PERFORMANCE ENAHANCEMENT OF GT 24 WITH WET COMPRESSION

by

Sanjeev Jolly, P.E.
Scott Cloyd
Caldwell Energy Company
Louisville, Kentucky, USA

Abstract:

The performance effects of applying wet compression to an advanced frame combustion turbine, the Alstom GT-24, are presented and contrasted to the performance of mature Frame combustion turbines that have been operated with wet compression systems for many years. The performance comparisons are based on combustion turbines that are equipped with evaporative cooling systems and dry low NOx combustion systems. The paper addresses the relative changes in compressor and turbine operating conditions and how these affect component life. Wet compression is not just haphazardly spraying water into the compressor inlet; care must be taken as there is an expensive and high precision turbine downstream. The system must be properly integrated with the turbine and turbine controls and any issues or concerns with wet compression must be thoroughly evaluated and addressed. The paper also reviews current assessment of applying wet compression systems to combustion turbines and provide performance and economic comparisons to alternative power augmentation technologies for these products.

Introduction:

Early experimentation with the continuous injection of large volumes of water into a compressor inlet, now referred to as Wet Compression (aka High Fogging, Overspray, supersaturation, inter-cooling, Inlet Fog Boost and Continuous Water Washing) began in the early 1990's. Being pioneers in the use of on-line compressor water wash systems, the Dow Chemical Company Employees began a program to determine how much water could be injected into the inlet of a W501A combustion turbine, a 1968 vintage turbine rated at 40 MW. Working together with engineers from Westinghouse Electric Corporation, an astounding increase in base load power output of 25% was achieved. The Dow Chemical Company was awarded Patents for this work and wet compression technology. Since that first system was designed and installed, there have been many design enhancements to the injection system, spray atomization nozzles, system controls, rotor grounding devices, and turbine hardware to reliably apply wet compression systems to combustion turbines. System and spray technologies applied to the wet compression process continue to be developed further.

The W501A combustion turbine was designed with an operating pressure ratio of 7.5:1. It had a firing temperature of 1615º F at the rotor inlet. Cooling air was provided to the row 1 turbine vane and to the rotor discs using an external cooling unit to cool the rotor air to 180º F. The compressor had air extractions for start-up, but did not use bleed air for any cooling purposes.

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At the time the prototype wet compression systems were applied in 1995, the combustion turbines had operated for nearly 200,000 fired hours. The compressor blades and cylinder had evidence of rubs from casing distortion due to upset operating conditions and an outdoor installation that allowed the casing to be cooled unevenly when it rained. Therefore, the water could not be carried from the compressor bleed points to the cooling passages of hot parts and the compressor blade tip clearances were already opened providing added margin for casing distortion.

Following the successful demonstration of wet compression on the W501A, a complete fault tree analysis was performed by Westinghouse Engineers to evaluate the application of the wet compression on a more modern combustion turbine, specifically, the W501D5A. This is a 120 MW rated combustion turbine with pressure ratio of 15:1, firing temperature of 2150º F at the rotor inlet, three compressor bleed air stages to provide cooling air to the turbine stages at the matched pressure requirements, and use of rotor air coolers. On many stages, the aerodynamic efficiency was improved by reducing the as-designed blade tip clearances. The units were in new and clean condition. Dry low NOx Combustion systems had also been introduced on this turbine, which required the development of control logic that was interactive with wet compression system operation.

To accommodate these advanced design features, the amount of water that was injected into the compressor, as a percentage of inlet air flow rate was reduced from 3% to 2%, or less, depending on the application specifics. Design concerns of water flowing into the compressor bleed lines were addressed with the addition of traps and drains on the low pressure compressor bleed lines. Also, as will be explained later, there is a change in the work distribution in the compressor, similar to a cold day operation, where a greater amount of work is done by the rear stages of the compressor and all stages of the turbine experience an increase in pressure, changing the relationship between supply and sink pressures in the cooling circuits. Therefore, modifications to intermediate and high pressure cooling circuits were required with the application of wet compression systems.

Erosion of compressor blades has also been a concern that has been closely monitored. A borescope inspection of a compressor was performed after a year of operation, with fogging and wet compression systems, at the Cardinal Cogen facility in Stanford University. The erosion observed from this operation and other units has been much less severe than some advanced frame combustion turbines with fogging systems. Experience with wet compression has been beneficial in helping customers address erosion issues with fogging systems.

The most advance combustion turbines with wet compression applied to-date are the Alstom GT-24 and GT-26 machines. These turbines are rated at 170 MW and 240 MW, respectively. They operate at pressure ratios of 28:1, have sequential dry low NOx combustion systems, and have elaborate cooling systems and metallurgy. With the application of wet compression systems, engineers addressed many of the same design concerns as had been done with predecessors.

The results of the performance testing with these combustion turbines are presented to compare and contrast the performance trends of gas turbines, as wet compression systems are operated at various levels. In developing these trends, the combustion turbine performance changes resulting from wet compression are estimated since the specific application of the GT24 application is based on a single shaft arrangement, where the combustion turbine and steam turbine drive a common generator.

The effects that wet compression has on turbine component temperatures and component life expectations are also discussed, since the results are much more favorable than with conventional steam and water injection systems or new supplemental compressor train based augmentation systems . The final section of the paper will provide some current cost / benefit comparisons of wet compression to other available augmentation systems such as inlet fogging, inlet chilling, and humid air injection.

Wet Compression Process Description:

Wet compression is a process in which small water droplets are injected into the compressor inlet air in a proportion higher than that required to fully saturate the air. As the air gets heated during work of compression, the "excess" moisture is absorbed by the air in subsequent compressor stages. Since it takes less energy to compress relatively cooler air, there is reduction in compressor work. A reduction in compressor work directly translates to increase in net turbine output since one-half to two-thirds of a turbine output is used to drive the compressor.

Another important contributor to increasing the turbine capacity as a result of wet compression is the ability to fire more fuel in the combustor, without raising the firing temperature. Because of the evaporative process in the compressor stages there is a reduction in the compressor discharge temperature. A lower entering temperature in the combustor allows more fuel to be added without raising the firing temperature. This is the reason why wet compression has also been occasionally utilized to reduce the firing temperature in cases where firing temperatures of units without wet compression systems in service have caused concerns with turbine component life and increased maintenance.

The third factor that contributes to increase in turbine capacity is due to increase in mass flow rate as a result of water spray and increased fuel flow, since turbine output is directly proportional to the mass flow rate.

Compressor Blade Erosion:

There are concerns associated with introduction of water droplets to the compressor inlet – the main one being the compressor blade erosion. There are other factors that need to be considered in the design – turbine casing distortion, dynamic pressure monitoring to safeguard combustor components, effects of excessive moisture in the compressor bleed lines, grounding of rotor to reduce static discharge and effect of demineralized water on duct liner panels. With thorough design considerations, the risks associated with wet compression can be properly managed. One must remember that there is a far more expensive and sophisticated machine downstream that must be carefully monitored and safeguarded.

Erosion resulting from water droplets impacting compressor blades has been a concern with any system that introduces water droplets at the inlet of a compressor. One of the major advantages of wet compression systems over fogging systems used for overspray purposes is the placement of the nozzles based on knowledge and patented processes from Dow (references 2&3). A result of locating the spray nozzles near the compressor inlet, as opposed to an area closer to the inlet filters is that the potential for droplet agglomeration and coalescence on objects within the duct are minimized. Therefore, the size of the droplets entering the compressor closely match those produced by the nozzles (This has been confirmed during shop testing of the GT-26 with a wet compression system, as reported in the 2003 ASME IGTI Panel Session on Inlet Fogging). Hence much attention in the development of wet compression systems remains focused on spray nozzles.

Recent erosion issues with fogging systems installed on GE7FA combustion turbines have highlighted this effect. In applications where the fogging nozzles have been installed in a section of extended duct downstream of the inlet silencing panels, droplets have coalesced on downstream components such as trash screens and grown into large droplets resulting in higher rates of compressor blade erosion. User intervention and maintenance resulting from this operation was required in as little as 200 to 300 hours of operation which was more severe than wet compression experience on other industrial frame gas turbines, which intentionally consumed much greater quantities of water to the compressor. The design modifications made to the compressor blade of this CT to make it more tolerable to erosion still do not address the cause of erosion. Solutions to these issues are being implemented and will be the subject of a future papers.

The results of a borescope inspection performed on a GE Frame 6B combustion turbine, after 1,300 hours of fogging and 1,100 hours of wet compression operation showed that erosion was present (See Figures 1A-C below) as is with all operating turbines with wet compression. Most of the erosion from wet compression occurs across the leading edge of the first rotating compressor blade. This blade helps to further atomize the droplets and sling them radially outward, as evident from the erosion on downstream airfoils being oriented more toward the compressor blade tips. Long term experience, 25,000 hours of wet compression resulted in a change in blade chord length of approximately 40 thousandths of an inch of a first stage compressor blade on a 120 MW combustion turbine. Inspection of the first stage of the GT-24 compressor showed similar wear patterns after more than 6,000 hours of wet compression system operation (See Figure 1-D). Use of latest nozzle designs and proprietary practices are expected to further reduce erosion by reducing droplet size.

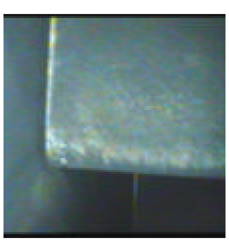


Figure 1A – GE 6B
1st Stage Blade Tip

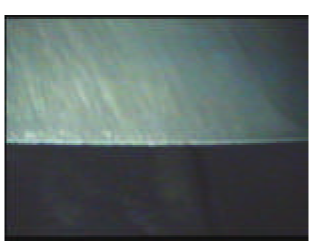


Figure 1B – GE 6B
1st Stage Blade Mid-Height

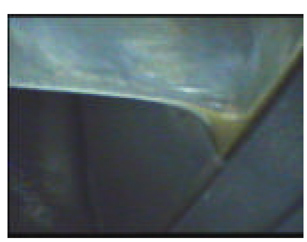


Figure 1C – GE 6B
1st Stage Blade Hub

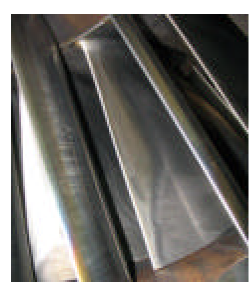


Figure 1-D GT-24
1st Stage Blade (Center)

System Description:

Wet compression system was successfully employed on a GT 24 at the Hermosillo jobsite in Mexico. The system was designed to spray 71 gpm (4.47 kg/sec) of demineralized water into the compressor inlet at a pressure of 2,000 psig (137.9 bars). The design dry bulb temperature was 80ºF (26.7ºC) and the design wet bulb was 79ºF (26.1ºC). These design dry and wet bulb temperatures were chosen because the wet compression system is installed downstream of evaporative cooler.

The small water droplets are created by specially designed nozzles that are optimally located near the compressor inlet so that water droplets stay small as they enter into the compressor inlet. See Figure 2 for location of the spray nozzles. The number and location of nozzles in each array was arranged to match with the air flow distribution in the inlet duct based on a CFD analysis. These nozzles are multi-faceted to increase water flow through each nozzle so as to minimize the number of nozzles in the available space.

Figure 2: Nozzles Arrays mounted in the duct.

Figure 3: Zones valves for water flow distribution.

The nozzles are welded to stainless steel pipe. These pipes with nozzles mounted on them are called nozzle arrays. Each zone has more than one nozzle arrays to control the amount of water sprayed into the inlet. Water through each zone is controlled by valves mounted on the roof of the turbine housing (See Figure 3).

The high pressure water is delivered to the nozzles by means of a high-pressure single-stage Pitot-tube pump. The water enters through the suction line into the rotor where it is accelerated. The water pressure is dictated by centrifugal force. A pitot tube is placed inside the rotor and has a circular opening near the largest rotor diameter. As the rotating water hits the pitot tube opening, the speed is transformed into pressure energy.   See Figure 4 for the pump used for this application. Also note that the pumps, instruments, electrical gear and MCC are placed inside a weather protected enclosure. The complete assembly was shop-fabricated and delivered in one-piece to save field installation time.   The enclosure is air-conditioned to remove heat generated by the pump and other auxiliaries.

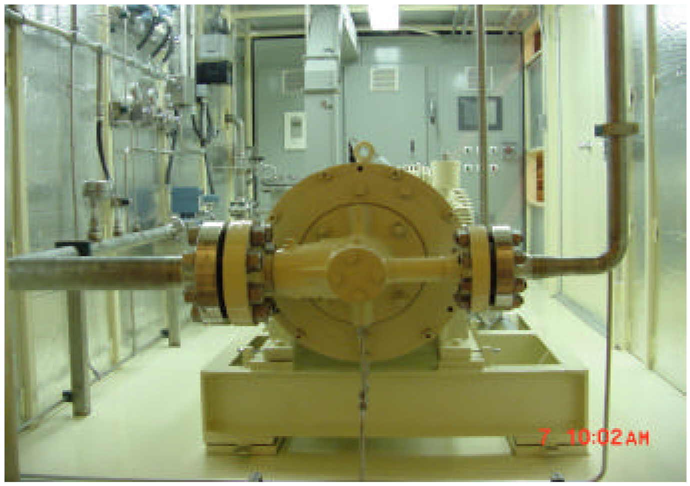


Figure 4: Pump Skid for High Pressure Water Delivery to the Nozzles

Performance Comparisons:

Wet compression systems have been applied to several different frames of industrial gas turbines. The performance gains associated with these applications have varied. With the implementation of wet compression on the W501A combustion turbine, an average performance gain of 1 MW was achieved for each 10 gallons per minute (gpm) of water injected into the inlet. The application of wet compression to the W501D5A has demonstrated a performance gain of 1 MW for a flow rate of approximately 5.5 to 7 gpm. GE Frame 6B, having a pressure ratio of approximately 12:1 and firing temperature of 2025°F showed performance gains of 1 MW for flow rate of 7 gpm.

Initial thoughts regarding the performance advantages were that performance gains were related to the pressure ratio and firing temperature of the combustion turbine. This then established the expectation that performance results would be significantly better with higher pressure/firing temperature turbines such as the Alstom GT-24, operating at a pressure ratio of 28:1. However, the performance gains obtained on this CT indicate the results for the CT are approximately 6.3 gpm per incremental mega-Watt as illustrated in Figure 5.

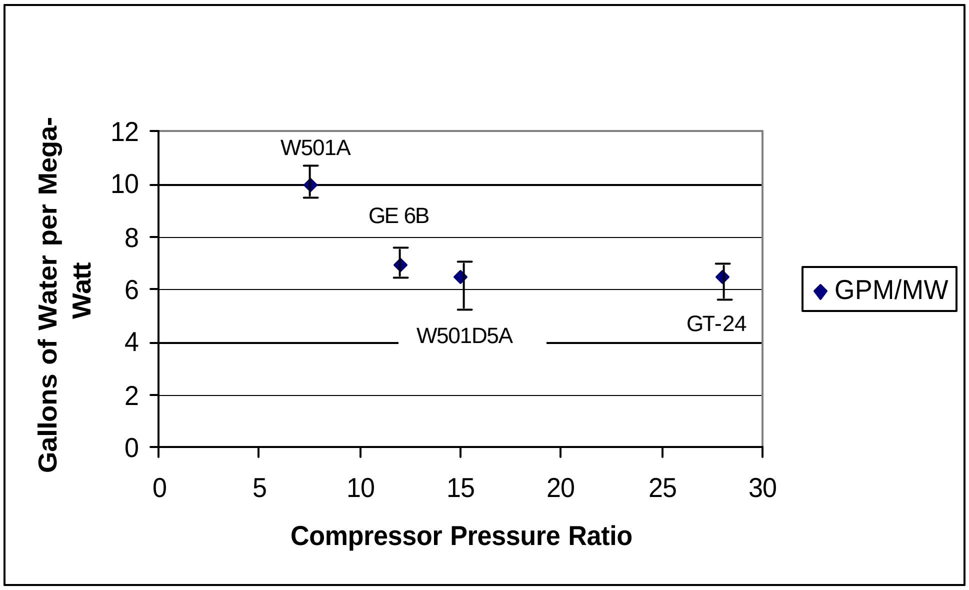


Figure 5: Performance Comparison per Unit of Water.

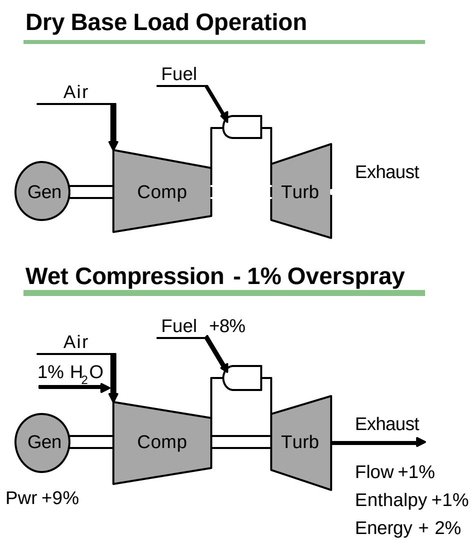
Tests results from wet compression systems on the same frame of combustion turbine indicate that there is a performance benefit of having smaller droplets. Noting that the W501A had very large droplets in relationship to the more recent applications, the retrofit of the wet compression system to this unit could flatten this curve. Differences in compressor designs between the frames also contribute to the performance differences between the combustion turbines as the water may change incidence angles of the air within the flow path. This can positively or negatively affect the aerodynamic efficiency of a specific compressor while still achieving the overall thermodynamic performance benefit of wet compression.

Additional performance comparisons of the changes in compressor discharge temperature, fuel flow, firing temperature, power output and heat rate changes are summarized for these combustion turbines to illustrate the overall effects of wet compression.

Table 1: Performance Comparison of Various Frame Turbines

Combustion Turbine	GE Frame 6B	SWPC W501D5A	Alstom GT-24
Overspray, %	1	2	1.2
Compressor Discharge Temperature Reduction, °F	50	100	48
Fuel Flow Increase, %	8.2	13.2	5.5
Change in Base Load Firing Temperature, ºF	No Change	No Change	No Change
CT Power Increase, MW	3.3	15	11.5
Steam Turbine Power Increase, MW	0.3 (estimated)	2 (estimated)	1.8 (estimated)
CT Heat Rate Improvement, %	1	2	2
Cycle Heat Rate Increase, %	1.2	1.7	Unchanged

It should be noted that there is an improvement in combustion turbine heat rate when operating with wet compression. Because additional energy is required to heat the compressor discharge air to the base load firing temperature, the percentage increase in fuel flow is almost equal to the increase in combustion turbine output. However, since the exhaust energy is only increased by the slight increase in mass flow and enthalpy is increased due to the added moisture content, steam turbine output increases by approximately 2 percent for each 1 percent of overspray. With the greater increase in combustion turbine power output and fuel flow increase, there is a slight increase in combined cycle heat rate when used with wet compression. This is further illustrated in Figure 6.



Estimated Cycle performance Effects:	
CT Power	+9%
CT Heat Rate	-1%
CT Fuel Flow	+8%
CT Exhaust Energy	+2%
Steam Production	+2%
ST Power	+2%
Cycle Power (2/3 CT + 1/3 ST)	
Cycle Power (2/3 * 9% + 1/3 * 2%)	+6.7%
Cycle Fuel Flow	+8%
Cycle Heat Rate (Heat Input / Power)	
Cycle Heat Rate (8%/6.7%)	+1.2%

Figure 6: Wet Compression Cycle Performance Effects

Compressor Work Distribution:

The evaporation of water in the compressor flow path alters the work distribution of the compressor by reducing the work done in the front stages of the compressor and increasing the loading on the latter stages of the compressor. This results from the thermodynamic effect of the air being cooler and not having to be compressed as much to pass through the converging flow path. The relative reduction in stage pressure follows a $PV = nRT$ relationship as the temperature drops. This trend reverses in the latter stages of the compressor where the compressor must then do sufficient work to pass the increased mass flow through the first stage turbine vanes which act as a nozzle, resulting in an increase in compressor discharge pressure. The increase in compressor discharge pressure is nearly proportional to the percentage of water injected. The pressure rise through the turbine decays until exiting the last row turbine blade, where the pressure is essentially the same as without wet compression. These trends are illustrated in Figure 7.

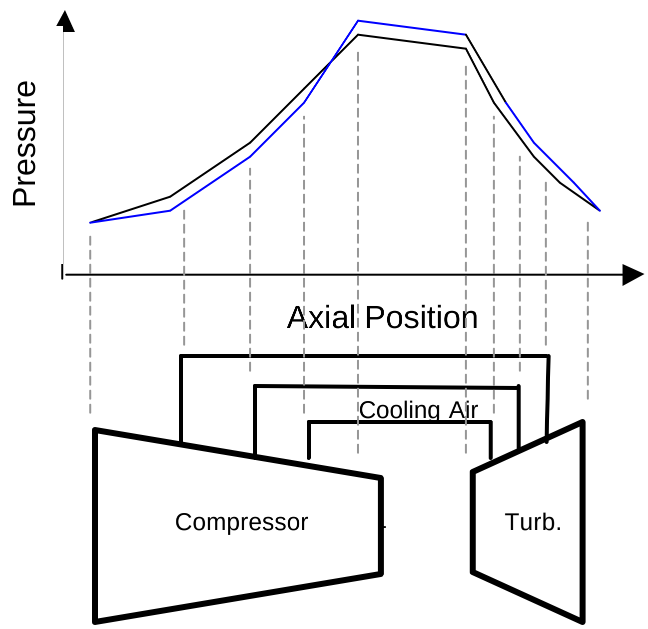


Figure 7 - Pressure vs. Axial Position (Relative to Schematic)

In the case of multi-shaft combustion turbines, the above temperature and pressure relationships will vary since the compressor spools may increase in rotational speed with the introduction of wet compression which will further increase the mass flow rate through the combustion turbine. Such an application was performed in May of this year on an LM2500 and is still being evaluated.

Because compressor stage pressure is reduced in the area of the compressor bleeds that are used to provide cooling air to the turbine end of the combustion turbines at the same time turbine stage pressures have increased, the differential pressure may not be sufficient to produce the required cooling air flow. In such cases, it is necessary to modify the cooling circuit to maintain the required flow. This can be done as a one-time modification by reducing the cooling circuit pressure losses or by installing a cooling flow modulation system.

Turbine Component Life:

Some OEM's maintenance intervals and part life expectancies are reduced when conventional steam or water injection systems are used for power augmentation and/or NOx control. The reasoning behind this is that injecting water or steam into the combustion section of the turbine will result in an increase in the compressor discharge pressure since greater pressure will be required to push the additional mass through the row 1 turbine vanes. The higher pressure increases the work that is done by the air on the inlet air stream, thereby increasing compressor discharge temperatures. For a gas turbine with a 15:1 pressure ratio operating at a 2:1 steam to fuel ratio, the increase in compressor discharge temperature will be approximately 14ºF. Because this air is used for cooling turbine hot parts, the hot part metal temperatures will increase. Similar affects will result from the application of other power augmentation systems that increase the pressure ratio of the combustion turbine, such as a parallel compressor train.

A second affect of injecting water or steam into the combustion zone is that the added moisture increases the heat transfer characteristics of the gases passing through the combustion system. Cooling air, which is extracted either from compressor bleed air pipes or from the compressor discharge piping does not typically see the increase in moisture content and therefore creates an added differential in heat transfer coefficients which also translates into higher hot part metal temperatures. The increase in metal temperatures can affect both creep life and the oxidation / corrosion rates of turbine hot parts. These heat transfer effects will result whenever the hot gases within the turbine are humidified without a corresponding increase in the humidity of the air in the cooling circuits.

Wet compression operation has several added benefits over conventional steam or water injection technologies. Although wet compression results in an increase in the pressure ratio of the compressor, the intercooling effects of the water more than offset the temperature rise from the added compression. Additionally, since most if not all the water is evaporated before the air is extracted for cooling purposes, the hot gas path and cooling air experience similar gains in the heat transfer coefficient which keep metal temperatures nearly constant.

Comparison to Alternative Augmentation Technologies:

The most commonly used power augmentation technologies for gas turbines are evaporative cooling (inlet fogging), wet compression, mechanical chilling (with or without thermal energy storage), and steam or water injection. Two other viable methods which have been applied on a limited basis so far are supercharging and humid air injection. A comparison of the various methods is shown in the table below. For the steam injection system, a combined cycle plant is assumed although the concept can be applied to simple cycle as well, but this will translate into an increased cost for a boiler.

The ambient conditions are assumed to be: 1) a dry bulb temperature of 95ºF with 50% relatively humidity, 2) a dry bulb temperature of 75ºF with 70% relative humidity, and 3) a dry bulb temperature of 59ºF with 60% relative humidity. These conditions translate to a wet bulb temperature of 79ºF, 68ºF and 51ºF. It is worth noting here that the gains by the relatively inexpensive methods are somewhat limited by the ambient conditions. For example, the gain realized by fogging is dependent upon the difference between the ambient dry bulb and wet bulb temperatures as illustrated by the incremental power gains at points two and three. However, the gains by wet compression are more consistent over a wider range of ambient conditions. The same gains can be realized as long as the ambient wet bulb temperature stays above 50ºF. This can have a significant impact on the payback because it increases the MWhr gain throughout the year considerably. As a result, the payback for wet compression system can be one-quarter or one-half of that for a chilling system. However they are complimentary systems and both can be applied to optimize gains. The comparison of available alternate technologies is shown in Table 2.

Table 2: Comparison of power augmentation technologies.

Method	Evaporative Cooling	Fogging	Wet Compression	Chilling	Steam/ Water Injection	Humid Air Injection	Super-Charging with pre / post evaporative cooling
		(ºF)	(%)	(%)	($/kW)		
Compressor Inlet Air Temp (ºF)	81	80	79	50	95	95	95
Output Increment (%)	5%	6%	8-15%	11%	6%-12%	8-15%	15%-30%
Heat Rate Improvement (%)	1%	1%	1-3%	-2% to 2%	-4% to –5%	-2% to -4%	N/A
Installed Cost ($/kW)	40-60	25-60	70-100	150-250	60 – 80 if steam source is available	180-250	240-300
Plant Integration	Inlet duct / silencing system treatment, Cooler design coordinated with inlet air system to minimize carryover, water supply and drains	Inlet duct / silencing system treatment (coating, lining, drains), Nozzle placement. De-ionized water supply & drains	Inlet duct treatment, control system integration for combustion and emergency response, cooling system modification, rotor grounding (all included in above pricing) De-ionized water supply & drains	Coil integration with inlet air system, Cooling tower and makeup water required, chilling units to be installed.	Combus-tion system hardware and software changes may be required. Steam or water supply	Humid air manifold to be added to CT, control logic integration required for upset conditions and base load firing temper-ature control, Cooling tower, HRSG and compress-or trains to be added.	Inlet System Pressure Rating, Turbine blade flutter possible. See Note 1. Control logic changes for response to upset conditions.
Maintenance	Low pressure pump, sump cleanliness, and periodic media replacement (approximately every 6 years)	Pumps, valves, nozzles and inlet system. Comp-ressor blades if carryover is excessive	Pumps, valves, nozzles, and compressor blades. Primarily the row 1 blade.	Mechan-ical chillers, inlet coils and cooling tower. Similar to operating CT in a cold climate	Increased hot part metal tempera-tures unless firing temperature is reduced. Compressor train, HRSG, and cooling tower.	Increased hot part metal tempera-tures unless firing tempera-ture is reduced	Evaporative coolers (2), electric fan, Inlet louvers.

Note that supercharging does not change the pressure ratio of the compressor section of the combustion turbine, but does raise the pressure ratio of the turbine since the exhaust pressure will be slightly above ambient conditions. The result is a higher exit velocity which increases the potential for turbine blade flutter. This operating limit should be evaluated by the OEM.

Conclusions:

Out of all the available technologies, wet compression offers the most in terms of performance gains, heat rate improvement, reduction in emissions, and ease of installation at a relatively modest cost. Unlike evaporative cooling or chilling, the gains are not restrictive at lower ambient temperatures as long as the ambient wet bulb stays above 50ºF. The technique of wet compression is very promising because of quicker payback. For example, the payback is less than half that of a chilling system.

While the application of this technology is recent, tremendous progress has been made in understanding the concerns/issues with this system and steps to be taken to assure satisfactory system performance. The GT-24 wet compression system has been operational for more than one year. Initially, it was run for 10-12 hours a day. At the present time, it is operated for 16 hours a day. A borescope inspection performed during a recent outage did not show erosion to be manageable within normally scheduled maintenance intervals and the customer continues to operate the wet compression system to boost their turbine output significantly.

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