WET COMPRESSION – A POWERFUL MEANS OF ENHANCING COMBUSTION TURBINE CAPACITY

by

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ABSTRACT

Wet compression is a patented process that increases the capacity of a combustion turbine (CT) by as much as 15 to 25% by purposely injecting water droplets into a compressor inlet (AKA – overspray, high fogging or supersaturation). The increase in capacity is primarily due to reduction in compressor work and ability for additional firing in the combustor, and secondarily due to increase in mass flowrate. This paper presents thermodynamic benefits of wet compression, the risks associated with applying wet compression systems to a CT, the steps that were taken to integrate and validate the system at a recent installation, and performance results of the system application on a GE Frame 6B combustion turbine, in which power output was augmented by 9%.

INTRODUCTION

Wet compression is a process in which water droplets are injected into the compressor inlet air and allowed to be carried into the compressor. As the water droplets evaporate in the front stages of the compressor, it reduces the air temperature and therefore reduces the amount of work that must be done by the compressor airfoils to pass the flow on to the next stage of compressor blades. The net effect is reduction in compressor work. Since one-half to two-thirds of the turbine output is typically used to drive the compressor, a reduction in compressor work directly translates to an increase in net turbine output. Wet compression also results in a significant reduction in the compressor discharge temperature which requires higher fuel flowrates to achieve base load firing temperatures. The additional mass flow of water and incremental fuel flow also contribute to the increase in power from the combustion turbine. The major benefits of wet compression are: an increase in turbine power output, an improvement in CT heat rate, and in many instances, a reduction in No_x levels, and this method is applicable to new as well as operating CTs.

Although the performance benefits of wet compression are attractive, the application of wet compression system requires careful evaluation and integration with the CT and its control system to manage the risks associated with this type of operation. The major objective of this paper is to discuss the benefits of wet compression theoretically as well as with the help of data from an actual installation. The effect of wet compression on various critical turbine parameters like the compressor casing temperatures and combustor dynamic pressure levels are also discussed. There are challenges, however, with wet compression that are also discussed in this paper. While the concept is not new, only recently has this application been gaining increased importance in enhancing CT capacity.

There is no other technology that offers so many benefits and yet is so economical. These results are very promising and suggest that this application will become, in the near future, a primary and effective means of increasing CT capacity.

COMBUSTION TURBINE INLET AIR COOLING

The output of a CT declines as the ambient temperatures rises. Typically, the reduction in output is 3-3.5% for every 10°F increase in the air temperature. Cooling the inlet air can restore or enhance the capacity of a CT. There are two basic methods of inlet air cooling – evaporative cooling and refrigerated cooling.

In evaporative cooling, the inlet air is cooled to near the ambient wet bulb temperature. In refrigerated cooling, the inlet air is cooled to below the dew point temperature. Since larger temperature reductions are possible with refrigerated cooling, capacity enhancements are correspondingly higher. The main advantage of evaporative cooling is simple design and low initial cost. The payback is quicker for evaporative cooling even though the capacity increment is limited by ambient wet bulb temperature.

TRADITIONAL INLET AIR COOLING

The traditional inlet air cooling technologies are based on the concept of cooling the inlet air before it enters the compressor inlet. For these systems, the gain in CT output is a function of reduction in inlet air temperature. The greater the reduction, the higher the gains. That is why higher gains are possible with chilling systems than with evaporative cooling. In a chilling system, the inlet air temperature is reduced below the dew point. For such cases, the cooling load primarily consists of latent load, which is the amount of energy that is consumed to condense the water from the air so that further temperature reductions are possible. The water vapor in the air works to our disadvantage. The opposite is true for wet compression. In this case, gain in output does not rely on condensing water vapor from air but adding more water into the air and allowing the fog to be carried into the compressor. As the fog gets evaporated in the subsequent stages of the compressor, there is a reduction in the air temperature and thereby in compressor work.

An increase in turbine capacity was found when the compressor water wash system was accidentally left open at one of Dow Chemical's facilities. This prompted further investigation into the process and resulted in patents issued to Dow Chemical on this technology. Since then, considerable efforts have been devoted to refining the methods of introducing water droplets into the compressor inlet and their impact on the turbine performance. These efforts are focused on droplet size distribution through selection of suitable nozzles, optimum placement of nozzle arrays in the inlet duct and its impact on the additional airside pressure drop due to blockage of inlet duct by nozzle arrays. These efforts have also been directed towards understanding the evaporation process through various compressor stages, its impact on the firing temperature, the resulting increase in turbine power output and impact on emissions. Despite these efforts, this method of increasing the turbine capacity is in its early stages of development. There are also challenges to the application of this method: erosion of the compressor blades due to impingement of water droplets, water carryover into extraction air taken at various compressor stages, compressor casing distortion due to non-uniform cooling, etc. These issues need to be addressed before the application of this technology can be successfully employed.

The objective of this paper is to discuss the wet compression mechanism in detail, the principle behind CT output increment and the factors to consider in the design of these systems. Finally, the application of wet compression is discussed with the help of an actual installation on a GE Frame 6B.

WET COMPRESSION

In evaporative cooling, the air is cooled by introducing water into the air either by conventional media type evaporative coolers or by direct spray through nozzle arrays. The reduction in the air temperature is limited by the ability of air to absorb water. The design goal was to add only the amount of water to saturate the air before it enters the compressor. The carryover of water into the compressor was to be avoided by all means. There has been a change in this thinking in the last 5-7 years.

The introduction of water into the compressor inlet results in considerable gains in turbine output provided proper care is taken to ensure uniform spray distribution, acceptable droplet sizes and monitoring of critical turbine parameters. This method of excess water spray into the air stream is often termed as “wet compression”, “over-spray”, or “high-fogging”.

The benefits of wet compression technology are as follows:
1. Increase in turbine output
2. Improvement in heat rate
3. Possibility of reduction in No_x levels

The following are the challenges to wet compression technology:
1. Compressor blade erosion due to impingement of water droplets
2. Water carryover into the extraction air taken from various compressor stages
3. Compressor casing distortion due to uneven water distribution
4. Combustion stability
5. Electro-static charge build-up on the rotor

CALCULATION PROCEDURE

The work of compression is

$$W_c = m\, C_p\, (T_2 - T_1) \qquad (1)$$

where T_1 and T_2 are compressor inlet and discharge temperatures, respectively.

When water droplets are injected into the compressor inlet air, and pass through the first few stages of the compressor, the latent heat of vaporization of water droplets is supplied by sensible heat of air. As a result, there is a drop in the compressor discharge temperature, T_2. From Eq. (1) above, a reduction in T_2 means a reduction in compressor work, W_c.

$$W_t = m\,C_p\,(T_3 - T_4) \qquad (2)$$

where T_3 and T_4 are turbine inlet and exhaust temperatures, respectively.

The net turbine output is

$$\begin{aligned} W_{net} &= W_t - W_c \\ &= m\,C_p\,\{(T_3 - T_4) - (T_2 - T_1)\} \quad (3) \end{aligned}$$

A reduction in the compressor discharge temperature and compressor work means an increase in net turbine output, W_{net}.

The efficiency of the gas turbine (Brayton cycle) is

$$\begin{aligned} ? &= W_{net}/Q_{in} \\ &= 1 - (T_4-T_1)/(T_3-T_2) \qquad (4) \end{aligned}$$

A decrease in compressor discharge temperature T_2 means that (T_3-T_2) is increased resulting in higher efficiency, ?.

Therefore, wet compression increases both the output and efficiency of the combustion turbine.

Let us assume that the turbine exhaust temperature T_4 does not change and the compressor discharge temperature as a result of water evaporation is T_2'. The heat added by combustion is

$$\begin{aligned} Q_{in} &= m\,C_p\,(T_3-T_2) \qquad (5) \\ &= m\,C_p\,\{(T_3 - T_2') - (T_2 - T_2')\} \end{aligned}$$

Eq. (5) is also the fuel energy added in the combustor. In the above equation, $m\,C_p\,(T_2 - T_2')$ is the fuel energy that can be added in the combustor. The amount is exactly equal to the reduction in compressor work or increase in turbine output. In other words, whatever is input as fuel energy ends up as increase in turbine output provided the firing temperature remains the same. That is why there is a net increase in the output and efficiency of the system.

Eq. (5) can also be viewed differently in that wet compression can be used to reduce the firing temperature if the output remains the same, or a combination of increase in output and reduction in firing temperature can be achieved.

The following scenarios are possible with wet compression:
1. Increase in output and efficiency for same firing temperature.
2. Reduction in firing temperature if output is kept the same
3. A combination of the above.
4. An improvement in efficiency and output at part-load conditions.

WET COMPRESSION SYSTEM APPLICATION

The plant consists of one GE Frame 6B CT equipped with a dry low NO_x combustion system operating in combined cycle mode at the Cardinal Cogen facility in Stanford, California. The design conditions are as follows:

$T_{dry\ bulb}$ = 92ºF
$T_{wet\ bulb}$ = 69ºF

Elevation = 300 ft. above msl
Airflow = 1,098,000 @ ISO

The scope of supply was broken down into two components – fogging system to cool the inlet air temperature to 1ºF above the wet bulb temperature and wet compression system to spray additional water into the compressor inlet.

Fogging System

The purpose of the fogging system is to cool and humidify the compressor inlet air during hot days to increase the capacity and efficiency of the CT and the plant. The fogging system installed consists of the following components:

1. High Pressure Pump Forwarding System – The pump is a triplex plunger design, high-pressure pump capable of supplying 14.1 gpm of demineralized water at 3,000 psi. Not all of the water is available for spray because of pump bypass requirements. The water requirement at the design conditions is 11.9 gpm.
2. A weather station capable of measuring the ambient temperature.
3. Programmable Logic Controller (PLC) mounted on the pump skid.
4. Manifold Array Module – A grid of nozzle arrays in the inlet duct to spray mist into the air stream. A total of 5 zones of cooling are provided to control air temperature to within 1°F. The bigger zones are further sub-divided through the duct cross-section for better distribution.
5. Stainless steel tubing to deliver water from the pump to the arrays.
6. A filtration system to clean water prior to entering the pumps.

Since the purpose of a fogging system is to cool the inlet air temperature, the nozzle arrays are placed as far away from the compressor inlet as possible (see Fig. 1). This is done to allow sufficient distance for water evaporation prior to air entering the compressor and to reduce droplet agglomeration. The spraying of water upstream of the filters can result in wetting of the filters. If nozzles are placed upstream of the filters, extreme caution needs to be exercised to make sure that sufficient evaporation distance is available and the spraying is such that the cool inlet air is not too close to the wet bulb temperature. Sometimes, the duct configuration is such that the downstream placement of nozzles is not possible without adding significantly to the cost associated with duct modifications.

Fortunately, sufficient space was available downstream of the filters for installation of nozzle arrays. Figure 2 shows a schematic of the nozzle layout in the inlet duct. Figure 3 shows the nozzle arrays installed downstream of the filters in a “V” format to allow for better mixing of spray with the incoming airflow. Figure 4 shows the nozzle spraying during the start-up procedure. Note that the turbine was not running during this procedure. The five zones shown are capable

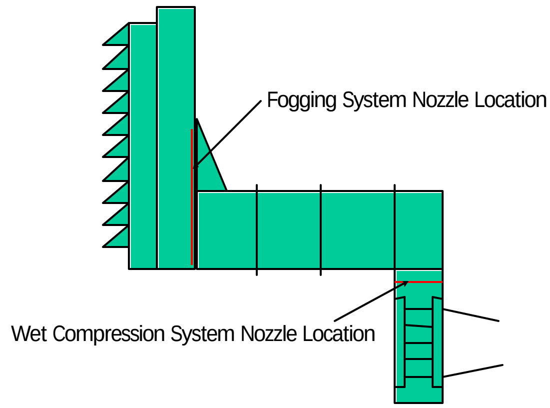

Figure 1: Preferred location of fogging and wet compression system nozzles.

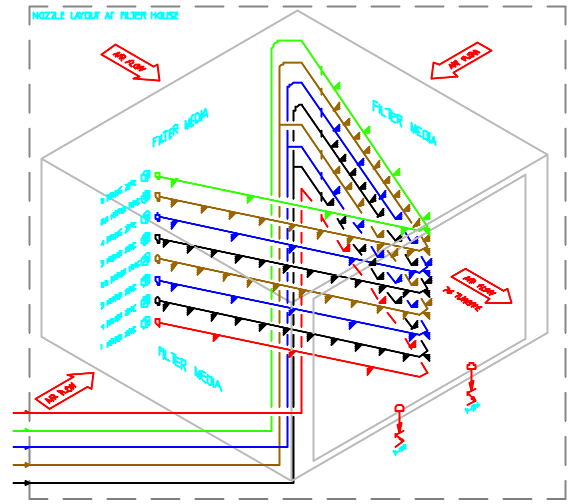

Figure 2: Schematic of fogging nozzle arrays.

of providing 22°F of cooling. The ability of the fogging system to cool within 1°F of wet bulb temperature was demonstrated during the performance test.

Figure 3: Nozzle layout in the inlet duct.

Figure 4: Water spray pattern.

Wet Compression System

The purpose of the wet compression system is to increase the power of the CT by reducing the compressor work due to compressor inter-cooling effect as a result of fine water mist evaporating in the first few stages of the compressor. With compressor inter-cooling, the compressor discharge temperature is reduced considerably allowing more fuel to be burnt in the combustor. A secondary increase in power output is due to increase in mass flow rate.

Design Conditions

The wet compression system was designed to the following parameters:

$T_{dry\ bulb}$ = 70ºF
$T_{wet\ bulb}$ = 69ºF

Water Spray = 22.6 gpm

This water spray corresponds to about 1% of airflow.

System Description

The wet compression system consists of the following major components:

1. High Pressure Pump Forwarding System – The pump is a triplex plunger design, high-pressure capable of supplying 26 gpm of water 2,100 psi. Some of the pump capacity is used for bypass flow requirements for the pump.
2. Manifold Array Module – A grid of nozzle arrays in the inlet duct to spray mist into the air stream. A total of 5 zones are provided for better spray control and introduce water into the air stream in stages during start-up.
3. Stainless steel tubing to deliver water from the pumps to the arrays.
4. A Programmable Logic Controller (PLC) to control the operation of the wet compression skid, which minimizes the number of interfaces required with the CT control system.

The wet compression spray nozzles were installed in the inlet duct downstream of the fogging nozzle arrays and the silencer (see Fig. 5 and 6). The objective is to place the nozzles as close as possible to the compressor inlet to prevent water agglomeration and water wastage prior to entry into the compressor. Two view ports were installed near the inlet bellmouth of the compressor. The lower locations were chosen for the ports to verify the flow pattern into the compressor inlet.

The water collecting at the bottom of the manifold could be viewed through the left side port. The water collecting on the right side port made viewing difficult. Overall, the spray pattern appeared to be well distributed as intended.

The water distribution for the wet compression system was better than expected considering that the nozzle rack was placed in the inlet duct with the 90° elbow just above it. The water followed the air path with minimum amount impacting the walls and draining from the inlet manifolds. Since demineralized water is used, the inlet duct was lined with stainless steel panels. Also a grounding brush was installed to eliminate the possibility of electro-static charge build-up on the rotor. This can be a concern because the electromotive force between the rotor and the casing or bearing material can result in material losses at the bearings and rotor resulting from electrostatic discharge.

Figure 5: Wet compression nozzle rack before shop acceptance test.

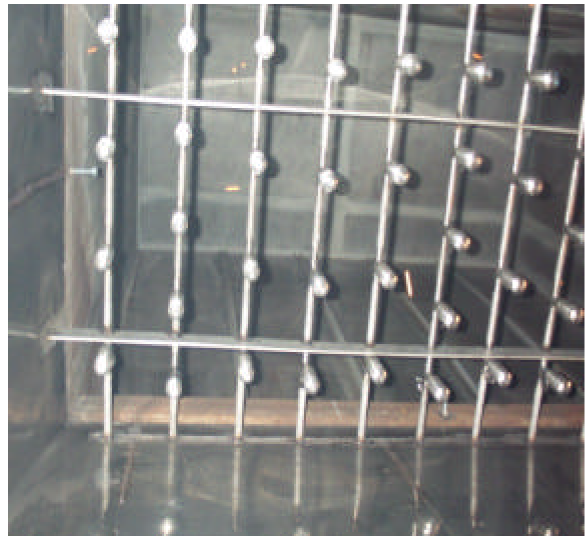

Figure 6: Installation of spray nozzle rack in the inlet duct.

Control System Integration

The PLC for the wet compression system and the CT or plant control system must be capable of communicating with each other to allow for normal operation control of the wet compression system. There are general permissives for wet compression system operation that must be validated before the water can be injected into the compressor inlet air, such as minimum inlet temperatures due to icing concerns and other operating limits.

In addition, the logic of each control system must include response to transient and upset or emergency conditions such as a trip of either the CT or wet compression system. In the case of a CT trip, the water must be shut off immediately to avoid filling a hot CT with water. In the case where the wet compression system trips, the fuel flow must be reduced to avoid an over-temperature event in the turbine since the heat sink resulting from the evaporation of water in the compressor inlet is lost, which could cascade into a trip of the CT based on an over-temperature or damage to turbine hot parts. (Note that more data on the performance of the CT during the wet compression testing are provided later in this paper).

Casing Temperature Measurements

A total of 30 thermocouples were selected to measure the compressor cylinder temperatures. These thermocouples were axially located at various compressor stages. At each axial location, 10 thermocouples were installed around the circumference of the cylinder. The thermocouple readings were taken locally with a hand-held meter and were also recorded with a data acquisition system.

See Tables 1 and 2 for casing temperature measurements without and with wet compression. All the thermocouples in plane 1 and thermocouple at the number 5 position in plane 2 appear to be influenced more by the enclosure air temperatures than the compressor operating conditions. The difference between the max and min temperature is within allowable range and suggest uniform water distribution at the compressor inlet. The casing temperature distribution did not appear to be impacted by wet compression and were not found to be limiting factor for this installation.

Table 1: Casing Temperature Measurements, March 6, 2002 9:30 AM Base Load

Axial Plane	1	2	3
Radial Position	Temperature (°F)		
1	215	353	568
2	207	393	572
3	193	365	568
4	189	360	561
5	189	235 (excluded)	516
6	166	366	544
7	158	393	569
8	198	358	571
9	182	358	558
10	196	356	550
Max-Min	49	40	56

Table 2: Casing Temperature Measurements with all five zones on, March 7, 2002 1:45 PM

Axial Plane	1	2	3
Radial Position	Temperature (°F)		
1	143	314	533
2	122	350	528
3	105	316	529
4	106	314	518
5	102	222 (excluded)	506
6	104	314	531
7	113	359	537
8	116	319	533
9	101	312	531
10	100	312	519
Max-Min	43	47	31

Combustor Dynamic Pressure Measurements

The dynamic pressure probes and transducers were installed through existing instrument tabs in the combustor shell cans to monitor combustion stability since excessive pressure pulsations can increase the wear of combustion system components or result in a failure of combustion system components. The transducers on the probes were used to record data in the 0-2500 Hz range. The dynamic combustor pressure was measured in the dry low NO_x combustion system with and without the wet compression system in service. The dynamic pressure level was found to be approximately twice the dry values when all five wet compression zones were in service. No efforts were made to tune the combustion system to reduce the combustion system dynamics. Such efforts may be made on future installations. An inspection of baskets was recommended the next time the unit was down to check for signs of increased wear due to increase in dynamic pressure.

Performance Evaluation

The performance test on wet compression system was conducted in April, 2002. The data was recorded automatically by plant's data collection system at intervals of 15 seconds. The ambient dry bulb and wet bulb temperature were recorded by the weather station as part of the system. The initial performance data was taken without the wet compression system on. The average over 30 minute period is shown in the second column of Table 3.

Table 3: Performance Test Results

Item	No Wet Compression	With Wet Compression
Ambient dry bulb	58°F	59°F
Ambient wet bulb	52°F	52°F
Compressor Discharge Temp	663.5°F	614°F
Compressor Inlet Air Temp	57.9°F	52°F
Fuel Flow	6.1 lb/sec	6.6 lb/sec
Turbine Exhaust Temp	1029.5°F	1017.9°F
Compressor Discharge Pressure	153 psia	158 psia
Turbine Power Output	35,333 MW	38,579 MW
Theoretical Firing Temp	2023.4°F	2023.6°F

The wet compression system was started and all the five zones were turned on one by one. The system was allowed to run in this mode until the data was stabilized. The fogging system was not operational during this time because of relatively small difference between the dry and wet bulb temperature. The data averaged over the 30-minute time interval is shown in the third column of Table 3.

From the data listed above, the increment in turbine output due to wet compression is 3,246 kW. Some of this gain is attributed to the fogging effect rather than wet compression in the compressor stages, but the resulting difference is small. Also note the drop in compressor discharge temperature of approx. 50°F and turbine exhaust temperature drop of 11°F.

In the calculation procedure, it was stated that theoretically, all the additional fuel energy input due to reduction in compressor discharge temperature ends upon as increase in turbine output. In reality, not all the energy is recovered because the latent heat of vaporization of water goes up the stack, the turbine is not 100% efficient in recovering the energy, and there are paddling losses as the liquid droplets impact the compressor airfoils which reduces the aerodynamic efficiency of the compressor.

CONCLUSIONS

The application of wet compression system should address the risks associated with spraying water into a CT inlet. The primary components of such risk included: (i) water distribution, (ii) degradation of compressor inlet duct materials and fouling of the compressor, (iii) compressor casing distortion, (iv) combustion dynamic pressure, and (v) control system integration.

The results of the design verification and performance testing of the wet compression system on the GE Frame 6B combustion turbine at the Cardinal Cogen's facility in Stanford, California demonstrated a gain in output of approximately 9% with an improvement in heat rate of about 1%. Since dry low NO_x combustors were used on this CT, there was no appreciable change in NO_x emission levels as noted with conventional combustors reported in Reference 3.

ACKNOWLEDGEMENT

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