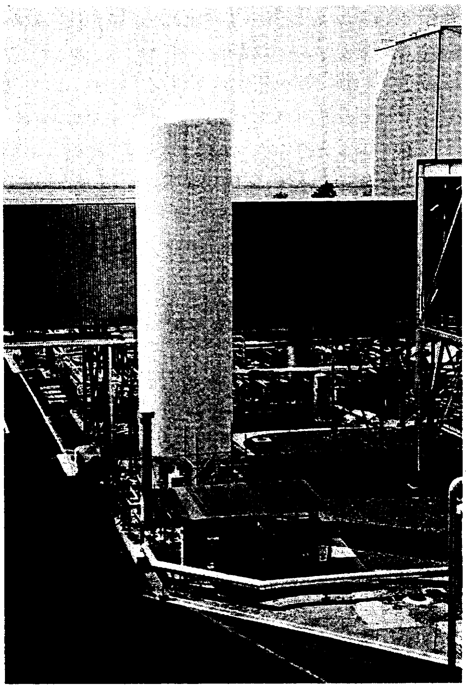

Fig. 5 **Figure of experimental apparatus for 150 MW class gas turbine**

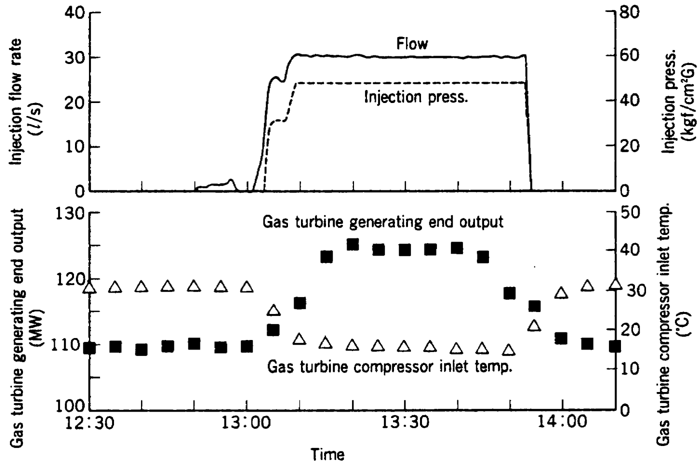

Fig. 6 Power output for 150 MW class gas turbine
The figure shows trend data of the gas turbine power output at the maximum injection flow rate.

nents. **Fig. 5** shows the appearance of the testing device. A storage tank with a capacity of 180 m^3, a feed pump with a rated discharge pressure of 50 kgf/cm^2G, and a flow rate of 2 100 l/min for very low temperature use were used, with 22 injecting nozzles arranged inside the gas turbine inlet air duct. The injection flow of liquid air was adjusted by setting the openings of two flow regulating valves, a feed valve and a circulating valve.

The tests were carried out at the No.2 Unit of the Chita Thermal Power Plant. This power plant is a re-combustion combined cycle plant equipped with combined gas turbines and boilers and has an integrated power output of 529 MW (gas turbine: 154 MW, steam turbine: 375 MW) at an atmospheric temperature of 5°C.

5.2 Testing method

The following points were verified by the inlet air cooling tests.

(1) The functions of the inlet air cooling device and decrease in the inlet temperature of the compressor using injected liquid air were verified.
(2) Characteristic of increase in power output by injecting liquid air
(3) Transient characteristic in trip of liquid air

Since the power generation plant used for the inlet air cooling tests was a commercial plant, performance was measured by the method capable of operating the power generation plant without changing the normal control setting.

In order to verify the inlet air cooling effect, the performance of the gas turbine both under the normal operation without liquid air injection and the operation with liquid air injection was measured and both of performances were compared. In the measurements of the performance of the gas turbine the gas turbine power output was adjusted manually so that an angle of IGV (Inlet Guide Vane) which significantly influences the performance of the gas turbine was equal in both cases. Further, the power generation plant being tested was operated under conditions in which the integrated power output of the gas turbine and the boiler was decreased so that the power output of the gas turbine subject to inlet air cooling was within the power output limits of the generator due to the power output limit of the generator on the gas turbine side relative to the atmospheric temperature.

The liquid air injected in this inlet air cooling test was produced by mixing oxygen and nitrogen in the storage tank.

5.3 Test results

Table 2 shows the test results of inlet air cooling. The tests were carried out over a period of 4 days. In the test number C2AC003, a maximum of liquid air flow of about 30 l/s was injected during the testing period. In addition, emergency shutdown tests were also carried out together in conjunction with the above test.

Fig. 6 shows the injection flow of the liquid air together with the test data of the gas turbine at intervals of 5 minutes in test number C2AC003. It can be seen that the injection

Table 2 Summary of 150 MW class gas turbine test results

Test No.		C 2 AC 001		C 2 AC 002		C 2 AC 003		C 2 AC 004	
Date		Aug. 15, 1996		Aug. 16, 1996		Aug. 18, 1996		Aug. 19, 1996	
Liquid air injection		off	on	off	on	off	on	off	on
Time		10:00	11:25	13:00	14:40	12:35	13:25	18:10	19:20
Injection flow rate	l/s		5.0		14.0		30.0		24.2
	(kg/s)		(4.2)		(11.8)		(25.3)		(20.7)
Gas turbine power output	MW	107.6	111.7	107.0	119.0	109.5	124.1	110.9	123.1
Inlet air temp.	°C	32.9	29.0	33.9	21.8	31.4	16.1	30.2	17.2
Atmospheric temp.	°C	31.6	32.3	33.0	34.3	30.7	30.8	30.0	29.1
Relative humidity	%	50.7	46.7	37.9	35.4	46.6	42.4	64.5	64.4
Injection period	min.		80		70		55		75

Note: Performance was measured at IGV angle of 13°.

device and the gas turbine were stable during liquid air injection.

(1) Decrease in inlet temperature of compressor

Atmospheric temperature, atmospheric humidity and liquid air injecting flow have an impact on decreases in the inlet temperature of the compressor caused by liquid air injection. In this test, inlet air cooling was roughly attained as planned.

(2) Characteristics of increases in power output

The performance of the gas turbine is affected by restraints due to the atmospheric temperature and control. The inlet air cooling tests were carried out over a period of four days. Since atmospheric conditions varied with each measurement, the test results were compensated for comparison in terms of atmospheric temperature, atmospheric pressure, inlet air loss, exhaust gas loss, IGV angle, exhaust gas temperature and the like.

Fig. 7 shows the power output increase ratio before and after compensation. In Fig. 7 the ratio in increase of power output in cases where only a decrease in the inlet air temperature at the compressor inlet was considered was plotted, as well. The gas turbine power output was increased in excess of the ratio in increase of gas turbine power output in cases where only decreases in the inlet air temperature at the compressor inlet were considered. The reason for this is that when the condensed water drops generated by the liquid air injection vaporize in the interstage of the compressor, an intermediate stage cooling effect is produced and a relative increase in the power output is generated by decreasing the driving force of the compressor.

A characteristic of increase in the power output due to liquid air injection was verified in tests using the actual gas turbine for power generation, as well.

(3) Influence on gas turbines

Vibration of the shaft, combustion, exhaust gas content, etc. of the gas turbine including inlet air cooling device trip test from start to end of the test were not found to be abnormal while the gas turbine was operated in the normal condition.

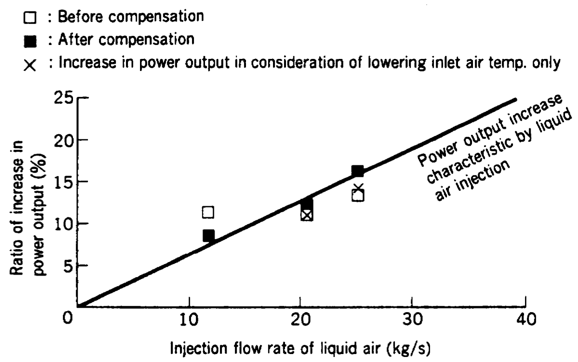

Fig. 7 Power output rate for 150 MW class gas turbine

In the inlet air cooling device trip test, the injection of liquid air was stopped from the injection flow of 30 l/s. When injection was stopped, a phenomenon in which both the power output of the gas turbine dropped immediately and the IGV angle changed instantaneously was observed, but thereafter operation stabilized at a power output level matching with that of the inlet air temperature and load command. It was confirmed in this test that there was no problem in the transient response of the gas turbine at the liquid air trip.

The test results verified the reliability of the gas turbine at the inlet air cooling operation, including at the inlet air cooling device trip.

6. Conclusion

Inlet air cooling tests using both a small-sized and actual gas turbine for power generation confirmed that the gas turbine inlet air cooling system using injected liquid air was effective in improving turbine performance. Further prospects for putting the liquid air injection technology to practical use were also obtained.

In the future the trial designs of the device applied to the actual gas turbine will be made making reference to the inlet air cooling test results and comprehensive studies will be conducted regarding putting the device to practical use both in terms of technology and economy.