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POWER OUTPUT INCREASE DUE TO DECREASING GAS TURBINE INLET TEMPERATURE BY MIST ATOMIZATION

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ABSTRACT

Decreases in inlet mass flow due to rises in ambient temperature during the summer lead to a decrease in the power output of gas turbines. In order to recover lost output, this study employed a mist atomization system using efficient spray nozzles, developed mainly as a technology for urban heat-island mitigation, installing the system in an inlet air flow path of a gas turbine at Higashi-Niigata thermal power station No.4 train, a commercial plant. The nozzles can efficiently decrease inlet air temperature of gas turbines because of their minute atomized mist size and highly-efficient evaporation properties. A flow path in the upstream of the inlet filter was used for mist evaporation by the system. This path is unique to the power plant, and is intended to prevent snow particles from direct entry. Model and field tests to confirm safe and effective operation of the system developed were performed in order to address possible concerns associated with the introduction of this system.

As a basic consideration, wind tunnel experiments using nozzles were performed. Through the experiments, the most suitable nozzles were chosen, and effectiveness of the mist atomization was evaluated. The basic specifications of the system were determined from the evaluation results. At the same time, flow-field in the inlet air channel of the intended gas turbine was analyzed, and positioning of the atomization devices optimized. The mist atomization system that was developed was installed in a gas turbine at the power plant.

To prevent excessive atomization from possibly causing erosion, a target value of 95% humidity at the compressor inlet was set, and a thermo-hygrometer was installed downstream of the inlet silencer to monitor humidity. As a result of the operation, no signs of erosion were detected in a major inspection conducted about one year following the introduction of the system. Another concern had to do with immediate changes in the state of the gas turbine due to mist atomization stoppages. To evaluate effects of the stoppages, field tests in the plant were performed, resulting in no significant changes in turbine inlet temperature and exhaust gas temperature. Combustion pressure oscillations was also not observed. From these results, it has been confirmed that the system can be operated safely. After activating the atomization system, inlet temperature decreased by up to about 7.5 degrees Celsius and power output increased by up to 13 MW in the gas turbine.

INTRODUCTION

It is generally known that the power output of gas turbines decreases due to ambient temperature increases. Inlet mass flow rate decreases because of ambient temperature increases and decreases in inlet air density, causing declines in output of gas turbine [1]. Demand for electric power increases in summers when ambient temperatures rise. Therefore, at the Higashi-Niigata thermal power station, water was sprinkled in gas turbine inlets for output recovery due to inlet temperature reductions. This existing equipment served to lower inlet temperature by about 2 degrees Celsius, resulting in increased power output by about 4 MW.

Further increase in power output was the aim of this study. In order to meet the sharp increase in demand for electric power in summer, efforts toward improving gas turbine inlet air cooling were conducted. The search for technology capable of more efficiently and greatly decreasing gas turbine inlet air temperature drew attention to mist atomization. Mist atomization is the technology that can efficiently cool air because of minute atomized mist size and highly-efficient evaporation properties.

The mist atomization technology with its efficient spray nozzles was developed mainly as a countermeasure for urban heat-island mitigation. Recently, the technology has come into wide use at outdoor event sites and outdoor commercial facilities. The aim was to obtain the effects of power output increase by introducing established state-of-the-art atomization technology in an existing commercial power plant without taking much time. The mist atomization system was to be introduced to a gas turbine inlet at the Higashi Niigata thermal power station.

A flow path in the upstream of the inlet filter was used for mist evaporation by the system. This path was unique to the power plant, and was formed as a countermeasure for heavy snowfall. In this case, erosion risk of air compressor blades and vanes could be reduced, compared with the case of the use of mist atomization in the inside of inlet duct.

In this study, basic consideration first took place to confirm the system's effectiveness and to set up the system. And then, the system was successfully introduced into the commercial power plant. A trial run period was then established with performance, effects, and influence of the system to be carefully investigated. Once it was established that there would be no problems, operation of the system continued until ambient temperature became low. This paper describes these processes and the obtained effects of power output increases in the actual plant [2]

BASIC CONSIDERATIONS FOR APPLYING MIST ATOMIZATION TECHNOLOGY

Mist Atomization Nozzles

As a first step, the most suitable nozzle with the largest amount of atomization mist was chosen from among four commercially-available varieties with atomized mist size of tens of μm. Experiments were conducted comparing atomizing mass flow rate under the same atomization pressure. Figure 1 shows the comparative experimental results of the amount of mist. Nozzle 2 in this figure was chosen. Table 1 shows the nozzle specifications provided by the manufacturer.

Evaluation of Effectiveness of Mist Atomization by Model Experiments

Model experiments were conducted in order to evaluate effectiveness of the mist atomization system.

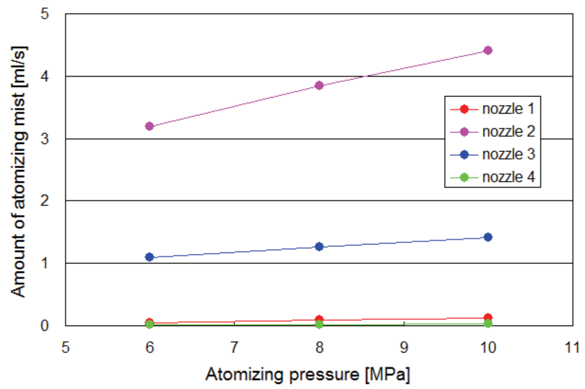


Fig. 1 Comparative experimental results

Table 1 Chosen nozzle data

Nozzle type	Particle size data			
	Spray derection	Spray Distance[mm]	Pressure[MPa]	Sauter mean diameter[μm]
YB1/8HJ-SS10	horizontal	500	5.9	20.9
			6.9	20.7
			7.8	20.2
			8.8	20.1
			9.8	19.7

This data are provided from Spraying Systems Co., Japan

Experimental Apparatus and Conditions

Figure 2 shows model experimental apparatus and Table 2 shows experimental conditions. The chosen nozzle type was then set in the duct. Air temperature and humidity were varied by using air conditioning equipment, and the air was led into the duct by a blast fan. Temperature and humidity changes between upstream and downstream portions of the nozzle were measured by setting up thermohygrometers in each position. Experiments were conducted under four dry bulb temperatures from 15-35 degrees Celsius, four relative humidity values from 30-80%, and a velocity range of 10-18 m/s. There were in all 25 cases of the various combinations.

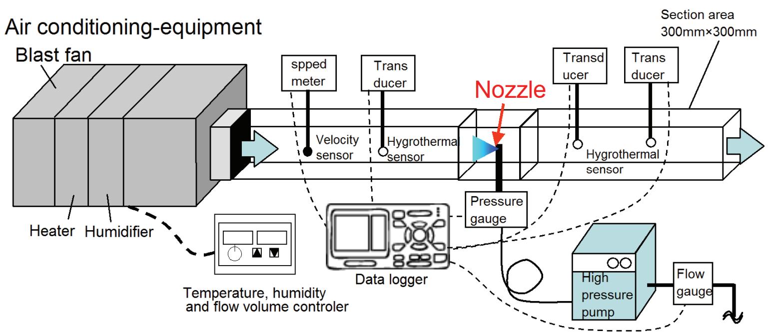


Fig. 2 Experimental apparatus

Table 2 Experimental conditions

Dry-bulb temperature	15, 20, 25, 30, 35 [degrees Celsius]
Relative humidity	30, 50, 70, 80 [%]
Center velocity	10-18 [m/s]
Total case number	25

Experimental Results

The results of the model experiments clarified the effects of mist atomization on temperature decreases. Figure 3 shows the amount of temperature decrease between upstream and downstream portions of the nozzle under 30% humidity, as a representative case. In this figure, the black line signifies temperature decreases between upstream and downstream portions of the nozzle where downstream temperature was decreased to wet-bulb temperature, calculated from dry-bulb temperature and relative humidity in upstream air. This wet-bulb temperature had a saturated air temperature of 100% humidity and indicated limits in air temperature decrease. Figure 3 demonstrates the effectiveness of mist atomization because air temperature in the downstream portions of the nozzle could be decreased to nearly wet-bulb temperature in all temperature experimental conditions. Additionally, air temperature could be decreased to wet-bulb temperature under other humidity conditions as well as the 30% humidity experiment [3]. Positive proof of this approach for introducing mist atomization system into the power plant was therefore obtained by conducting these model experiments.

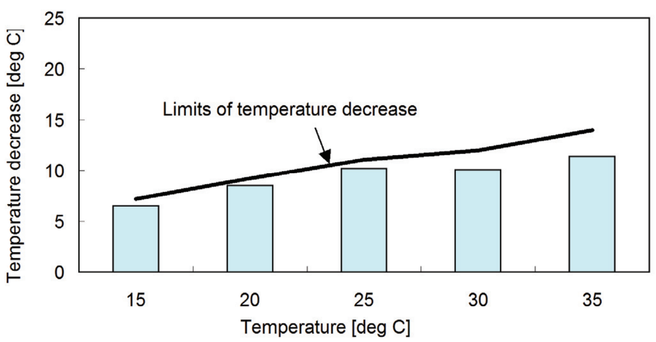


Fig. 3 Temperature decrease between upstream and downstream

Flow Field of Inlet Air Path

Flow field in the inlet air path of intended gas turbine was analyzed for the purposes of evaluating actual internal conditions and for determining positioning of atomization nozzles.

Inlet Air Path of the Intended Gas Turbine

The intended gas turbine has a unique inlet structure making an inlet air path. This structure was built as a countermeasure for heavy snowfall because the Higashi-Niigata thermal power station is located in a comparatively snowy region. The flow path is shown in Figure 4. Ambient air is sucked in from an air inlet tower atop the roof, then flows down to air inlet filter rooms. In the last portion of the inlet filter rooms, air is then cleaned by inlet filters, and flows into air compressor through an inlet duct. One-half the amount of inlet ambient air is sucked in from right or left sides of the gas turbine.

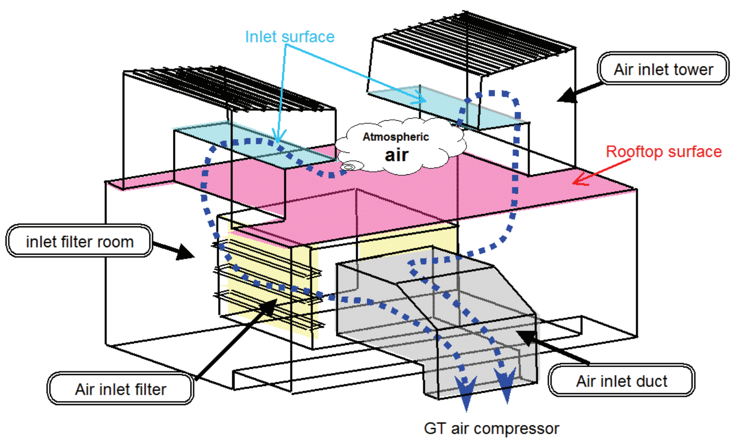


Fig. 4 Flow path of inlet air

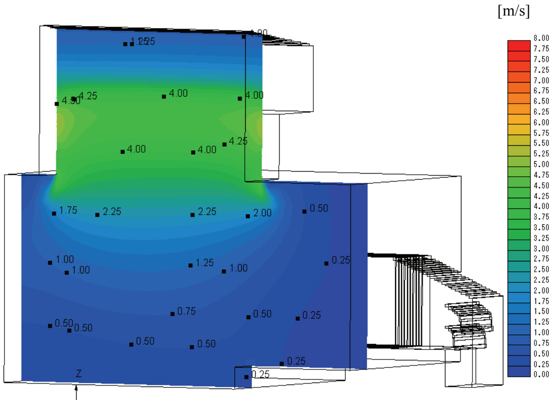
Numerical Analysis

The flow fields and velocity distributions of half of the inlet flow path were analyzed using a mirror condition because the path is symmetric. The conditions of the numerical analysis are shown in table 3. This analysis was conducted using a general-purpose numerical analysis software, STREAM, and standard k-ε model as a turbulence model.

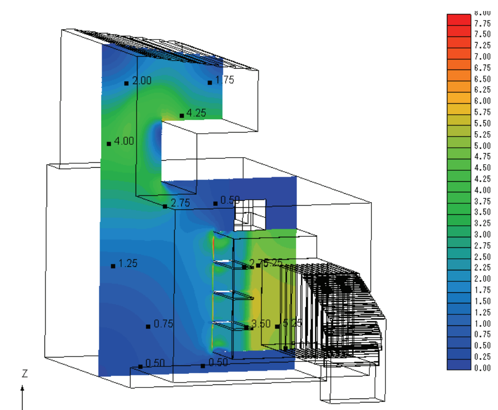
The results are shown in figure 5, where (a) is a contour figure of velocity distribution at the gas turbine's axial section and (b) is the result at a vertical section. At the air inlet tower, turbulence intensity was strong with flow velocity also high. However, after passing down to the inlet filter room, flow rapidly stabilized, followed by another velocity increase in front of the inlet filters. Flow fields and velocity distributions in the inlet air path were thus clarified.

Table 3 Conditions of numerical analysis

Turbulence model	Standard k-ε model Steady state (isothermal condition)
Calculation code	STREAM (general-purpose software)
Cell number	2×10^{6} cells



(a) At gas turbine axial section



(b) At gas turbine vertical section

Fig. 5 Contour figures of velocity distribution

INTRODUCING THE SYSTEM IN A REAL PLANT

Hereafter is described considerations to introduce the mist atomization system into the actual commercial plant.

Intended Gas Turbine

The intended gas turbine was 4-4GT, a gas turbine of the No.4 train at the Higashi-Niigata thermal power station with a rated output of 284MW. The gas turbine specifications are shown in Table 4.

Table 4 Intended gas turbine specifications

Rated power of GT (Rated power of plant)	284MW (1610MW)
Tubine inlet temperature	1450°C
Unit thermal efficiency (LHV)	about 56%
Manufacturer	MHI, Ltd.
Operating company	Tohoku epco.
Start of commercial operation	2006.12

Positioning of Atomization Nozzles

The positioning of atomization nozzles was very important for getting a larger effect of inlet temperature decrease due to mist atomization. A good point of the mist atomization was to improve inlet temperature decreases due to the highly-efficient evaporation of mist by atomizing water particles to minute size. It was thus most important to make more atomization mist evaporate in the space upstream of the inlet filter to achieve the maximum effect of this system. The generation of useless mist that cannot be evaporated due to growth in particle size, and thus becoming nothing more than drainage water, was believed to be the worst outcome. Conditions of nozzle positioning to which most attention was paid at the time were as follows:

1. Maintain a steady flow field
   A position of less turbulence and low velocity should be chosen since the possibility of useless mists accruing due to gathering of mist particles would increase under a flow field of strong turbulence or high velocity.
2. Minimize obstacles
   The nonexistence of obstacles as much as possible was needed to prevent mist particle from turning into useless drainage water when colliding with such obstacles. For example, beams were avoided.
3. Keep some distance between nozzle and inlet filter
   In order to obtain a residence time for evaporation of more atomization mist, sufficient space was ensured between nozzle position and the inlet filter.
4. Workability of installation and maintenance.
   Workability for installation and for subsequent maintenance was also important in the case of actual equipment.

As a result of considering the conditions mentioned above and the results of previous numerical analyses, the position of the bottom of the air inlet tower where turbulence begins to weaken was determined as the optimal nozzle position.

Composition and Specifications of the System

Basic specifications of the system were determined from a rated amount of inlet air of the intended gas turbine and the highest climatic temperature in Niigata. From factors of temperature, humidity, and the amount of the inlet air, the necessary amount of water for the system was calculated. This amount of water could evaporate about 11t/h. A maximum atomization pressure of 10MPa and a requirement of 700 nozzles were derived from the experimental results of the nozzle atomization described above. Multiple independent systems using ten small capacity pumps were chosen as the composition of mist atomization water supply for decentralization and reduction of failure risk. In order to adjust the amount of atomization water to fluctuating atmospheric conditions, a pump number control method using 10 pumps specifying the amount of atomization was chosen.

Figure 6 shows the composition of the mist atomization system introduced. Five nozzle headers were set up in positions

I and II (see figure 6, this position was discussed above), and about 70 nozzles were set on each header. Ten pumps were used each with individual receiving tanks. Five units were set up at positions of III and IV (see figure 6). The maximum specifications of the mist atomization system are summarized in Table 5. However, because the maximum specifications became unnecessary in actual operation, as will be described later, only about 70% capacity has been in operation. And demineralized water is used in the system. Figure 7 shows the mist atomization situation in which this system is operated.

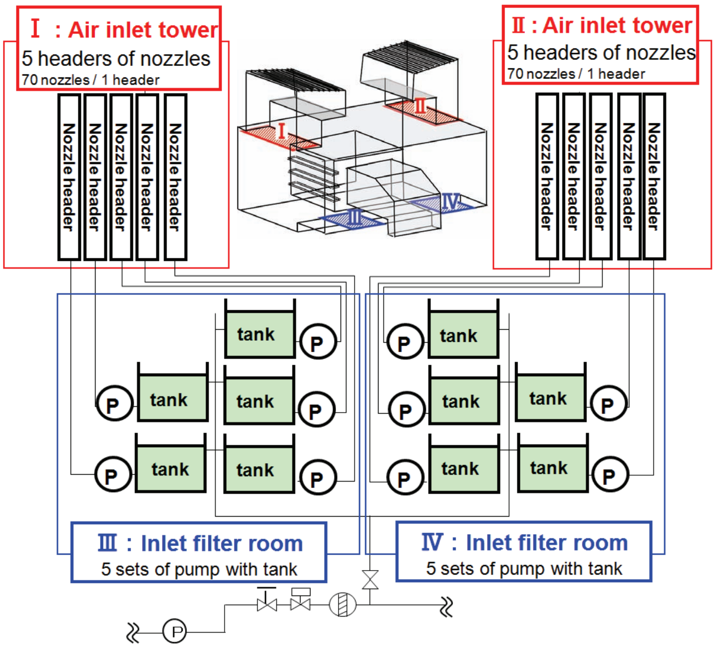


Fig. 6 Composition of the system

Table 5 Maximum specification of the system

Pump type	Plunger type	
Pump discharge rate	Over 20L/min	
Pump discharge pressure	6-12MPa	※
Tank capacity	140L(Full level)	
Nozzle number	Over 700	
Atomization pressure	Maximum 10MPa	
Atomization flow rate	Maximum 11t/h	
Nozzle pore size	0.28mm	

※ These values are shown per 1 unit of pump and tank

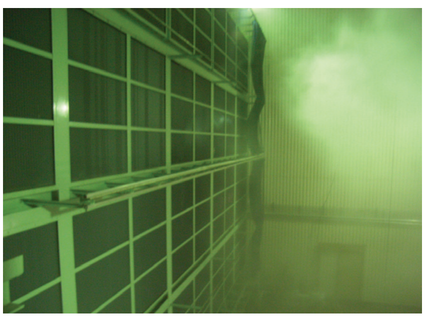


Fig. 7 Mist atomization situation

PROBLEMS DUE TO MIST ATOMIZATION SYSTEM INTRODUCTION

Influences of the System and Safety of Gas Turbine Equipment

There had been no prior results involving atomization of minute water particles of tens of μm in upstream portions of the gas turbine air filter. Therefore, there were some serious concerns about the possible effects it might have on gas turbine equipment accompanying the introduction of the mist atomization system into the gas turbine inlet. Those concerns were addressed as follows.

Erosion on Compressor Rotor Blades and Stator Vanes

The risk of erosion on the compressor rotor blades and stator vanes was reduced significantly by means of atomizing mist into the upstream portions of the gas turbine's inlet filter in this system, compared with the case of atomizing mist into the inlet duct. However, in the case of inlet air super-saturation due to mist over-atomization, it was difficult to evaporate all of the atomizing mist. So there was concern that erosion of the compressor rotor blades and stator vanes was caused by the minute mist particles passing through filters [4, 5].

A decision was made to avoid super saturation of inlet air completely as a countermeasure for blade and vane erosion. By setting up a temperature and humidity measurement system with thermo-hygrometers, shown in Figure 8, the humidity in the air compressor inlet was able to be monitored at all times while the mist atomization system was being driven. In order to precisely manage humidity of compressor inlet (see F in figure

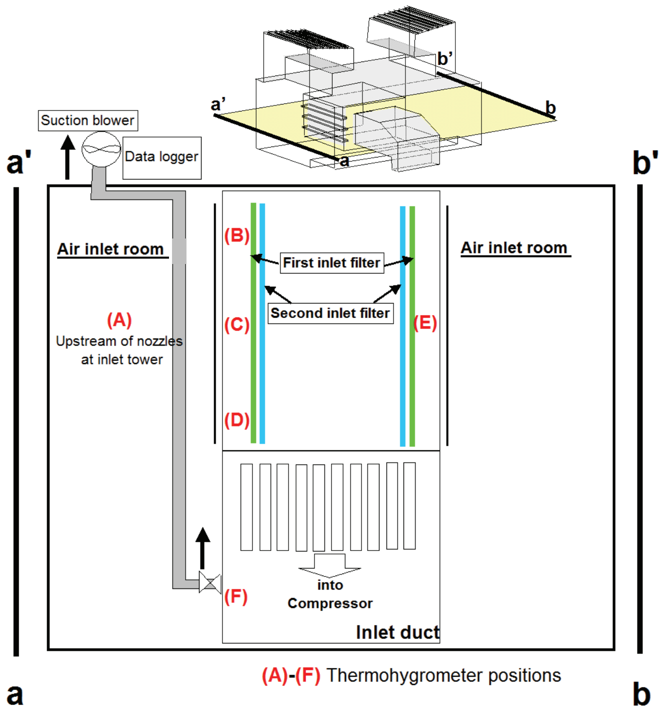


Fig. 8 Temperature and humidity measurement system

8) should the humidity measurement value there reach 95% or more, the mist atomization system was stopped.

In this way, the humidity in the compressor inlet almost was maintained at 95% or less, though humidity in there exceeded the limiting value somewhat (about 2%) occasionally for the trial run period or in field tests. Now, a controlling value of 90% has been installed for greater safety, and humidity has been automatically controlled.

The mist atomization system was in operation from July to November in fiscal 2008. One result was that no signs of the feared erosion damage on rotor blades or stator vanes were detected in a 4-4GT major inspection conducted about one year following the introduction of the system. From this result, it was validated that compressor rotor blades and stator vanes erosion could be avoided by keeping compressor inlet humidity at 95% or less.

Moreover, in relation to the thermo-hygrometer system, temperature and humidity were measured in not only the compressor inlet, but also in the upstream portion (1 position, See A in figure 8) of the mist atomization nozzles at air inlet tower and also the upstream portions of the inlet filters (4 positions, See B, C, D and E in figure 8). Monitoring of inlet air conditions in each position and determination of driving pumps numbers (equal to the amount of mist) were then performed.

Overshooting Temperatures after Mist Stoppage

There was a possibility that turbine inlet temperature (here after, TIT) and exhaust gas temperature might temporarily overshoot when some atomization pumps were stopped simultaneously and exceed their limit values.

When the supply of mist is stopped all together, inlet air temperature soars and inlet mass flow decreases in an instant. Therefore, until the control feedback reduces fuel mass flow, TIT and exhaust gas temperature temporarily soar.

To evaluate effects of mist supply stoppages, field tests involving the simultaneous stoppage of all driving pumps were performed.

Reducing Effects of Stoppages due to Inlet Filters Getting Wet

Figure 9 shows temperature and humidity measurement results. The values in the compressor inlet were measured at the position of F in figure 8, and the values in upstream portions of inlet filters were average of results in B, C, and D shown in Figure 8. This result was obtained during field test involving the simultaneous stoppages of eight pumps. Temperature and humidity in upstream portions of the inlet filters showed rapid change after the pump stoppages, but those in compressor inlet, on the other hand, showed delayed changes and smaller change rates. Results of the other tests showed the same tendency to a greater or lesser extent.

It was presumed that this tendency was caused by the filter getting wet. It is difficult to avoid increase of the grain diameter for certain amounts of atomization mist because of cohesion of the mist and collision with obstacles. Such mist is captured as droplets by the inlet filters. It was presumed that the captured droplets continued evaporation and deprived inlet air of heat evaporation. It can be thought that this phenomenon was the reason for the slower change of temperature and humidity in the compressor inlet after the pump stoppages. These field tests clarified that this wet filter effect lessened the effects of mist atomization stoppages more than was originally expected.

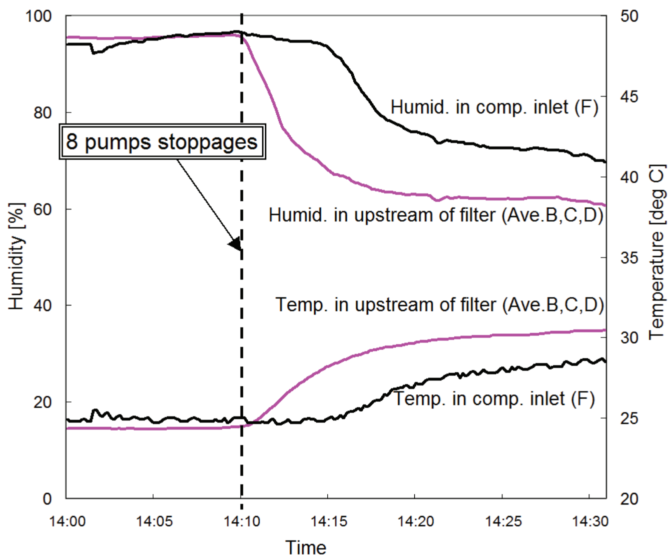


Fig. 9 Slow changes of humidity and temperature in compressor inlet after pump stoppages

Effects of Maximum Amount of Mist Atomization Stoppages on Overshoots

It could be clarified that operating this mist atomization system presented no problem in terms of increases of TIT and exhaust gas temperature.

Figure 10 shows the field test result of eight simultaneous pump stoppages, and that there was little effect of atomization stoppage on the temperature overshootings in the case of eight pumps being stopped.

When the ambient conditions were high temperature and low humidity, ten pumps could be driven, and the maximum amount of mist in this system was thus atomized. After it had been confirmed that the state of the gas turbine was sufficiently stabilized, field test involving the simultaneous stoppages of ten pumps was performed to evaluate the overshoot behaviors of TIT and exhaust gas temperature in the case of maximum amount of mist stoppage. The result of the test is shown in Figure 11. Overshoot of exhaust gas temperature was considered to be negligible, at about five degrees Celsius. On the other hand, overshoot of TIT was less than fifteen degrees Celsius, and it was also within acceptable levels. In the comparison figure 11 with figure 10, the number of operating pumps, or the amount of atomization mist, mainly determined the increases in temperature overshoots because overshoots in the case of 10 pumps stoppages were relatively large while absolute value was within acceptable levels, though the values shifted up-and-down somewhat along with conditions in the inlet filter and atomization, as previously discussed. Even in the case of maximum amount of mist stoppage, there was no temperature increase to levels concerned. And it was confirmed that there was tolerance of temperature increase in both the turbine inlet and exhaust gas.

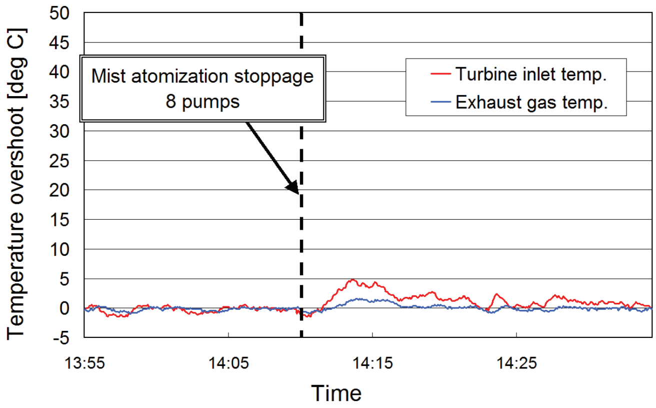


Fig.10 Temperature overshoots in the case of 8 pump stoppages

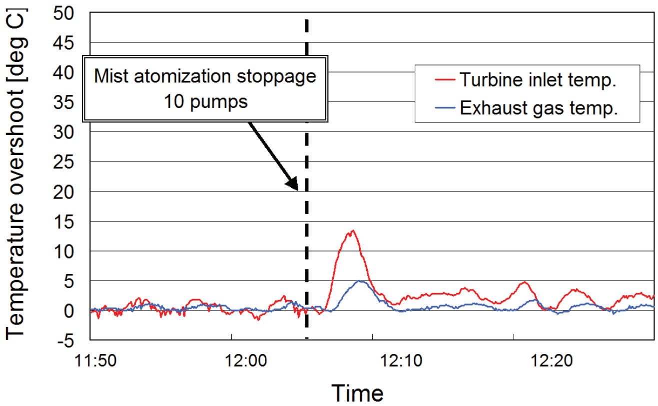


Fig.11 Temperature overshoots in the case of maximum amount of mist atomization (10 pumps)

Effect of Mist Stoppages on Combustion Condition Changes

One of the most serious concerns had to do with the generation of combustion pressure oscillation. Until the control feedback of fuel flow control is stabilized, air-fuel ratio decreases temporarily with inlet mass flow decreases, due to mist stoppage. Therefore, it was possible that the combustion conditions change greatly, raising initial concerns about generation of combustion pressure oscillation. As a result of the field tests of maximum amount of mist stoppages, changes were not observed in the data on combustion pressure oscillation. Moreover, no such trouble was found in the results of other tests.

EFFECTS OF OUTPUT INCREASE IN THE SYSTEM

No significant problems due to the operation of the mist atomization system were detected from results of evaluating system performance and system influences on the gas turbine for the trial run period. Therefore, operation of the mist atomization system continued throughout the period until atmospheric temperature decreased (2008.09-2008.11). The effects of output increase in that period are described as follows.

Long-Term Operation Results

The data in the case where compressor inlet humidity as 95%±2% and that the driving gas turbine state was roughly stabilized were extracted from the system's long-term operating data.

Figure 12 shows the temperature decrease between temperature in the upstream portion of the nozzle (see A in figure 8) and compressor inlet temperature (see F in figure 8) against ambient humidity. In the mist atomization system, the lower ambient humidity, the more amount of mist can be evaporated and the larger effect of inlet temperature decrease can be obtained. In figure 12, temperature decreases shows a clear inverse proportional relationship to ambient humidity. And it can indicate the effects of temperature decreases due to mist atomization. Moreover, in figure 13, the output increase ratio to power output characteristics (at 75% in ambient humidity) of the subjected gas turbine 4-4GT is shown against inlet temperature decreases. A clear proportional trend between output increasing effects and inlet temperature decrease is demonstrated in this figure. These two figures confirm the targeted effect of power output increases due to decreasing inlet temperature by mist atomization.

In figure 14, the output increase ratio to power output characteristics is shown against ambient humidity. It is clear that a power output increase effect due to the mist atomization becomes larger as ambient humidity decreases. When averaging in each ambient humidity band, the power output increase ratios to characteristics are about 4% in the 40%-50% humidity range, about 3.5% between 50%-60% humidity, about 2% between 60%-70% humidity, and about 1% in the 70%-90% humidity range. Thus, it can be confirmed that the output increase effects can be obtained as the equivalent of ambient humidity at all humidity bands.

Additionally, in figure 15, the output increase ratio to power output characteristics is arranged by ambient temperature. This figure demonstrates that an output increase can be obtained at a comparatively lower ambient temperature around fifteen degrees Celsius and at a middle ambient temperature band. Thus, the output increase effect of the system is obtained not

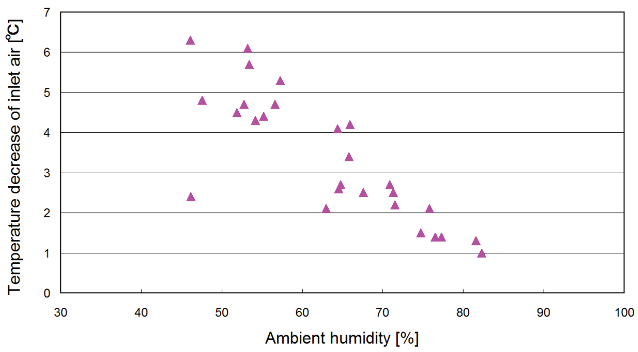


Fig. 12 Temperature decrease between upstream and downstream portions of nozzles

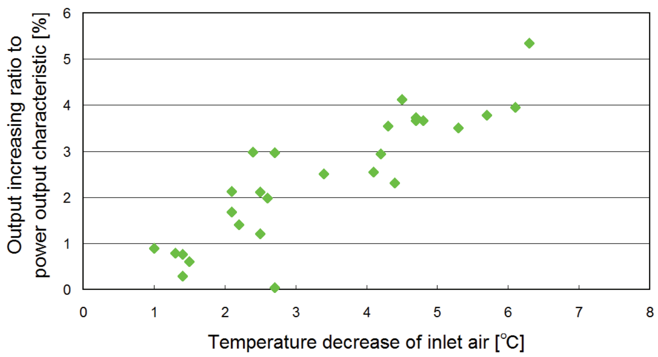


Fig. 13 Output increase due to inlet temperature decrease

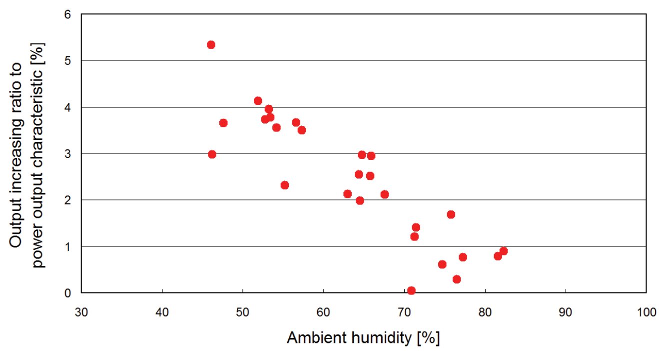


Fig.14 Output increase due to inlet humidity

only in summer as a high ambient temperature season, but over long periods showing a broad range of ambient temperature.

Maximum Output Increases in the System

The atmospheric conditions in which maximum amount of the mist could be atomized were satisfied one day in September of 2008. The conditions were high temperatures and low humidity. Maximum amount of the mist atomization was

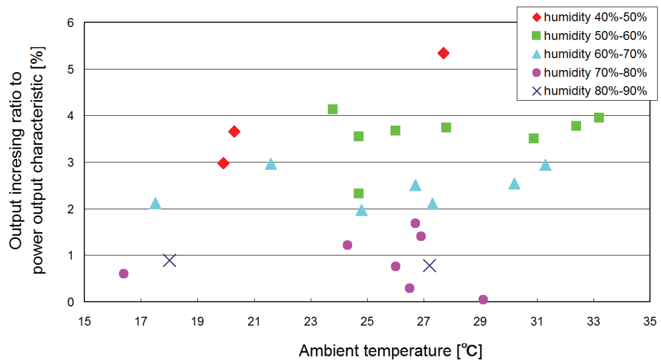


Fig. 15 Output increase at a broad range of temperature

accomplished by driving ten (the total number of atomization pumps) pumps on the morning of this day one by one. When the gas turbine was operated in the rated load, the first six atomization pumps were started at ten o'clock, and other four pumps were started one by one. Then, ten pumps were driven at the same time for about one hour or more. Finally, after it was confirmed that the gas turbine state was steady, a field test involving the simultaneous stoppage of all ten pumps was conducted. From the start of the first six pumps to the end of the field test, there was little change in atmospheric conditions. The conditions of the driving and the stoppage test are shown in Table 6. The time series behaviors of the gas turbine inlet temperature and power output while the pumps were being driven and stopped are shown in figure 16. As a result of the mist atomization, compared with conditions before the atomization, the inlet temperature decreased by about 7.5 degrees Celsius and inlet mass flow rate increased by about 2%. Gas turbine output was increased by about 13 MW, representing increase of 6%.

Table 6 Atomization conditions

	Before atomization	During atomization	Amount of change	After atomization
Ambient temperature [degree]	28.9	29.9	-1	29.7
Ambient humidity [%]	46.4	42.2	4.2	42.8
Ambient Pressure [hPa]	1013	1012	-1	1011
Number of driving pumps	0	10	-	0
GT inlet temperature	30.4	22.9	7.5	30.0
Ratio of GT output	–	+5.5	+5.5	-
Inlet mass flow increase [%]	-	+2	+2	-
pump starting time	pump 1	10:00	pump 6	10:00
	pump 2	10:00	pump 7	10:24
	pump 3	10:00	pump 8	10:24
	pump 4	10:00	pump 9	10:50
	pump 5	10:00	pump 10	10:50

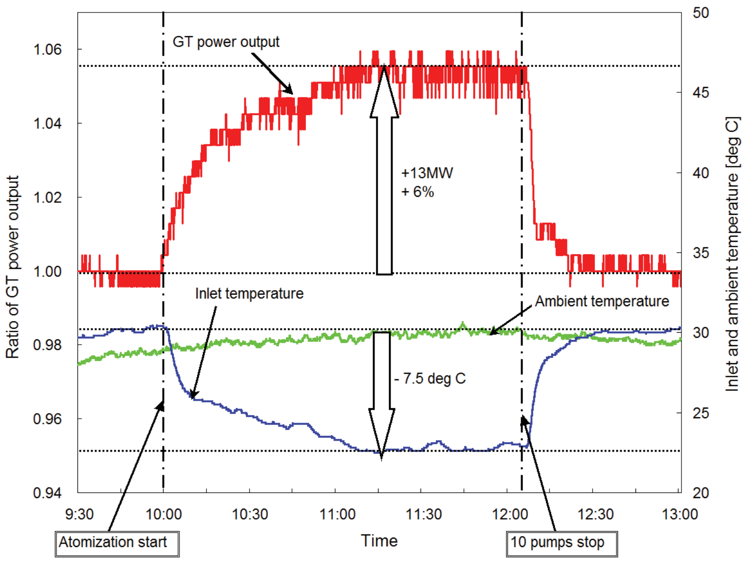


Fig. 16 Maximum effect of mist atomization

CONCLUSIONS

In order to obtain effects of power output increases, efforts toward decreasing gas turbine inlet air temperature using mist atomization technology were conducted. The mist atomization system was then introduced to an actual commercial plant, the Higashi-Niigata thermal power station, and evaluating its influence and effectiveness was conducted. As a result, the following conclusions have been obtained.

1. Effectiveness of mist atomization was confirmed through model experimentation of a mist atomization system, and base specifications of the system were determined from the results of the experiments and the numerical analysis of the inlet flow path.
2. A mist atomization system was designed utilizing the unique inlet flow path of the Higashi-Niigata thermal power station. In this system, it was possible to significantly reduce erosion risk of compressor rotor blades and stator vanes through mist atomization in upstream portions of inlet filters.
3. Operation of this mist atomization system did not produce any serious problems to the gas turbine equipment nor to the stable operation of the gas turbine resulting from field tests and system operation.
4. A power output increase effect of this system was obtained as follows.
   (1) Power output increases can be obtained over the long term during not only periods of higher ambient temperatures but also during periods of relatively low ambient temperatures.
   (2) In the case where a maximum effect as obtained, inlet temperature decreased by 7.5 degrees Celsius and power output increased by 13 MW, for a 6% increase.

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