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High Fogging Tests and Performance Model for High Fogging

Juergen HOFFMANN and Collins OJO

Alstom (Schweiz) AG

Brown Boveri Str. 7, 5401 Baden

Switzerland

Phone: +41-56-2052638, FAX: +41-56-2054738, E-mail: juergen.hoffmann@power.alstom.com

ABSTRACT

High fogging refers to water injection upstream of a compressor intake beyond saturation. This leads to water droplet evaporation within the compressor and as a result to a reduction in compressor outlet temperature. This form of compressor intercooling leads to enhancement of the overall gas turbine power output. High Fogging systems were developed by Alstom and have been commissioned and tested in the Alstom Test Center on the GT8C2 and the GT26 in 2001.

In this paper, the main principles of inlet cooling systems and High Fogging are described. Initial concerns during commissioning and testing are presented. Operation concept and special supervisions during the tests are discussed. The main effects of the High Fogging operation on the gas turbine are presented. Especially the transient effects and impact of the High Fogging on the cooling air system of the gas turbine are shown.

To analyze and simulate the influence of High Fogging on the gas turbine, an analytical model using empirical corrections is presented.

The model used is based on an existing conventional performance model with a compressor map for a dry compressor. It includes an algorithm for simulation of the evaporative cooling. The interest is to know how the dry compressor map is changed with High Fogging water injection. Correction factors are derived from measurements.

NOMENCLATURE

f	[-]	high fogging correction factor
h	[kJ/kg]	specific enthalpy
j	[kJ/kg]	irreversibility term (dissipation)
p	[bar]	pressure
q	[kJ/kg]	adiabatic term (specific heat)
s	[kJ/kgK]	specific entropy
T	[K]	Temperature
v	[m^3/kg]	specific volume
Δh	[kJ/kg]	required specific energy
$\int vdp$	[kJ/kg]	polytropic stream work
η	[%]	polytropic efficiency

Abbreviations and Subscripts

p, a	adiabatic polytropic
p, na	non-adiabatic polytropic

INTRODUCTION

In recent years inlet air cooling systems such as fogging, evaporative coolers and chillers became increasingly popular (Diesel & Gas Turbine World, Mee). They are used for base load and peak load operation. Their potential to achieve considerable power increase at low risk and reasonable costs are commonly recognized.

As extension to conventional inlet cooling injection of fine water spray beyond the 100% humidity limit of the intake air, normally referred to as High Fogging, over spray or wet compression, have increasingly drawn (Nolan, Utamura) attention.

In the first part of this paper a short introduction into the main inlet cooling systems and an introduction to High Fogging is given. This includes an overview of main concerns and reservations towards High Fogging. Based on analysis and test results these concerns are

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discussed. Application of High Fogging to a modern gas turbine and special measures to safely operate a modern gas turbine under High Fogging conditions are presented.

In the second part an empirical model, which was developed to analyze and predict gas turbine performance under High Fogging conditions, is introduced

INLET COOLER SYSTEMS AND HIGH FOGGING

Main inlet cooling systems

In principal there are two kinds of inlet cooling system: one use an external heat sink and requires a heat exchanger in the gas turbine's air inlet system, the other takes advantage of the evaporative heat of water injected into the intake air.

In general, systems with external heat sinks plus heat exchangers are referred to as chillers. Chillers require relatively high initial investments. Their main application is for power plants, which operate at base load with the cooling system on for a large fraction of the year.

Inlet cooling systems, which take advantage of the evaporative heat of water to cool down the intake air, use two different methods to facilitate evaporation. Either water is evaporated on large wetted surfaces inside the air intake (evaporative cooler) or water is injected as fine spray into intake air (fogging). Evaporative coolers are in general of a simple robust design. Their main disadvantage compared to fogging systems is the pressure drop they cause. Their preferred application is for base load in regions where dry ambient conditions allow the effective use of evaporative cooling for majority of operations during the year.

Fogging is commonly used for base load and peak load applications. Since the pressure drop is negligible and normal dry operation the gas turbine performance is not penalized, fogging is often used to add peaking capability to gas turbine power plants.

Figure 1 shows a schematic overview of a gas turbine filter house with inlet cooling and the most relevant measurement locations for the example of an evaporative cooler.

Ambient conditions have to be measured at the entrance of the filter house (plane A). An evaporative cooler is typically downstream of the filter. The water is evaporated in a fine mesh like material. Since large droplets can be carried away with the airflow, a droplet separator is placed into the airflow downstream of the cooler. Conditions at the compressor inlet are measured in plane C. Fogging systems and chiller systems are typically placed at the same locations as is indicated for the evaporative cooler in Figure 1. (for an overview of the GT8C2 test facility see reference; Hoffmann). Since Chillers can cause water condensation they are also equipped with a droplet separator. For fogging systems droplet separators are generally not used.

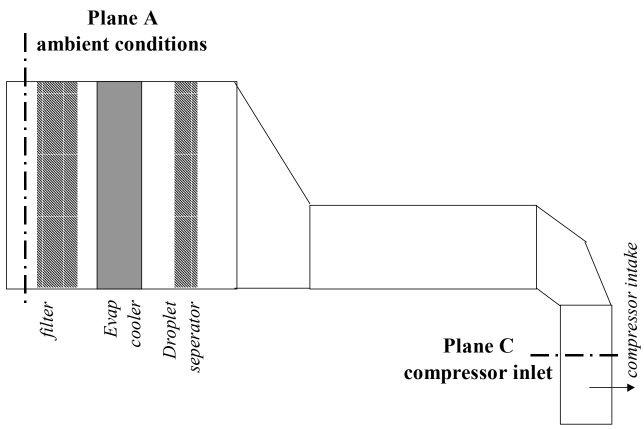

Figure 1 Schematic overview of an air intake with an evaporative cooling system.

Main components of a High Fogging system

The main components of a High Fogging System are a high-pressure pump skid and an injection frame. The injection frame holds the spray nozzles and is typically placed as close to the compressor bellmouth as possible to minimize the chance of secondary droplet formation. One preferred location is in the downward section of the air intake manifold (plane C in Figure 1). A part of a nozzle rack injecting into the GT8C2 intake bellmouth is shown in Figure 2.

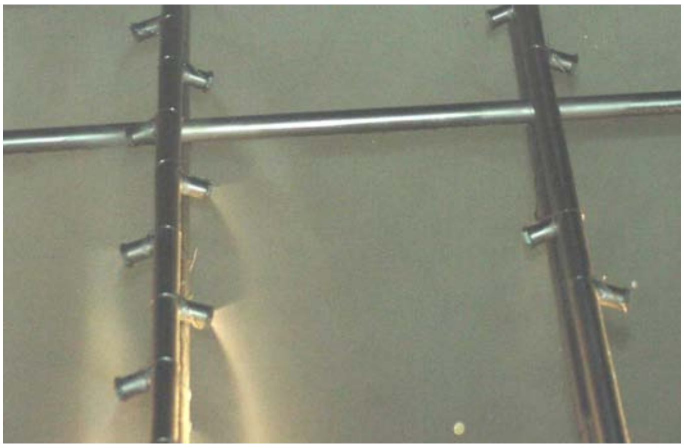

Figure 2 High Fogging rack spraying at reduced mass flow into the intake manifold of the GT8C2 during gas turbine operation (at plane C in Figure 1).

Preferably, High Fogging systems are installed in addition to inlet cooling systems. In this case the inlet cooling system is used to increase the intake air humidity close to 100% and the amount of water used for overspray or High Fogging is reasonably well defined.

Inlet cooling operation

Typically a gas turbine is loaded to base load before inlet cooling systems come into operation. The cooler comes into operation, once the gas turbine has reached stable base load operation and inlet cooling release criteria are met.

The main limiting factor for the operation of inlet cooling systems is icing danger. For some applications the generator capacity can also become a limiting factor, since the added power may exceed the generator design limits.

In contrast to evaporative coolers, which only have a simple on / off control, chiller and fogging systems are typically powered up with a controlled gradient.

Fogging systems usually are powered up to inject the maximum possible water flow. Ambient conditions, air intake mass flow and “quality” of injection nozzle distribution determine the injectable water flow.

Depending on ambient conditions there is a considerable power step when the evaporative cooling or fogging system comes into operation. To reach any power set point between operation with cooler on and off the gas turbine load is controlled according to normal operation concept, e.g. by a reduction in the hot gas temperature or closing of the variable inlet guide vanes of the compressor.

With chilling systems the gas turbines power output beyond base load power (without cooler) is typically controlled by the cooling power of the chiller.

Deloading is done in the reverse order: first the inlet cooling system is deloaded /switched off and then the gas turbine deloads according to normal operation concept. Before shut down of the plant, a dry out period is advisable.

When operating inlet air cooling systems protection against two main concerns has to be assured. These are icing danger and temperature distortion.

Inlet cooling can lead to icing conditions (high relative humidity and temperature below approximately 8°C) at relatively warm ambient conditions. These can for example be reached at an ambient temperature of about 20°C in case of very low ambient relative humidity. Besides icing, inlet cooling systems can lead to a significant temperature distortion at the compressor inlet. This can reduce the surge margin and increases the danger of a compressor stall (Hoffmann).

High Fogging Operation

The main purpose of High Fogging is to increase the power output of the gas turbine. High Fogging is typically initiated after the gas turbine reached base load (typically turbine inlet temperature at design value and variable inlet guide vanes in open position), and the conventional cooling systems are operating. For typical peaking applications the High Fogging system will be used at its design capacity, injecting the maximum allowable water mass flow, and the gas turbine remains at base load. If a load set point is below the power with maximum water injection, the water mass flow will be reduced to reach the target power output. For practical reasons this will be done with discrete steps in the water flow. Final adjustment of the power will be done according to the normal operating concept of the gas turbine with fixed High Fogging water mass flow.

Deloading is done in the reverse order: first the inlet cooling system is deloaded /switched off and then the gas turbine deloads according to normal operation concept. Before shut down of the plant a dry out period is advisable.

Limitations due to icing danger are similar to those valid for conventional inlet air cooling systems.

Main Common Concerns on High Fogging Applications

The main concerns commonly raised in discussion about High Fogging systems and their operation are the following:

- **I** Erosion and Corrosion of compressor blades
- **II** Peaks of hot gas air and metal temperatures during transient operation of the High Fogging system, especially after a trip of the system.
- **III** Change of the gas turbine's cooling air system, especially the cooling air supply pressure and temperature.
- **IV** Cooling air cooler outlet temperature during fast transients of the High Fogging system
- **V** Water droplets which might reach the secondary air system (thermal shock).
- **VI** Compressor distortion resulting in a reduced surge margin due to inhomogeneous distribution of the water spray at the compressor inlet.
- **VII** Mechanical integrity of the fogging system, especially Eigenfrequencies of the nozzle rack.
- **VIII** If the High Fogging system continues to inject water in case of a gas turbine trip the injected water might rapidly cool down metal parts, which could result in excessive thermal stress of hot parts.

High Fogging Tests and Operation with High Fogging

Up to date four test campaigns with fogging and High Fogging systems were carried out in the Alstom Test Center in Birr, Switzerland. For the first test campaign in summer 2000 only a simple fogging system was installed in the GT8C2 at the test center. The system was located just downstream of the filters. It was used for fogging and overspray tests.

For the second test campaign in summer 2001 a newly designed High Fogging system was added to the GT8C2. In fall 2001 first High Fogging tests were carried out on the GT26 of the test center. Additional tests followed in fall 2002.

Obviously the main target is an increase in power output. The achieved power output increase was in the expected range. Figure 3 shows the relative power and High Fogging water mass flow over time for the first GT26 test campaign.

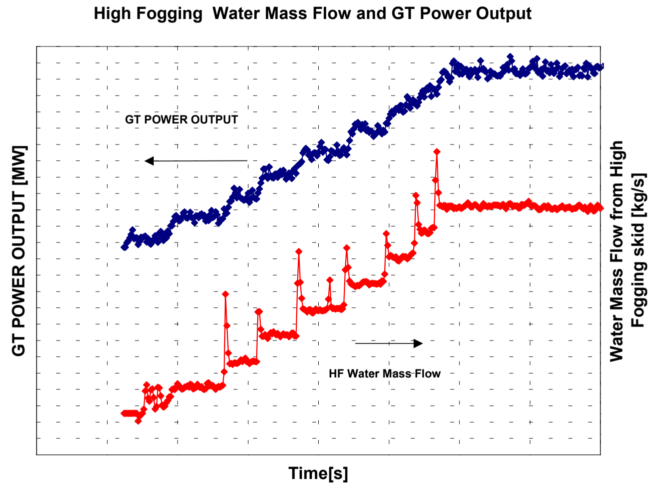

Figure 3 Power of the GT26 with High Fogging over time with stepwise increase of the High Fogging water mass flow (peaks in water mass flow are measurement errors during fast transient).

Emissions were only slightly effected. NOx typically appears to decrease with increasing High Fogging water mass flow. However, the effect is small and often limited to 10% or less. CO tends to increase with High Fogging water mass flow. Under base load operating conditions where the CO emissions are small (typically <5 ppm) High Fogging has a negligible influence on CO emissions.

To account for the concerns mentioned earlier extensive test precautions were established.

I To minimize erosion a careful selection of the nozzles was conducted. Based on measured droplet spectra with the selected nozzles erosion rates were estimated. Estimation was carried out in a semi-empirical way taking into account experience from steam turbine development and operation. Based on CFD simulations of the intake nozzle positions were optimized to avoid excessive spray on surfaces, which can lead to harmful secondary droplets.

The detailed inspection plan, which was put in place to detect erosion or possible excessive corrosion, shows the effect of these measures. No negative signs, nor on visual inspections nor on surface roughness using a replica technique could be detected in several field engines with up to approximately 4000 High Fogging operating hours to date.

II Steady state cycle simulations confirmed that High Fogging lead to a slight shift in the hot gas temperature if dry TIT (turbine inlet temperature) formulas are applied without any adoption. As countermeasure a modified TIT formula analogue to those used for oil operation with NOx water injection or operation with steam injection for power augmentation was implemented. This takes into account the amount of water injected for High Fogging.

Another concern evaluated was the effect of fast transients of the system. Sudden increase or decrease of the fogging water mass flow can change the turbine inlet temperature because the conventional control system is not designed to detect fast changes of this kind. In theory the sudden increase of water injection can be avoided by applying a slow slope of the water injection. However, a trip of the system can not be excluded. Our operational philosophy is that any cooling or High Fogging system failure should not affect the gas turbines operation in normal "dry" operation.

The operating concept and turbine control system has to be able to compensate any influence of the High Fogging system

Effects of a High Fogging system trip on the turbine inlet temperature without any adaptation of the operating concept are qualitatively shown in Figure 4.

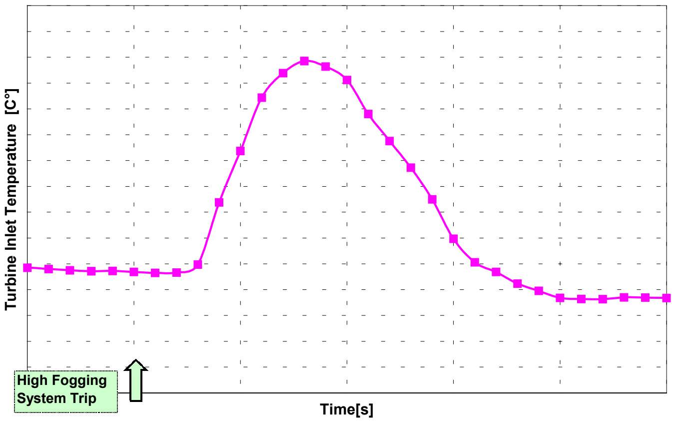

Figure 4 Transient changes of the turbine inlet temperature with High Fogging with conventional control logic.

Shortly after the trip the hot gas temperature shows a sharp increase before normal control system counteracts effectively and reduces the turbine inlet temperature back to the design value.

This effect was already monitored during an intentional fogging system trip, when the fogging system was operated at maximum capacity with overspray. Based on theoretical estimations and the observations from this test, a feed forward control was developed and successfully implemented to stabilize the hot gas temperature during fast transients of a High Fogging system.

III An effect of any High Fogging system is a change in the boundary conditions for the gas turbine's cooling air system. Due to the "inter"-cooling of air in the compressor by water evaporating inside the compressor, the temperature of air entering the cooling air system is reduced. Further, the thermal properties of the air are changed due to the increased humidity. In general these are welcome effects for better cooling. However, these effects can also lead to increased thermal stress if the hot gas temperature remains unchanged.

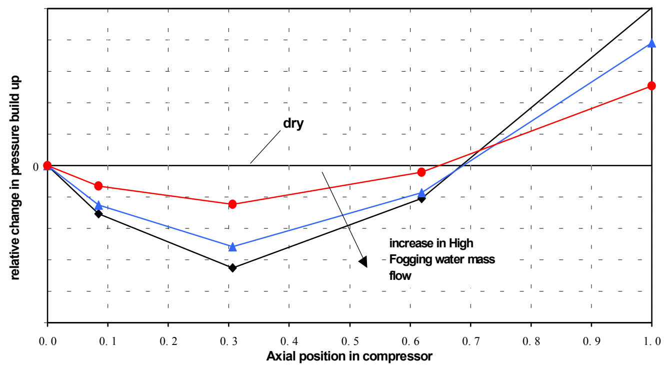

Figure 5 Typical change in compressor pressure build up due to High Fogging relative to dry operation

Due to the change in temperature inside the compressor, the aerodynamics change and the pressure build up in the compressor is shifted towards the rear end of the compressor (see Figure 5).

As a result the cooling air supply pressure can be reduced for part of the cooling air system. The change in relative cooling air pressure is obvious without any corrections when analyzing a fast transient of the High Fogging system such as a trip of this system. The boundary conditions for the gas turbine are almost identical before and after the system trip and therefore all observed changes are due to the High Fogging.

In Figure 6 the development of the relative cooling air supply pressure of a pressure cooling air system is shown over time with a High Fogging system trip. A steep increase of the cooling air pressure can be observed after the trip. At the same time the turbine inlet pressure, which is shown for comparison, decreases due to the reduced mass flow without High Fogging.

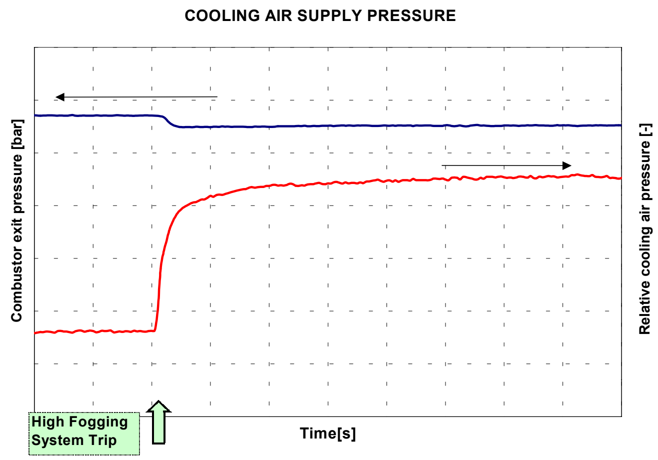

Figure 6 Relative pressure of the medium pressure cooling air system, and inlet pressure of the low-pressure turbine during a trip of the High Fogging system

High Fogging decreases the uncooled cooling air temperature. In principle the lower cooling air temperatures tend to compensate for the reduced cooling air supply pressure. The high-pressure cooling air system benefits from higher supply pressure and reduced cooling air temperature (Figure 7).

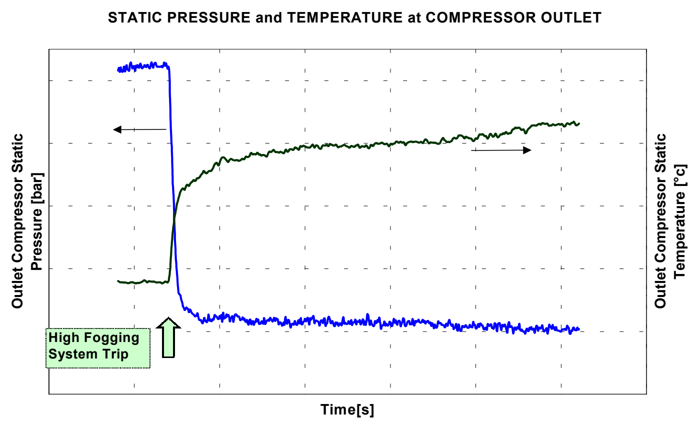

Figure 7 Relative high pressure cooling air supply pressure and temperature during a trip of High Fogging system

The reduced cooling air temperature of course does not improve the conditions for cooling air systems with a cooling air cooler since the cooling air is cooled to a fixed temperature. Cooling systems where the positive pressure margin could sink below a critical value have to be checked before High Fogging can be applied. This would be for example the minimum pressure ratio required to assure effective shower head cooling of a blade.

In preparation of the High Fogging tests the cooling air system was slightly adjusted and critical pressure margins were carefully supervised during testing.

IV Cooling air coolers are usually controlled to maintain a constant outlet temperature independent of inlet or operating conditions. As described above the inlet conditions to such a cooler change considerably if High Fogging comes into operation or is switched off suddenly. As for the turbine inlet temperature (see II) a fast transient of the High Fogging system can influence the outlet temperature of cooling air coolers. For example during a trip of a High Fogging system the cooling power of a low pressure cooling air cooler of a GT26 has to be increased by more than 200% within a short period of time. Simulations proved that the outlet temperature can be maintained very close to the design value with adequate controls. During the test campaign fast testing of transients started with small steps. The response of the gas turbine was evaluated and the total transients increased up to system trips from maximum High Fogging water mass flow.

V One interesting questions is if waters droplets might propagate into the cooling air system. These could possible lead to thermal stress and corrosion. To remove possible droplets water separators were installed in the low pressure cooling air system. Additional temperature and humidity measurements were installed in the cooling air systems.

Detailed tests under different operating conditions confirmed the safe operation of high fogging. Test to the limit of droplets reaching the cooling air system give a good basis for engine specific checks.

These checks for the possibility of droplet ingestion have to be carried out for each gas turbine type.

VI Like conventional inlet cooling (see Inlet cooling operation) a High Fogging System can create compressor distortion. In case of a High Fogging system the impact can potentially be bigger because of the higher injected water mass flow.

A distortion created by a High Fogging system cannot be detected by temperature measurement upstream of the compressor inlet because typically an inlet cooling system upstream of the High Fogging system already assures a homogeneous high humidity. Even with a considerable mismatch between airflow and injected water mass flow, wet bulb temperature and close to 100% humidity will be reached at almost any location downstream of a High Fogging system.

To investigate the effect of distortion the High Fogging system was modified to create a defined distortion pattern by blocking part of the system. The distorted injection can be seen even at the end of the compressor down into the compressor plenum. In case of a distorted test, the measured compressor exit temperature spread got up to approximately 15°C for an average overspray of only about 0.5% High Fogging water relative to the intake air mass flow; under the specific test conditions this was equal to about 1% aerodynamic speed. Local distortion might be even higher than detected by the instrumentation available at that time.

The influence of temperature distortion on the surge margin of the compressor was quantified by surge tests of the gas turbine with an intentionally distorted High Fogging system.

VII Since any part of the High Fogging nozzle rack which might come lose during the gas turbine operation will most likely lead to a catastrophic foreign object failure of the gas turbine special attention was given to mechanical integrity of the injection system and locking systems. In addition to Finite element simulations, which were used to check the design of the system, acceleration probes were applied to the racks to confirm the design.

VIII In order to avoid excessive thermal stress of hot parts by continuous high fogging water injection after a trip of the gas turbine, a trip signal is forwarded to the high fogging system and a fast shut down of the water supply is assured.

HIGH FOGGING PERFORMANCE MODEL

To analyze the GT performance under High Fogging conditions the performance models were modified. These modifications are based on an analytical approach to the phenomena in compression with High Fogging. The resulting model is adjusted to fit the measured test results.

Overview of methodology

The following equation is a consequence of the combination of the first and second law of thermodynamics.

$$Tds = dh - vdp \qquad (1)$$

This can further be expressed in this form

$$\int Tds = j \pm q = \Delta h - \int vdp \qquad (2)$$

For a reversible adiabatic process, j and q are both zero and equation 2 reduces to

$$\Delta h_{ideal} = \int vdp \qquad (3)$$

For an irreversible adiabatic process, only q is zero and equation 2 then becomes

$$\Delta h_{real} = \int vdp + j \qquad (4)$$

The polytropic efficiency of adiabatic compression is defined, as the ratio of the polytropic stream work (eqn. 3) and the specific energy required for the compression (eqn. 4).

$$\eta_{p,a} = \frac{\int vdp}{\int vdp + j} \qquad (5)$$

For a non-adiabatic irreversible process, q is not zero, and equation 2 applies. The polytropic efficiency of this process is then given by equation 6.

$$\eta_{p,\,na} = \frac{\int vdp}{\int vdp + j \pm q} \tag{6}$$

Substituting equation 5 in 6, the polytropic efficiency of a non-adiabatic compression process is expressed in terms of that of the adiabatic compression as shown in equation 7.

$$\eta_{p,\,na} = \eta_{p,\,a} \cdot \frac{\int vdp + j}{\int vdp + j \pm q} \tag{7}$$

Substituting equation 4 in 7 gives

$$\eta_{p,\,na} = \eta_{p,\,a} \cdot \frac{\Delta h_{real}}{\Delta h_{real} \pm q} \tag{8}$$

Where for the case of cooling, the negative sign applies and Δh has a direct relationship with the compressor power. The adiabatic term is related to the evaporative enthalpy of the sprayed water. Heat does not cross the boundary of the compressor, as the cooling is an internal phenomenon of the compressor. This is accounted for in the heat balance of the compressor model. Figure 8 shows the representation of these processes in the h-s diagram. For the purpose of deriving the equations presented, a constant pressure has been assumed for the end states of compression for both dry and wet points (ideal case).

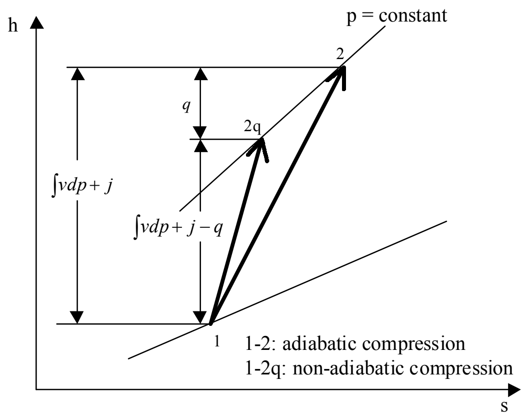

Figure 8 h-s diagram showing both adiabatic and non-adiabatic compression processes

Based on measurements for high fogging points, $\eta_{p,\,na}$, Δh_{real} and q can be calculated from the existing compressor model in the gas turbine performance simulation platform. From these calculated quantities, the adiabatic polytropic efficiency $\eta_{p,\,a}$ is obtained from equation 8. This polytropic efficiency corresponds to the efficiency that will be obtained if there exists a compressor map with high fogging. However, this is not the case. Fortunately, the dry compressor map can be corrected from this calculated efficiency by using the relationship

$$\eta_{p,\,a} = f \cdot \eta_{map} \tag{9}$$

Where η_{map} is the efficiency from the dry compressor map.

The calculated high fogging correction factor is very well dependent on the dry point and it is necessary to have very good measurements for this point. This applies equally well to the high fogging points. These equations are applied to the overall compressor and as well as to the air extraction points leading to efficiency correction factors for the overall compressor and for the part compressors. It has also been shown that there is a pressure decrease with increasing high fogging water for the compressor air extractions and as result pressure correction factors can be calculated from the model based on measurements. It has also been proven that there is a decrease in compressor intake mass flow with high fogging water and as a result correction curve for the compressor intake mass flow can also be determined from the model using measurements as well.

Effect relative to the dry compressor map

The efficiency correction factors for the overall compressor and the extraction points can be regarded as the total effect of high fogging on the dry compressor map. They are presented as functions of the high fogging water mass flow relative to the compressor intake mass flow at the dry point. These total effects include changes in both the aerodynamic losses and the thermal properties. The increase in aerodynamic losses with high fogging is overcompensated by the positive effect of the change in thermal properties resulting in a specific benefit – decrease in compressor specific work.

The high fogging correction factors in the compressor performance model were calculated using engine measurements. These correction factors are efficiency correction for the overall compressor, efficiency correction for the part compressors i.e. from intake to each extraction, pressure correction for each extraction, correction of the compressor intake mass flow. During the high fogging test campaign in Birr, the ambient relative humidity was at saturation and therefore the total sprayed water was equivalent to the high fogging water. Generally, with lower ambient relative humidity, a relative humidity in front of the compressor is assumed for the dry point and the fogging points in the fogging model on the basis of which the correction curves are evaluated. This implies that any sprayed water evaporation taking place before the inlet of the compressor up to this level of assumed saturation would have no effect on the dry compressor. This is actually the fogging effect. The high fogging correction starts from this point because the ideal gas law and Mach number similarity no longer applies as we then have a two-phase mixture.

Figures 9 and 10 show the overall efficiency and compressor intake mass flow correction curves calculated from the high fogging model using measurements. At the reference dry point, the correction factors are 1. In addition to these two correction curves presented, efficiency and pressure correction curves for the compressor air extractions can also be calculated from the model.

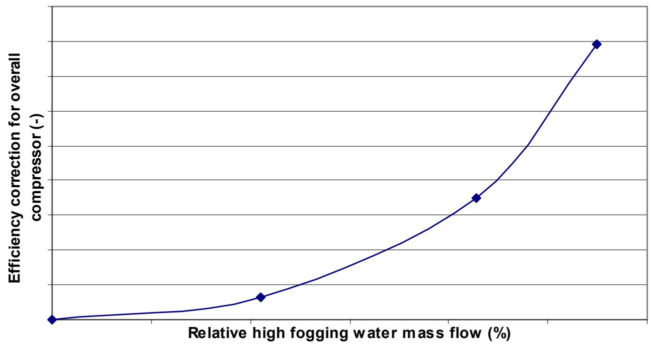

Figure 9 Efficiency correction factor for overall compressor relative to the dry compressor

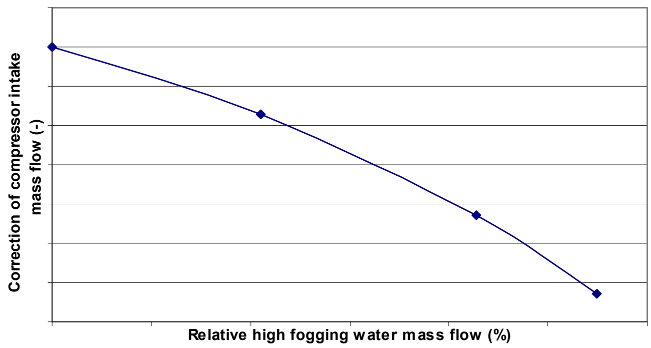

Figure 10 Compressor intake mass flow correction relative to the dry compressor

Comparison of model to measured data

In figures 11 to 13 a comparison of the mass flow, pressure and temperature relative to the dry point for the first compressor extraction point calculated from the high fogging model and those obtained from measurements are given as an example. The model curve was obtained using the gas turbine model corresponding to the dry point with high fogging correction curves (such as figures 9 and 10), which were derived from High Fogging test results. As shown, the values obtained from the model compares well with those from measurements. This implies that the high fogging model with the correction curves can be used to predict the behavior of compressor with high fogging water.

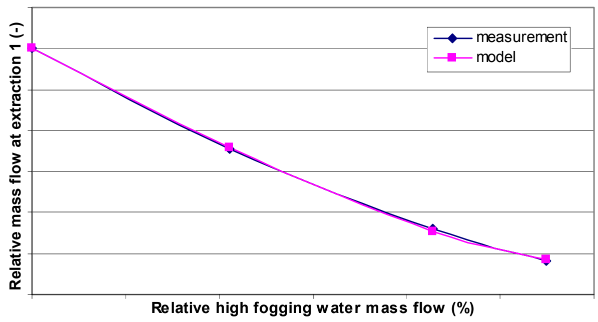

Figure 11 Compressor extraction 1 relative mass flow

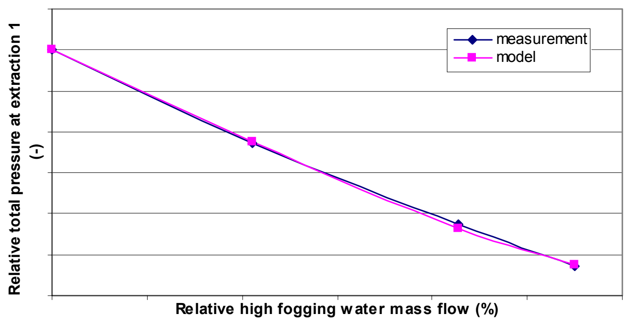

Figure 12 Compressor extraction 1 relative total pressure

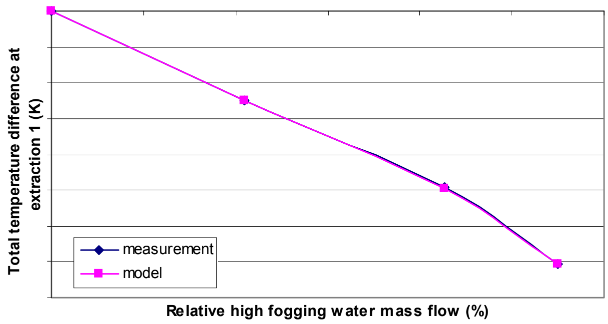

Figure 13 Compressor extraction 1 total temperature difference

CONCLUSIONS

Based on extensive tests safe and reliable High Fogging operating concepts and systems were developed. Substantial gas turbine performance increases were proven. As a result commercial operation with High Fogging has commenced.

The principal operating concepts for inlet air cooling systems and High Fogging are outlined. The main concerns and areas, which need special attention in relation to High Fogging operation are presented. These are:

- erosion and corrosion of compressor blades
- overfiring during fast transients of the High Fogging system
- change of cooling air system and water carry over
- compressor distortion
- mechanical integrity of additional systems in the intake

Critical points and ways to mitigate possible risks are shown. However, several critical questions cannot be answered in a general way during transient operation, changes experienced within the gas turbine's cooling air system, and compressor distortion and resulting reduction in surge margin. These issues have to be specifically investigated and defined for each gas turbine type. Some issues, as for example nozzle distribution in the intake manifold, currently require evaluation for different installations of the same engine type.

Primarily, the current knowledge base for the appropriate methods to install High Fogging systems into industrial gas turbine engines is based on empirical test results. Based on these results, semi-empirical models have been established to predict gas turbine behavior with High Fogging systems installed. The developed high fogging compressor performance model can be used for future prediction of the behavior of the compressor with a high fogging system. Further, it provides boundary conditions for evaluation of all major gas turbine components when operating under High Fogging Conditions.

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