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ASPECTS OF THE GT INLET SYSTEM THAT AFFECT GT EFFICIENCY, INCLUDING A FOCUS ON THE CORRECT APPLICATION OF POWER AUGMENTATION

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ABSTRACT

With the ongoing environmental and geopolitical concerns in this modern world, it has never been more important to consider and optimise the efficiency of gas turbine installations. Beit, to reduce carbon emissions or fuel consumption, increase power output or improve availability.

The combustion air inlet system is one of the contributing factors that plays an important role in the efficiency of the gas turbine (GT) system. It has been recognised in recent years, with many papers already published, that reducing GT fouling by increasing the dust removal efficiency of the inlet system can offer a significant improvement to GT efficiency. The standard recommendation today is to upgrade to EPA rated filters, which are now available from most filter vendors.

The session to be presented here focuses on other, lesser discussed aspects of the inlet system that also contribute to improving the efficiency of the gas turbine, to ensure they do not get forgotten or overlooked and these will include; control of moisture to minimise unwanted side effects such as spikes in pressure loss, the role of and considerations for, hydrophobic and oleophobic properties of filters to reduce GT fouling or eliminate salt penetration, and the use and types of combustion inlet air cooling, with pros and cons and application advice.

INTRODUCTION

The goals of today's gas turbine operators are to; reduce emissions, improve fuel consumption, increase available output and improved availability, all of which can be achieved through improving gas turbine efficiency.

Aspects of gas turbine efficiency that can be affected by the inlet air filtration system are gas, turbine fouling, gas turbine corrosion, pressure loss, and changes in air density. To control gas turbine fouling the air inlet system minimises ingested contaminant. To reduce gas turbine corrosion the inlet system minimises ingested corrosives. To optimise pressure loss the inlet system needs to maintain a low-pressure loss throughout the life of its filters. The density of the air into the gas turbine can be controlled by changing its temperature as it passes through the inlet system.

NOMENCLATURE

GT: Gas turbine
CFD: Computational fluid dynamics
EPA: Efficiency particle arrestance
HEPA: High efficiency particle arrestance
F9: Filter efficiency rating to BS EN ISO 779
E10: Filter efficiency rating to BS EN ISO 1822
H12: Filter efficiency rating to BS EN ISO 1822

GT FOULING

Gas turbine fouling occurs when contaminants pass through the engine and attach to the blades of the machine causing a change to their surface finish or physical dimensions, leading to higher fuel consumption, lower power output and reduced engine efficiency. These contaminants can be in the form of, solid particulates, liquids, or gases, see Figure 1.

Particulates are removed from the inlet airflow using media filters. Liquids are removed with water removal stages such as weather hoods and coalesces, but also hydrophobic filters. Gases or Vapour are generally not removed today as there is no practical filtration system to do this.

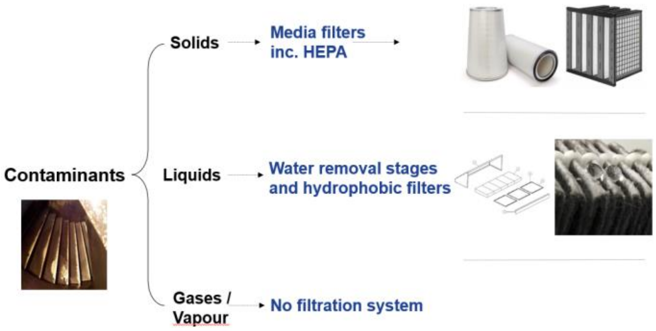


Figure 1, Forms of contaminants that can cause GT fouling

There are typically two methods to reduce or eliminate gas turbine compressor fouling. The first is to install very high efficiency filters into the intake system such as EPA or HEPA (E10 to H12) filters, which remove virtually all the airborne solid particulate. This method has been previously discussed in many published papers and is not going to be discussed in any detail within this paper, although some of the additional challenges this solution brings will be touched on in this paper.

The second method is to prevent any solid particulate that does pass through the gas turbine from sticking to the blades by preventing sticky contaminants such as salts and hydrocarbons from entering the machine. This is achieved with the use of hydrophobic filters which addresses liquid forms of contaminants entering the gas turbine.

Once fouling has occurred to a significant degree it is usual practise to shut down the gas turbine and perform an offline water wash to remove the contaminants from the compressor section, which recovers most of the performance. But this process requires the gas turbine to be offline which affects its availability and is often necessary between scheduled outages which makes it harder to plan for.

Figure 2 shows an example of real-world gas turbine performance data (Hiner 2015) for three consecutive years of running. The filtration particulate efficiency is the same, F9 rated to EN779, for each of the installed filters for the entire period.

The graph shows gas turbine performance variables on the vertical axis with pressure loss lower most, then heat rate or fuel efficiency, then gas turbine power output and finally two measures of gas turbine compressor efficiency.

As can be seen for the first year of operation, fouling occurs on the gas turbine compressor reducing power output and increasing heat rate or fuel consumption leading to four GT shutdowns for compressor washing. After the first year the filters were changed to hydrophobic filters with the same particulate efficiency rating. It is clear from the data that this change has made a massive difference to the performance of the gas turbine with very little fouling or performance degradation occurring during the yea,r and no need to shut down the GT for compressor washing. After this second year of operation, the original filter type was reinstalled and the degraded performance returned.

This example clearly shows the benefit that came from the installation of hydrophobic filters, despite having the same particulate removal efficiency.

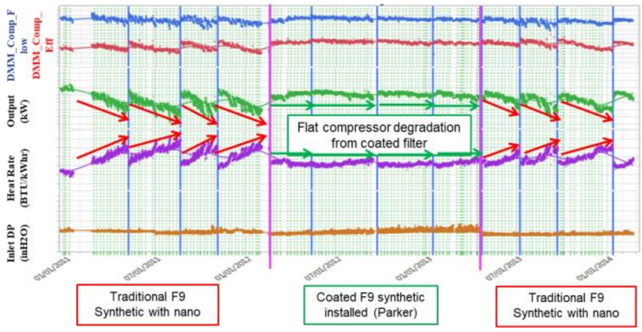


Figure 2, Example real-world GT running data

Figure 3 shows many other similar examples of real-world gas turbine data with significant performance improvements following the installation of hydrophobic filters with the same particulate efficiency rating.

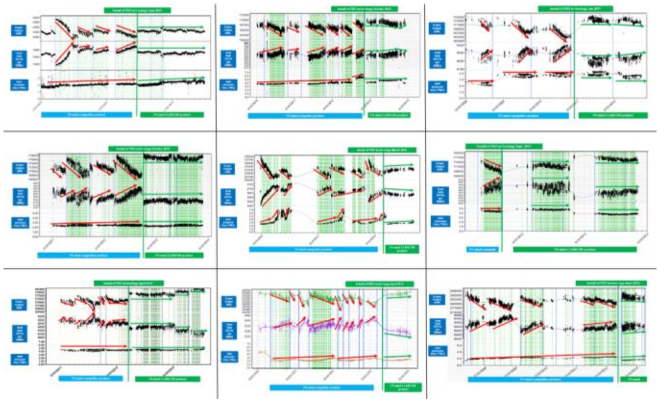


Figure 3, Many other examples of GT performance improvement following installation of hydrophobic filters

To design a filter with good hydrophobic properties is not just about making the filtration media hydrophobic (Hiner 2016), other aspects of the design are also very important. This includes how the media packs are potted into the filter frame to ensure no gaps or cracks occur that could lead to leaks and how the media is pleated to minimise damage at the pleat tips, which is achieved through careful design of the pleating tooling as well as optimised pleating machine settings. The design also needs to consider drainage, typically with the media pleated vertically and drainage features added to the design of the filter. And finally, the seal to the filter house holding frame needs to be robust and the clamping mechanism designed to optimise the seal of the filter once installed.

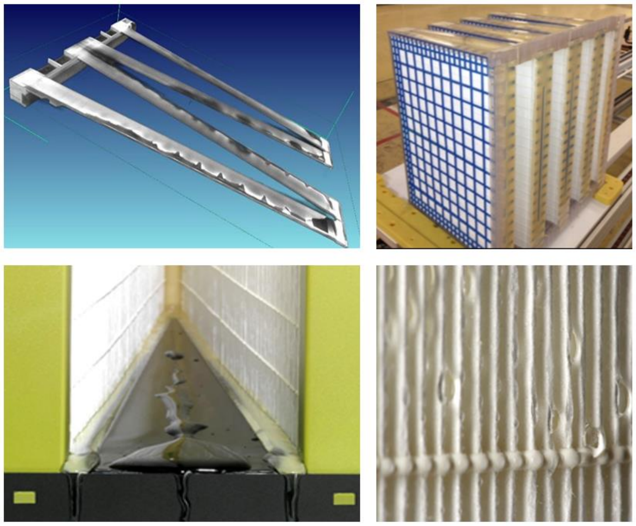


Figure 4, Optimising filter media potting and drainage design features

GT CORROSION

Gas turbine corrosion occurs when corrosive contaminants pass through the machine. Corrosion can occur in all parts of the machine from the compressor all the way through to the turbine, and once again corrosive contaminants can enter in the form of, solid particulates, liquids, or gases and vapours, see Figure 5.

GT blade pitting corrosion is often caused by sulphates and chlorides, while in coastal and offshore locations the sodium in sea salt can combine with sulphur in the fuel to cause accelerated hot end corrosion of the gas turbine.

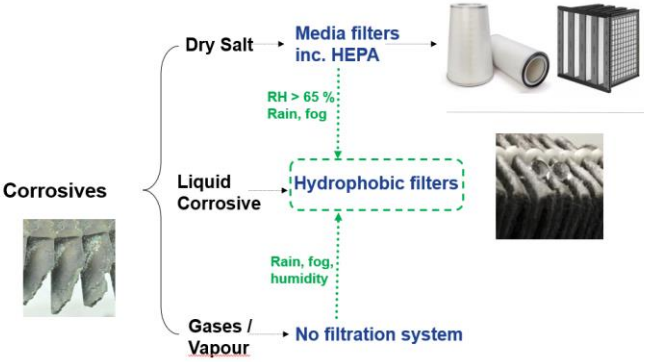


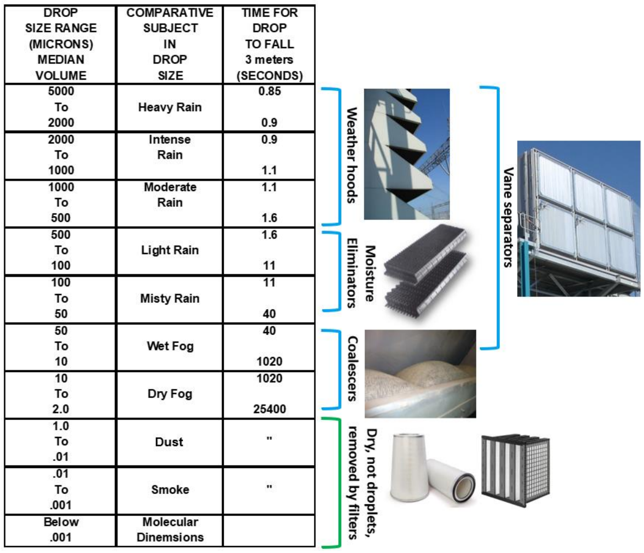
Figure 5, Forms of contaminants that can cause GT corrosion

Many of these corrosive elements in the form of particulate or gases and vapours often enter the gas turbine in liquid form, after transforming to liquid by combining with, relative humidity, rain and fog or other forms of moisture in the environment. Sea salt is a particularly interesting substance as it is typically a dry particle below the relative humidity of 65% but as humidity increases the salt readily absorbs moisture and deliquesce into liquid form (McGuigan 2004). So even if dry salt has been captured as a particle in a particulate filter, once it turns to liquid form, under high humidity conditions it can then leach through the filter and pass to the gas turbine.

The removal of contaminants in liquid form is therefore extremely important to reduce gas turbine corrosion and this is primarily achieved today utilising hydrophobic filters (Hiner 2016, Woodward 2015). As with particulate filters, hydrophobic filters have an “effective” life with their hydrophobic properties becoming less effective over time as the fibres of the filter media become coated with dirt. It is therefore very important that hydrophobic filters are replaced on a regular basis even if their pressure loss has not reached the change out value. Typical effective life is one to two years of operation.

CONTROL OF ENVIRONMENTAL MOISTURE TO MANAGE THROUGH LIFE PRESSURE LOSS

Environmental moisture comes in many forms, from heavy rain and drizzle, to mist and fog. Each type has a different droplet size and volume and therefore requires a different technology to remove it from the air entering the gas turbine (Hiner 2011), see Figure 6.



DROP SIZE RANGE (MICRONS) MEDIAN VOLUME	COMPARATIVE SUBJECT IN DROP SIZE	TIME FOR DROP TO FALL 3 meters (SECONDS)
5000 To 2000	Heavy Rain	0.85 0.9
2000 To 1000	Intense Rain	0.9 1.1
1000 To 500	Moderate Rain	1.1 1.6
500 To 100	Light Rain	1.6 11
100 To 50	Misty Rain	11 40
50 To 10	Wet Fog	40 1020
10 To 2.0	Dry Fog	1020 25400
1.0 To .01	Dust	"
.01 To .001	Smoke	"
Below .001	Molecular Dinemsions	

Figure 6, Removal methods for different forms of environmental moisture

If the atmospheric moisture is not adequately removed this can lead to wet filters, where the moisture then combines with captured dirt, which can result in pressure loss spikes, contaminant wash through the filters leading to degradation of the gas turbine and potentially unscheduled outages.

Very high efficiency filters such as EPA and HEPA filters can be extra sensitive to very fine moisture such as mist and fog as they are more efficient at removing contaminants of this size. In this case the very fine droplets are filtered in exactly the same way as they would be if they were particulate, but because of the vast quantity of droplets present it is like the filter experiencing a sandstorm of very fine particulate, and the pores of the filter media very quickly get blocked, leading to an accelerated increase in pressure loss, see Figure 7for a real-world example, which can rapidly lead to a gas turbine shut down.

Very fine droplets caught in the filter find it difficult to drain due to complex surface tension effects and will remain until the relative humidity drops, when they will evaporate and the pressure loss of the filter return to normal.

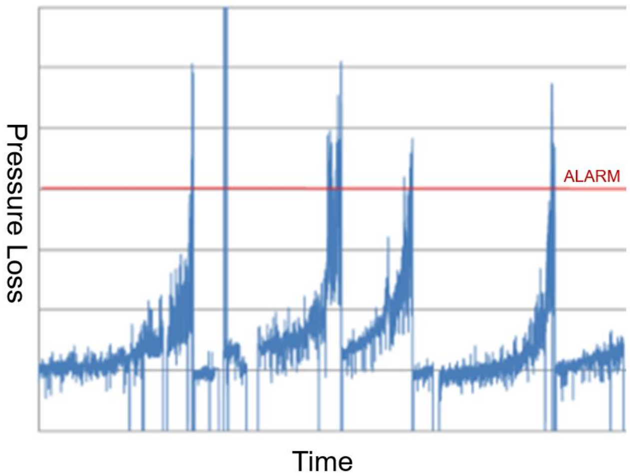


Figure 7, Real-world GT running data of HEPA filter pressure loss during a fog event

Coalescing filters are used in the gas turbine inlet system to prevent fine mist and fog droplets from reaching the filters. These do not remove the mist and fog but instead coalesce these fine droplets into much larger droplets, see Figure 8, which then drain easier and have much less effect on the downstream filters.

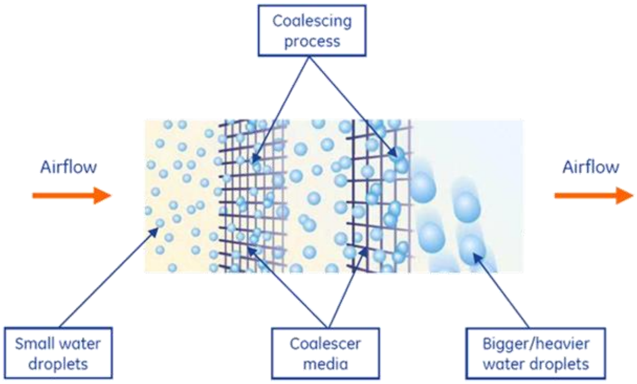


Figure 8, The coalescing process

Many different types of coalescer filter are used today, see Figure 9, and most of these will also perform some filtering of dust and so need to be maintained on a regular basis, although this can most often be performed with the gas turbine still online. This can however be problematic in areas of high dust although more advanced designs are available with minimal dust removal properties, to maximise operational life and minimise maintenance requirements (Kippel 2016). Contact Parker Gas Turbine Filtration division if you would like more information on such products.

Figure 9, Different types of coalescer filter installed in the weather hoods

To demonstrate the effectiveness of this type of coalescer filter a dirty used gas turbine final filter was returned from the field and tested in the wind tunnel against mist (Nicholas 2020). The graph in Figure 10 shows the results.

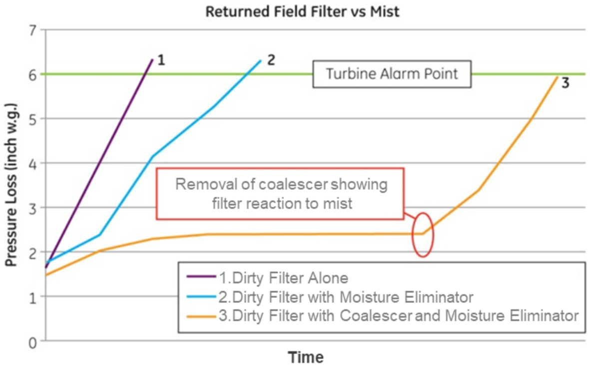


Figure 10, Performance comparison of field returned filter, with and without coalescer installed

The purple line plots the pressure loss of the dirty used filter with no coalescer installed in the wind tunnel, which experiences a rapid increase in pressure loss.

The blue line plots the pressure loss of the dirty used filter with a moisture eliminator installed upstream in the wind tunnel. This experiences a slightly slower, but still rapid increase in pressure loss.

The orange line plots the pressure loss of the dirty used filter with the coalescer filter and moisture eliminator installed upstream in the wind tunnel, this line exhibits a slight increase in pressure loss before reaching a steady state for an extended period, only once the coalescer filter is then removed from the wind tunnel does the pressure loss of the dirty used filter rapidly increase.

This testing clearly demonstrates the effectiveness of the coalescing filter that prevented the dirty used filter pressure loss from rapidly increasing when challenged with mist.

BASELINE PRESSURE LOSS

For every one-inch water gauge (250 Pa) of pressure loss on the inlet system, a gas turbine will experience around a 0.4% reduction in power output and a 0.1% increase in heat rate or fuel consumption, so minimising the filter system pressure loss has a meaningful effect on the efficiency of the gas turbine.

The pressure loss of any given filter is driven by several design aspects. One of these is aerodynamics and the dynamics of flow through the filter.

The following is an example of an advanced cartridge filter design, but similar examples exist for other types of gas turbine filters, which demonstrates how lower baseline pressure loss can be achieved.

This enhanced cartridge filter design fits into existing filter houses using the original installed hardware and so no modifications are required.

The pressure last through a cartridge filter system is dominated by the pressure loss through the aperture at the filter house tube sheet. The enhanced cartridge design as shown in Figure 11, optimises the airflow distribution through the tube sheet aperture, which minimises its overall pressure loss.

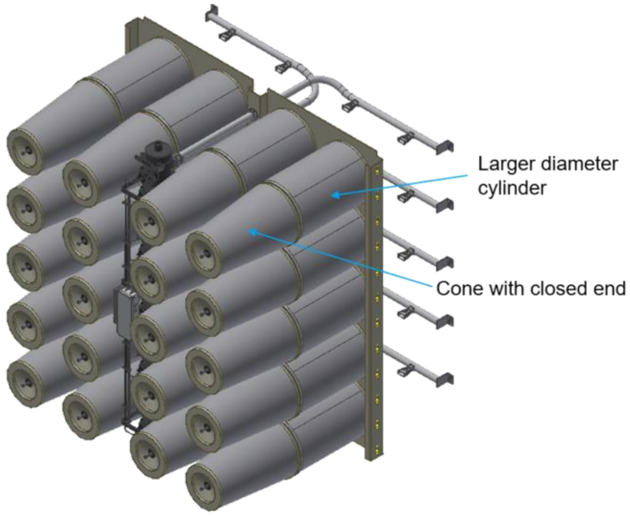


Figure 11, Improved cartridge geometry with lower pressure loss

This has been achieved using computational fluid dynamics (CFD), see Figure 12, and proven through testing in the wind tunnel, as shown in Figure 13, which demonstrates a pressure loss improvement of up to 25% over the original cartridge design.

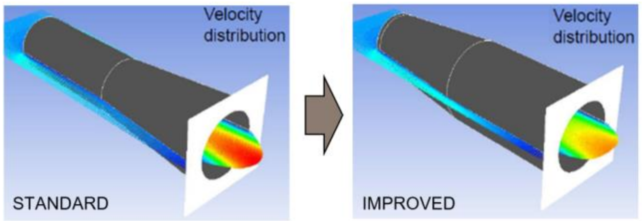


Figure 12, Computational fluid dynamics used to optimise airflow through tube sheet aperture

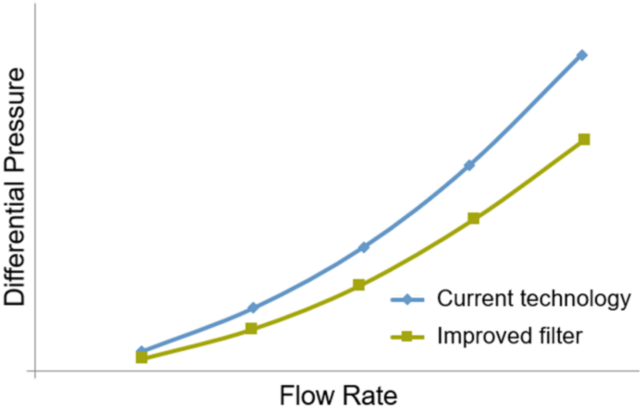


Figure 13, Wind tunnel testing of improved cartridge design vs. standard

CONTROLLING AIR DENSITY THROUGH INLET AIR COOLING

Gas turbines are mass flow machines, lower air density means, less mass flow into the engine which results in decreased engine efficiency, increased heat rate or fuel consumption, higher emissions, and lower power output.

The density of air is determined by the ambient temperature and the altitude of the installation, the higher the ambient temperature or altitude the lower the air density.

It is typical to expect around 0.4% reduction in power output, see **Figure 14,** Reduction in GT output vs. inlet temperatureFigure 14, plus 0.1% increase in heat rate or fuel consumption for each 1°F (0.55°C) rise in ambient temperature above 59°F (15°C) (McGuigan 2018).

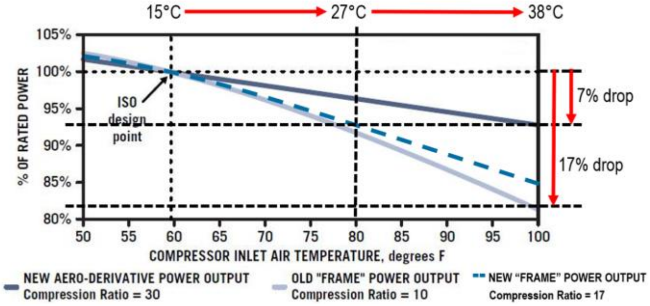


Figure 14, Reduction in GT output vs. inlet temperature

Altitude has a minimal effect on heat rate or fuel consumption but for each 1000ft (305m) increase in site elevation above sea level, there is about a 3.5% loss in power output.

Cooling the air into in the gas turbine increases its density which will recover much of these losses. There are three main methods used today to cool the inlet air going into a gas turbine which are, wetted media evaporative cooling, fogging evaporative cooling and chilled water chilling coils, and each one has a different set of pros and cons with no single optimum solution to best fit all applications.

WETTED MEDIA EVAPORATIVE COOLING WORKING PRINCIPAL AND SYSTEM CONFIGURATION

GT inlet air passes through a vertical bank of water-soaked evaporative cooler media. Evaporation of water contained in the media lowers the temperature of the air.

A sump with pumping system is installed at the base of the wetted media packs to capture drained water and recirculate it to a spray system mounted at the top of the evap cooler media packs, see Figure 15, where it is distributed evenly to ensure uniform cooling of the GT air.

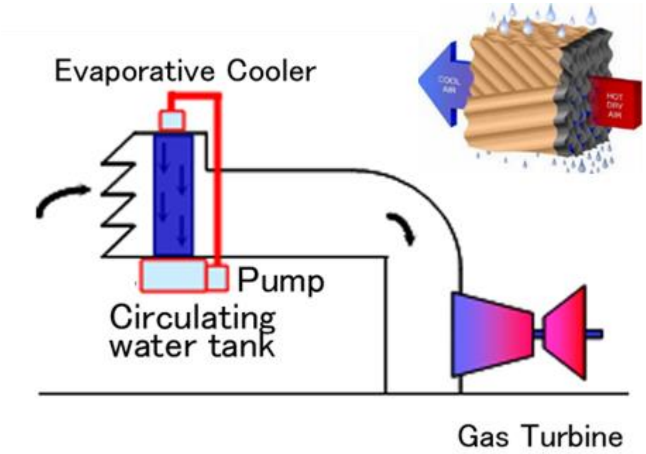


Figure 15, Wetted media evaporative cooler system overview

New water is continually added to the system to replenish that which is lost through the evaporation process. The system is usually supplied with potted water as this eliminates the need for a water treatment facility and so is the most economical.

Over time dissolved minerals from the evaporated water will build up in the water within the system requiring a large portion to be replaced to dilute the concentrations. An automatic system is installed utilising a conductivity sensor to control this water drain and refilling cycle, known as “blow down”. Eventually however, some of the dissolved minerals will build up as deposits on the wetted media packs requiring them to be changed at regular intervals.

A drift eliminator is mounted downstream of the wetted media packs to capture any free droplets that may carryover from the evaporative media and so prevent them from entering the gas turbine.

The cooling process through evaporation results in the downstream air having a very high humidity and so an evap cooler should only be mounted downstream of the air filters to prevent them getting wet.

FOGGING EVAPORATIVE COOLING WORKING PRINCIPAL AND SYSTEM CONFIGURATION

The working principle is similar to that for a wetted media evaporative cooler, but this time it is the evaporation of very fine droplets that cools the GT inlet air.

An array of very high-pressure fogging nozzles is mounted within the GT inlet duct and a high-volume fog of very fine pure water droplets is injected directly into the airstream, see Figure 16.

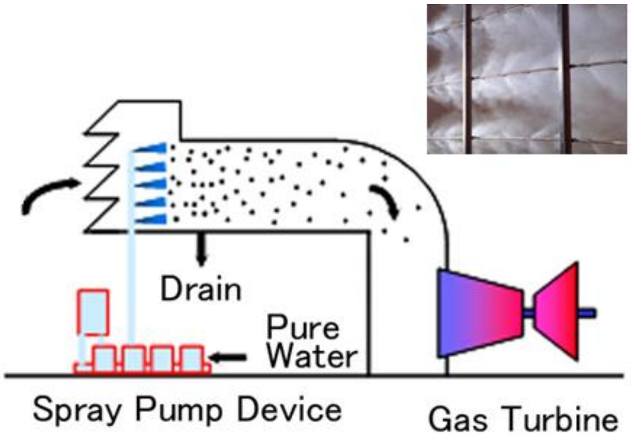


Figure 16, Fogging evaporative cooler system overview

Pure water is required so that no dissolved minerals are left in the air to enter the gas turbine after the water has evaporated as these could cause fouling of damage to the gas turbine. The pure water is supplied by a water purification plant and very high-pressure water pumps, both of which will require additional.

The volume of water that can be evaporated into the air is directly related to the ambient temperature and relative humidity and so is a constantly changing value. Unlike the wetted media evaporative cooler that supplies more than enough water to the wetted media packs and only the volume of water that can evaporate will, for a fogging system it is very important that all of the water injected into the GT inlet duct is evaporated and no droplets are left which could otherwise possibly cause erosion of the compressor blades. The control of the volume of water fed to the fogging nozzles is therefore very important and so an automated system is installed with a local weather station to minimise the possibility of over spray of more water than is possible to evaporate at the time.

The rate of evaporation of the droplets is directly linked to the droplet size, the smaller the better, and the residence time within the duct, which needs to be sufficiently long in length to allow the droplets to completely evaporate before the air reaches the gas turbine.

With such a large volume of very fine droplets in a confined space, it is inevitable that some of these will collide and coalesce into larger droplets which are less likely to evaporate and more likely to reach the GT. Fogging nozzles will also wear over time due to the high pressure of the feed water and can get blocked, both of which will also affect droplet size, producing larger droplets, so gas turbine compressor erosion is the biggest concern when installing such a system.

By its very nature, fogging creates a very wet environment downstream and as such it should only be installed downstream of the air filters to prevent them from getting wet.

CHILLED WATER CHILLING COILS WORKING PRINCIPAL AND SYSTEM CONFIGURATION

A finned, liquid to air heat exchanger coil (chilling coil) is mounted directly in the gas turbine air inlet duct and supplied with cold water/glycol mix from an externally sited chilled water refrigeration plant, through a closed loop system of insulated pipework, see Figure 17. The gas turbine inlet air is cooled as it passes over the fins of the heat exchanger, which also condenses any water vapour present in the air, leaving cooled dry air to enter the GT.

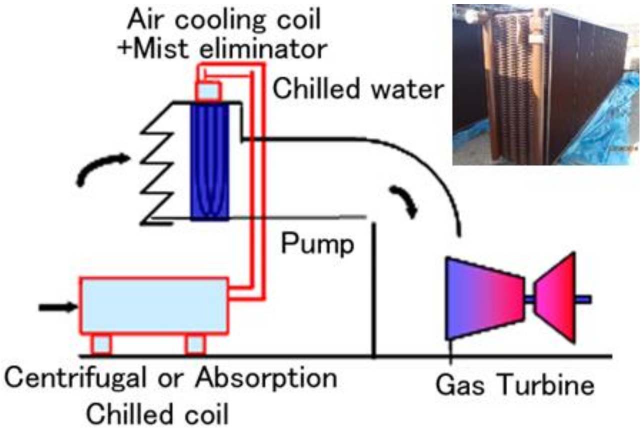


Figure 17, Chiller coil system overview

A vane separator is mounted downstream of the chilling coil to capture any water condensate that does not drain completely from the fins of the coil, to prevent droplets entering downstream.

It is possible but unusual to use the same coil for heating as well as for cooling, if this is required to address other performance concerns, such as icing in cold weather.

As the air leaving the chilling coil is drier than the ambient air it will not affect the air filters and so the installation of the chilling coil is more flexible and can be located upstream or downstream of the filters, note however that if mounted upstream of the main air filters, fouling of the fins of the coil themselves should be considered which may require the installation of guard filters.

A COMPARISON OF THE THREE GAS TURBINE COOLING METHODS

Wetted Media Evaporative Cooling

Advantages

- Wetted media evap cooling is the most common method used today to cool GT inlet air.
- The system is relatively simple.
- Uses potable water so no water treatment is required.
- Induct cooling components can be removed when not required, to minimise inlet pressure loss.

Disadvantages

- Due to the physics of evaporation, the air temperature cannot be lowered below the wet-bulb temperature, so the cooling effect is significantly reduced in locations with high ambient humidity.
- The system consumes significantly more water than that which is evaporated in the GT inlet.
- The wetted media components add a small increase in pressure loss to the GT inlet system.
- The system must be drained in low ambient temperatures to eliminate the risk of icing.
- Retrofitting the system into an existing GT installation is difficult as the evaporative cooler must be installed downstream of the air filters.

Fogging Evaporative Cooling

Advantages

- Adding fogging nozzles into the air inlet duct adds virtually no additional pressure loss
- The system only consumes the volume of water that is evaporated in the GT inlet.
- Retrofitting of the system can be easy if sufficient ducting downstream of the air inlet filters already exists.

Disadvantages

- Due to the physics of evaporation, the air temperature cannot be lowered below the wet-bulb temperature, so the cooling effect is significantly reduced in locations with high ambient humidity.
- The system uses pure water and so a water purification plant is required, with associated additional maintenance requirements.
- An automated water flow rate control system is required to minimise the possibility of overspray, which adds a level of complexity and risk.
- The system must be drained in low ambient temperatures to eliminate the risk of icing.

- Retrofitting the system into an existing GT installation can be difficult as the evaporative cooler must be installed downstream of the air filters, but it may be possible to install into the existing ductwork.
- There are significant concerns around the possibility of causing compressor erosion.

Chilled Water Chilling Coils

Advantages

- Air temperature can be lowered below the wet bulb temperature and the cooling effect is independent of ambient humidity and so is effective at any location and time of year.
- The system does not consume water.
- Chilling coils can be installed upstream or downstream of the air inlet filters.
- The chilling coils can be used for inlet air heating if required.

Disadvantages

- The chilling coil adds significant pressure loss to the inlet system, and this is present all year around and the coil cannot be removed once installed.
- The system requires a water chilling plant which adds to the maintenance requirements of the system.
- The system consumes a high parasitic electrical load from the gas turbine, which can be up to one third of the power gained by cooling the air.
- The initial investment cost is high to install the system.
- Even though the chilling coil can be installed either upstream or downstream of the air inlet filters, retrofitting the system into an existing GT installation can still be difficult as the chilling coil is very heavy and will likely require additional support steel work to be installed.

CONCLUSIONS

The GT inlet system offers worthwhile opportunities to improve GT efficiency leading to; reduced emissions, improved fuel consumption, increased available output and improved availability.

Increasing filter particulate efficiency is valuable, but other changes can lead to improvements.

A filter's hydrophobic properties play an important role in keeping the GT compressor clean and reduce fouling and are critical in reducing GT corrosion.

The appropriate removal of moisture in all forms is vital to keep operating pressure loss low and avoid unplanned outages.

The addition of inlet air cooling can significantly improve GT efficiency, but care must be taken to the application of the most appropriate cooling technology as each has a different balance of compromises, there is no one best solution that fits all requirements.

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