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GAS TURBINES AND ASSOCIATED AUXILIARY SYSTEMS IN OIL AND GAS APPLICATIONS

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ABSTRACT

This tutorial elaborates on the various gas turbine auxiliary systems; for mechanical drive applications in oil and gas projects, from an EPC contractor perspective. The tutorial briefly introduces the basics of gas turbines including thermodynamics, types, arrangements, components and combustion technologies. However, the focus of this tutorial remains on the gas turbine auxiliaries where the functions and technology selection options are explained; furthermore, the relevance on the gas turbine performance and availability and the technical constraints for implementation are described. This tutorial contributes; in addition to what have been previously published, by being focused on the engineering of interfaces between the gas turbine, it's auxiliary systems, and the plant in oil and gas onshore and offshore projects.

INTRODUCTION

The gas turbine is a complex example of rotating equipment where three major machinery systems contribute together to deliver the required driving performance of the gas turbine: 1) Axial air compressor; 3) Combustion System and 3) Power Turbine. The temperature inside the gas turbine may reach up to 1500°C (≈ 2700°F) within the combustion chamber, and the compressor discharge pressure values could be up to 55 bara (≈ 800 psia), and power delivery above 100 MW (≈ 143000 hp). Gas turbines are indeed at the cutting edge of technology. Gas turbines for the oil and gas industry are covered by API 616 for on-skid and off-skid systems.

In oil and gas application, gas turbines are used as drivers for pumps, compressors and electric generators, and the power outputs of gas turbines in such applications range from 5 to 120 MW (≈ 6700 to 161000 hp). Gas turbine drivers are implemented in various oil and gas (& petrochemical) sectors such as in liquefied natural gas (LNG) plants, ammoniac & urea plants, offshore applications such as fixed platforms, floating platforms, floating production storage and offloading facilities (FPSO), floating liquefied natural gas (FLNG). In the power generation industry, gas turbines could reach hundreds of Megawatts and are especially used in combined cycle applications.

Gas turbines are in general considered as standard machinery products, with few manufacturers competing on a similar range of power, however, selecting and qualifying a gas turbine by developers and engineering contractors remain a challenging task. Many contributing factors shall be considered such as track of field experience, environmental conditions, emissions levels, fuel types and ranges that are available, maintenance plan, the actual application, and operator's preferences ... etc. Qualification of an upgraded or new gas turbines could require months/ years of studies by the end user/ engineering consultant before implementation/ commercialization in a project.

In the last 15 years, some new gas turbines have been introduced (or uprated/ upgraded) in the aero-derivative, industrial and heavy-duty segments to meet the evolving requirement of the offshore and LNG market. Some aero-derivative gas turbines could now reach output power of 70 MW (≈ 94000 hp); whereas some heavy-duty gas turbines have been improved in their design to reach an efficiency of 40%. Gas turbines are subject to continuous research and development activities to improve power output/ efficiency and reliability/ availability through the upgrade of internal components and/ or design modification.

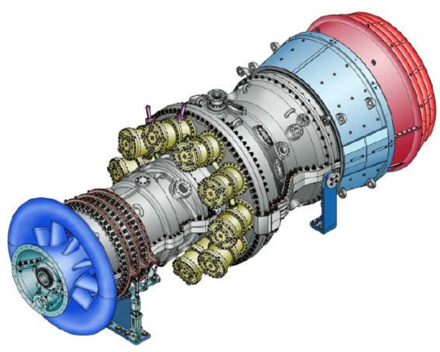

Figure 1: H100 Gas Turbine (Courtesy of MHPS)

More stringent environmental legislations are pressuring gas turbines manufacturers to reduce the Nitrogen Oxide (NOx) and Carbon Monoxide (CO) levels. While 25 ppm of NOx emissions were allowed previously, the new target levels are single digit. If the gas turbine could not satisfy the required emissions levels through its combustion technology, then other external systems could be added to achieve the target emissions such as a SCR (selective catalyst reduction). SCR controls the NOx levels in the flue gas through reaction with Ammonia (NH_3) in presence of oxygen (O_2). It is also possible to add a catalyst in the SCR to reduce the Carbon Monoxide (CO) emissions. Other solutions are applied to reduce CO emissions at partial load; referred as CO turndown. This is achieved by partially diverging the inlet air flow from fully entering the gas turbine combustion chamber.

BASICS OF GAS TURBINES

Thermodynamics

Gas turbines operate according to the principles of Brayton thermodynamic cycle as shown in Figure 2: Ideal Brayton Cycle . This cycle is composed of three stages as follows:

- From 0 to 2: Compression within the axial compressor with an increase of temperature and air density;
- From 2 to 3: Combustion (compressed air + fuel + heat source) within the combustion chamber;
- From 3 to 4: Expansion within the turbine close to the atmospheric pressure;

The actual thermodynamic cycle slightly differs from the ideal Brayton cycle due fuel mass, bleed flows, pressure drops …etc.

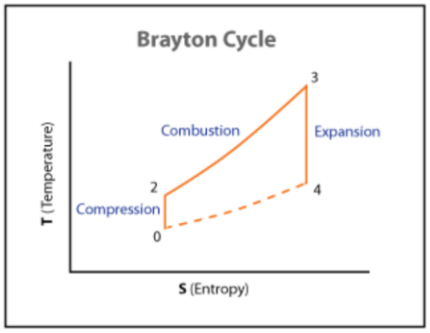

Figure 2: Ideal Brayton Cycle

How Does It Work?

The combustion air is introduced into the gas turbine after being filtered through a static or pulse jet inlet air filter. The combustion air at the inlet of the axial compressor is therefore at a pressure slightly below atmospheric pressure due to the pressure drop in the inlet air filter. Then the combustion air is compressed in the axial compressor to reach between 12 bara (≈ 170 psia) to 55 bara (≈ 800 psia); depending on the gas turbine design. Eventually the combustion air flow is therefore split into two paths:

1) One is mixed with the fuel and burned in the combustion chamber,
2) The second is used for material cooling (mainly combustion chamber) and control of the flame position;

Downstream the combustion chamber, high pressure flue gas at high enthalpy is expanded through the turbine. The high-pressure turbine will drive the axial compressor, and will also drive the driven equipment in case of single shaft application. In two shaft engines, the high-pressure turbine (HPT) drives only the axial compressor (assembly referred to as Gas Generator - GG), while the driven equipment is driven by another free turning low-pressure turbine (LPT). The power that is generated by the gas turbine is used to drive the axial air compressor, the remaining power is used for the driven equipment.

Full flow flue gas at high temperature (> 400ºC (≈ 750 ºF)) downstream the gas turbine flows to the atmosphere through the exhaust stack. However, part of the heat energy could be recovered by using a waste heat recovery unit (WHRU) in which oil or water is circulated and heated or heat recovery steam generator (HRSG) in which water is circulated and steam is generated by the heat energy. The adaptation of those energy recovery systems depends on the application.

Output Power Considerations

Gas turbine power output that is reported in manufacturers catalogues are the so-called ISO Power. ISO power is the gas turbine output power that is guaranteed at ISO conditions as follows:

- Fuel is natural gas (pipeline specification);
- No losses (pressure drops) at inlet air system neither at exhaust system;
- Application at sea level: Atmospheric pressure 1.013 bara (14.5 psi);

- Ambient temperature (at axial compressor inlet) = 15°C (59°F);
- Relative Humidity is 60%;

As soon as the ambient conditions and fuel gas characteristics are different from the ISO conditions, correction shall be applied to the expected gas turbine power output. Rules of thumb:

- Power decrease for each rise of one ºC above 15°C (59°F) by 0.8%;
- Power decrease for each 305m (1000 ft) above sea level by 3% to 4 %;
- Power decrease for each 1 inch water gauge inlet pressure loss by 0.4%;
- Power decrease for each 1 inch water gauge exhaust pressure loss by 0.15%;

For power decrease due to differences in fuel heating value and ambient air relative humidity, the manufacturer shall furnish the power correction curves accordingly.

Types & Arrangements

Gas turbines are classified into three categories: 1) Heavy-duty; 2) Industrial; 3) Aero-derivative.

Heavy-duty

Heavy duty gas turbines were initially developed for power generation applications. Most heavy-duty gas turbines are single shaft; accordingly, they operate at fixed speed. Typical speed for heavy duty industrial type one shaft gas turbines are either 3,000 or 3,600 rpm. Speed variation is only around 97% to 103%. Heavy-duty gas turbines are characterized by lower efficiency compared to aero-derivative gas turbines. Heavy-duty gas turbines are relatively less expensive than aero-derivative gas turbines and they require less maintenance. Heavy- duty gas turbines could generate tremendous amount of power reaching hundreds of megawatts. While previously used for power generation applications, heavy-duty gas turbines are now selected to drive LNG compressors.

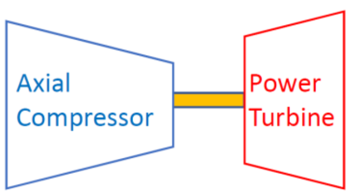

Figure 3: Typical Single-shaft Heavy-duty Gas Turbine Arrangement

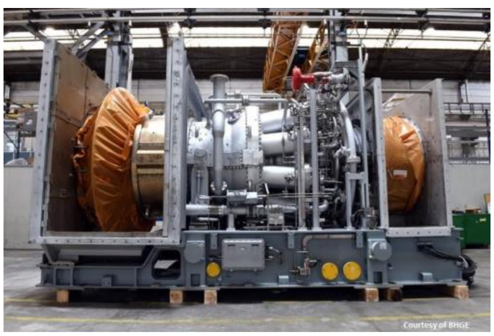

Figure 4: Single Shaft Frame-6 Gas Turbine (Courtesy of BHGE)

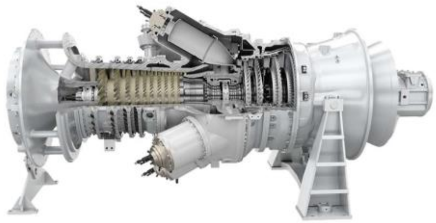

Figure 5: Heavy-duty Gas Turbine Core Components

Aero-derivative

The aero-derivative gas turbines are derived from engines that are used in the aviation industry. Aero-derivative gas turbines are lighter and more compact than heavy-duty gas turbines, with higher firing temperature and higher efficiency (around 40%) compared to heavy-duty gas turbines (around 35%). However maximum commercialized power output (ISO) is around 65 MW (≈ 87000 hp). Most aero-derivative gas turbines are two shaft engines (some are three shaft); accordingly, they can operate at different speeds. Since the power turbine spins freely from the gas generator, the speed can be higher and can more accommodate the required speed of the driven equipment. Gas turbines with a two-shaft or three-shaft design can achieve higher speeds for the shaft connected to the driven equipment. The speed can go up to 6,400 rpm. A speed variation from 70% to 105% can be easily achieved. The speed flexibility of a two-shaft or three-shaft arrangement is not the only advantage, aero-derivative gas turbines have also better re-start capabilities being equipped with free power turbine; which means for compressors, no complete depressurization is required for re-start allowing to avoid loss of inventory. On the other hand, aero-derivative gas turbines require a synthetic oil system to cater for the higher bearing temperatures.

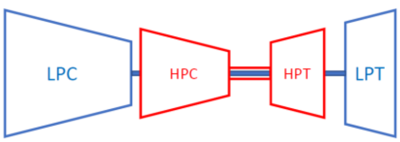

Figure 6: Two-shafts Aero-derivative Gas Turbine Arrangement (without a free Power Turbine)

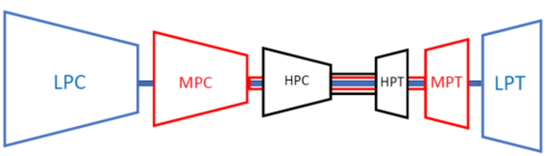

Figure 7: Three-shaft Aero-derivative Gas Turbine Arrangement

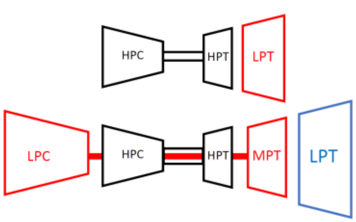

Figure 8: Typical Two-shafts Aero-derivative Gas Turbines with free Power Turbine)

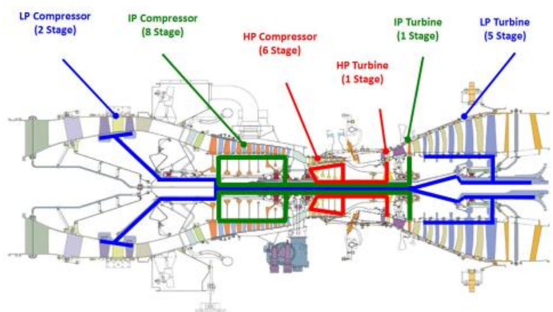

Figure 9: Gas Turbine with three-shafts Arrangement (Courtesy of Siemens)

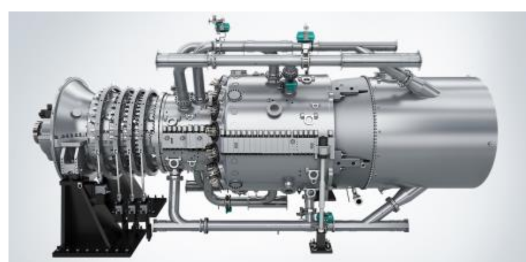

Figure 10: Gas Turbine Core Components

Industrial

Between these two categories, industrial gas turbines are covering a range from few MWs (also known as "light Industrial") to 30 MW (≈ 40000 hp) (ISO). Industrial gas turbines could be implemented in single-shaft (power generation applications) or two-shafts arrangements (core engine and power turbine). Industrial gas turbines utilize hydrodynamic bearings and a common lube oil system; in contrast to rolling element bearings that are used for aero-derivative gas turbines. They are characterized with relatively lower emissions.

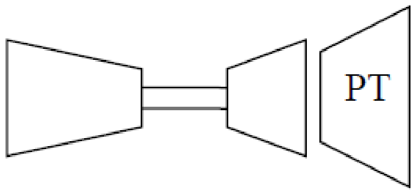

Figure 11: Typical Two-shafts Industrial Gas Turbine Arrangement (with Free Power Turbine)

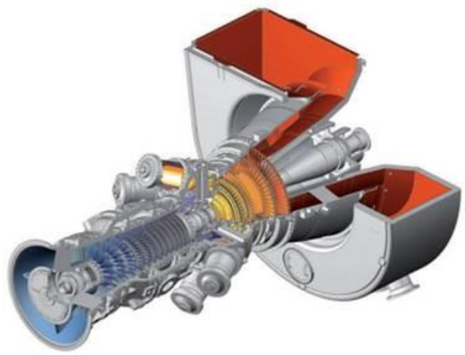

Figure 12: Gas Turbine with Two-shafts Arrangement

In the recent developments, heavy-duty gas turbines are more and more being equipped with a free power turbine to improve the efficiency by increasing the core engine speed. On the other hand, the aero-derivative gas turbines developments are focused on improving the maintenance plan (extending periods between maintenance). However, the weight factor remains a strong differentiator.

Combustion Technologies

The combustion chamber in a gas turbine is normally divided into two zones; the primary zone and the secondary zone. In the primary zone; most of the fuel combustion takes place. In the secondary zone, unburned air is mixed with the combustion products to cool the hot gas before it enters the turbine. Some combustion chamber designs might have an intermediate zone as to optimize and stabilize the combustion. Combustion in the gas turbine combustion chamber shall be able to sustain itself in a continuous manner. In addition, the combustion temperature shall be controlled to be less than the maximum allowable working temperature in the turbine.

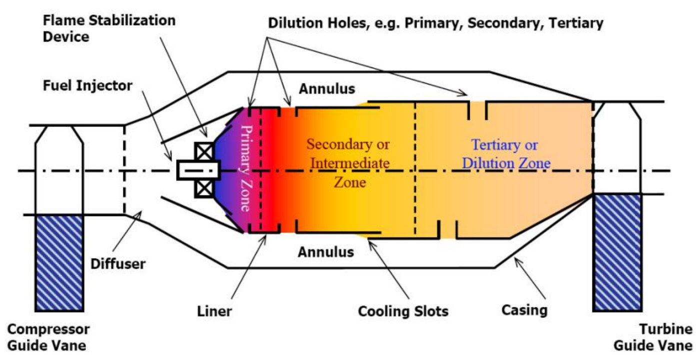

Figure 13: Zones of Combustion Chamber

Combustion systems are usually designed as canned type combustors or as annual combustion chambers. Most combustors are designed to have the main combustion taking place in diffusion burners with diffusion flames that are very stable. Diffusion flames have also the flexibility of using different types of fuels. The main disadvantage of diffusion-type combustors is its contribution to high level of emissions. Gas turbine combustion process emits several pollutants that need to be monitored & controlled. Pollutant emissions are: Nitrogen Oxides, Carbon-monoxide, Sulphur Oxides, soot, particulates and unburned chemicals; NOx being the main pollutant species. High temperature of the primary zone favours the production of large amounts of NOx for fuel gas and even more when burning liquid fuels. Several techniques have been developed to reduce the amount of NOx produced in conventional combustors. In general, it is difficult to reduce NOx emissions while maintaining a high combustion efficiency as there is a trade-off between NOx production and CO and unburned hydrocarbons (UHC) production. Decreasing combustion flame temperature in GT combustors results in reduced and maintained levels of NOx emissions. Normally mechanical drive derived from heavy duty gas turbines achieve lower emissions (NOx <10ppm and CO ≈10ppm), than aero derivative gas turbines (around 25 ppm for NOx and CO emissions).

In general, emission reduction can also be achieved by wet or dry technologies. Water/steam injection into the combustion system is considered as the wet technology. Dry Control technologies for NOx reduction are:

- Lean Head End;
- Dry Low NOx (DLN) for Heavy Duty GTs;
- Dry Low Emission (DLE) for Aero-derivative GTs;

Dry technologies work by creating a premixing zone in the combustion system, in which air to fuel ratio is precisely managed and thus NOx emissions properly controlled. Wet technology works by reducing the combustion zone temperature using the latent heat of water.

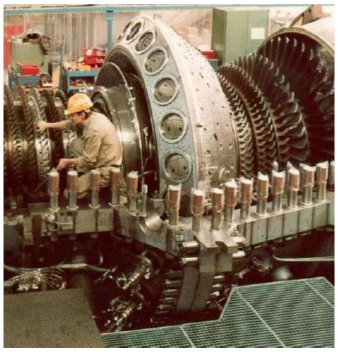

Figure 14: Gas Turbine Annular Combustion Chamber

GAS TURBINE AUXILLIARY SYSTEMS

Air Inlet Systems

Inlet Air Filter Systems

Inlet air filter systems are necessary to ensure good quality of combustion air entering the gas turbine, it is subject to site environmental conditions. Two different types of inlet air filter systems are used: Static and self-cleaning. Static filter consists of several filtering stages (usually three stages) with the high efficiency stage located downstream the first two stages (pre-filters, moisture coalescers and inertial separators). Larger particles are removed by the first filtration stages; while high efficiency filters; usually of three types EPA, HEPA and ULPA, captures finer particles down to 0.12 microns. Static filters require the change of filter cartridges after a pre-defined period (depending of site conditions) to ensure continuity in filtration efficiency. Self-cleaning inlet air system regenerates itself by pulsing compressed air to knock-off filtered impurities (ex: dust, dirt …etc.) fall in adequate areas where they are collected for disposal; eventually cleaning the filter media.

Figure 15: Cylindrical Cartridge Self-cleaning Filter. Source: Donaldson (GTS-102)

Inlet air filter systems play a critical role in both the life and performance of the gas turbine. Millions of cubic meters of air passes through a mid-sized inlet air filter system per day. Inefficient filtration could lead to axial compressor fouling and reduced life of the gas turbine; whereas excessive pressure drop in the inlet air filter system will result in reduced power output from the gas turbine. The selection of inlet air systems shall consider proper understanding of the local air quality and wind direction. The trade-off shall also be considered; pressure loss in inlet air filters increase with the increase in inlet air filters efficiency.

Air inlet filter systems are enclosed within an inlet air filter house; it consumes a considerable space in the plot and its design shall be slightly customized according to the project needs. The face of the inlet air system shall be obstacle-free with a free-cone-space that need to be defined by the supplier. Inlet air filter systems are sometimes associated with anti-icing systems or inlet air cooling systems.

Figure 16: Inlet Air Filter House (Courtesy: CAMFIL)

Inlet Air Chilling System

Gas turbine power output is highly sensitive to ambient air temperature (eventually the combustion air temperature). As described before, the power output of a gas turbine is adversely affected by the increase in ambient air temperature. Inlet Air Chilling systems boosts gas turbine power output during hot ambient conditions and thus assure a constant power output of gas turbines throughout the year. The application of an Inlet Air Chilling system is safe and technically proven. It can achieve an air temperature cooling gradient of 20 °C depending on air flow and ambient conditions. Giving a power boost up to 15 % for Heavy Duty gas turbines and up to 25 % for Aero-derivative gas turbines (at very hot ambient). Inlet air chilling system operates by either circulating chilled water into pipes that are coiled inside the gas turbine inlet air filter house, or by evaporative cooling methods.

Figure 17: Inlet Air Chilling System Header (Courtesy of BHGE)

Anti-icing Systems

Gas turbines that are installed in areas where icing conditions could exist shall be equipped with an anti-icing system. In general, ambient temperature dropping below 4ºC (39 ºF) with high humidity could be subject to icing problems. Icing could induce very significant pressure drop in the inlet air filter house which leads to gas turbine power output deterioration.

Bleed Air

Anti-icing can be achieved by using intra-compressor bleed air, dispersed into the inlet air stream with a bleed rake (specially designed piping to evenly distribute the bleed air over the area of the filter house inlet). Bleed rake design requires finite element analysis (FEA) to ensure uniform flow of warm air into the filter housing. Using bleed air will result in a performance loss to the engine which will have to be determined after analysis of the bleed air requirements and icing conditions. The loss will be a function of the mass flow rate of bleed air and from which bleed system it is taken.

As an example of anti-icing on a gas turbine bleed is taken from a higher-pressure compressor section results in around 2% of total engine air flow loss.

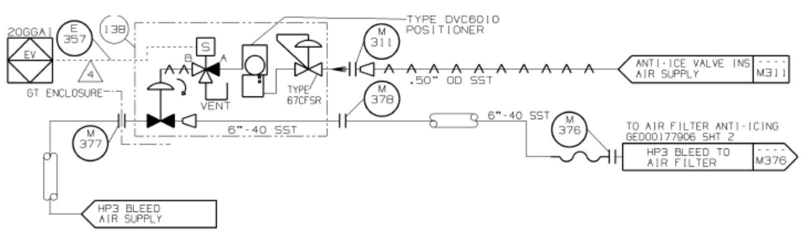

Figure 18: Bleed Air Anti-Icing System (Courtesy Trent 60 – Siemens)

Advantages:
- Simple design;
- Additional pressure drop added by the filter house is small;
- It may be possible to use CO turndown bleed as a source of anti-ice air;
- No additional systems required;

Disadvantages:
- Results in a loss of performance, thereby reducing the maximum possible shaft power;

Exhaust Recirculation System

An exhaust recirculation system mixes portion of hot exhaust gas with cold ambient air. A by-pass line installed from the exhaust system to the air intake inlet system disperses evenly through a distribution skid hot exhaust gas directly into the inlet air stream.

Advantages:

- Heat source is available;
- Additional pressure drop added by the system is small;

Disadvantages:

- Moisture in exhaust gas can create problems;
- Impurities in the exhaust gas can create compressor fouling;
- Exhaust system is a low-pressure system which can create difficulties in directing the exhaust gas flow to the inlet system;
- Exhaust gas is CO_2 rich and will adversely impact combustion and power available;

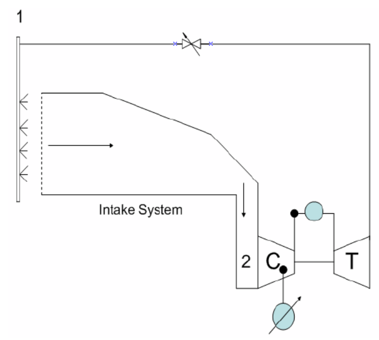

Figure 19: Exhaust Recirculation Anti-Icing System

Slipstream of ventilation exhaust

Depending of heat requirement parts or the entire filtered ventilation air for the gas turbine enclosure can be directed to the inlet of the air filtration housing. The warmed-up air from the enclosure will be mixed with the cold inlet air.

Advantages

- Heat source is available;
- Little effect on performance;
- Easy installation;

Disadvantages

- Content of hydrocarbon in ventilation air possible and possibility of hydrocarbon concentration build up;
- Safety risk;
- Additional gas detection devices might be required;
- Hydrocarbon in ventilation air might result in GT trip or auto ignition in combustor;

Ambient air blown through a coil in the Gas Turbine Exhaust Stack

Exhaust gas from the turbine outlet passes through a heat exchanger which is in the exhaust duct. Ambient air flow extracted from a specific point downstream of the inlet filter system and with the help of a fan the air is blown through the heat exchanger. The ambient air will be heated up by the exhaust gas and directed to the inlet air system and heats up the inlet air.

Advantages

- Little effect on performance;
- Amount of warmed up ambient air can be controlled;
- Dry heating system;

Disadvantages

- More complex system, inlet throttling probably required to control flow;
- Requires extra space in the exhaust system;
- If fan fails anti-icing system does not work;

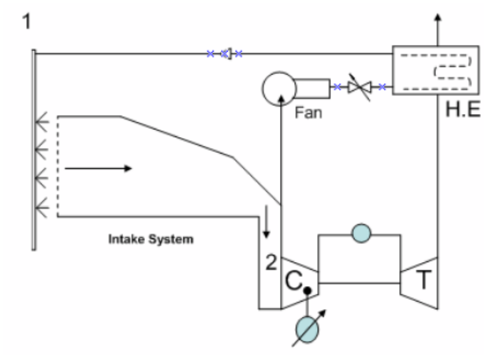

Figure 20: Heat Recovery Anti-Icing System

Hot Water Heating Coils

Anti-icing can be achieved by heating the inlet air as it passes across a hot water heating coil. The heating coils would typically be installed upstream of all filter elements and weather vanes. Gas Turbine manufacturer will provide the coils and interfaces for the customer's water supply near the edge of the filter house. All other components are typically in the customer's scope of supply.

Advantages

- The design is simple;
- Hot water-glycol can be provided from any source or from a standalone system;

Disadvantages

- Heating coils will add a pressure loss to the filter house;
- Heating coils are exposed to dirty air, as they are installed upstream of the filter elements;
- Requires additional ancillary systems (and footprint) to provide the water glycol which is used for a very small portion of total operational time;

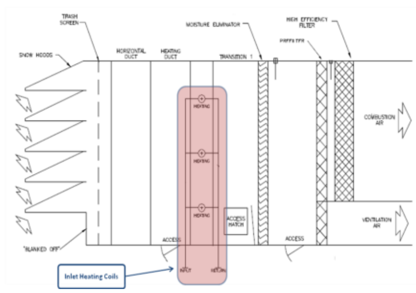

Figure 21: Inlet Air Filter Heating Coil

Electro Thermal System

Electro thermal system consists of resistance wires which are imbedded in rubber pads which are mounted on the icing surface which must be protected.

Advantages

- Heats up only the icing points;

Disadvantages

- Locate the critical points where ice can be found;
- Safe, no hazardous area;
- Hot spot potential, possible non-uniform heat distribution;
- Complexity of wiring runs;

Compressor Bleeds Air (or Gas Film Heating)

Compressor bleed air is like turbine blades gas film cooling technique. Canals will be drilled in the components which have a great hazard for ice build-up such as filter, IGVs and parts of the inlet duct. Hot air, which can be extracted from the compressor or the exhaust gas, passes through these canals and warm up the surface of these components.

Advantages

- Heats up only the components for potential ice build-up and blockage;

Disadvantages

- Very complicated manufacturing process;
- Very expensive;
- Rarely used in stationary gas turbine installations;
- Design change of IGVs possible;
- Complex spare parts replacement;
- Potential to “puff” dirt off filters and quickly clog filters located below;

Pulse filter

A pulse filter system will provide the anti-icing function in standard configuration. As ice forms on the filter elements, the differential pressure across the filters increases and upon reaching the programmed cleaning set point, the control system will initiate pulse cleaning of the filters. Any ice and dirt which have collected on the filter elements is knocked off and extracted from the filter house by the ASC (Augmented Secondary Air Circuit) system. The frequency of pulse operation is dependent upon the severity of the icing conditions.

Advantages

- Standard design for some gas turbine manufacturers;
- Maintains clean pre-filters as well as providing anti-ice function;

Disadvantages

- Uses a large amount of compressed air;
- System is more complex than other types of anti-ice systems;
- Pulse filter system creates a higher-pressure loss in the filter house;
- Generally, not used in offshore applications due to high moisture content;

Infrared heating

Thermal radiation from an infrared source, typically infrared lamps, may be used to heat surfaces to prevent ice from forming on them. There must be enough thermal radiation to sufficiently heat surfaces above the temperature of incoming air. This type of system may not be suitable for equipment operating in or near a hazardous area, due to the high temperatures created by infrared lamps. The system is composed of the infrared bulbs, thermal safety, and an electrical switching circuit operated by the package or engine control system.

Advantages

- The design is simple;

Disadvantages

- Infrared bulbs create high heat, which will not be suitable for areas which may contain gas;
- Areas of the filter house with irregular or no air flow are subject to overheating;

Weather vane trace heating

Special trace heating tape may be applied to the leading edges of the weather vanes to prevent ice formation on them. As air passes over the heat trace, it absorbs energy and its temperature rises. The heat trace will ensure that ice cannot form on the surfaces to which it has been applied.

The system is composed of the heating elements, thermal safety, and an electrical switching circuit operated by the package or engine control system.

Advantages

- The system design is simple;
- Can be procured for hazardous area duty;

Disadvantages

- The trace heating only de-ices the surfaces to which it is applied and would have to be used in conjunction with another type of anti-ice system to protect the entire combustion air inlet;

Air Cooling

The performance of a gas turbine; its efficiency (heat rate) and the generated power output, strongly depends on the inlet air temperature which will decrease the output power with the increase in air temperature. Different inlet air cooling systems are available in the market. Each technology has its advantages and inconveniences according to different factors such as ambient conditions, investment cost and payback time, power output increase and cooling capacity.

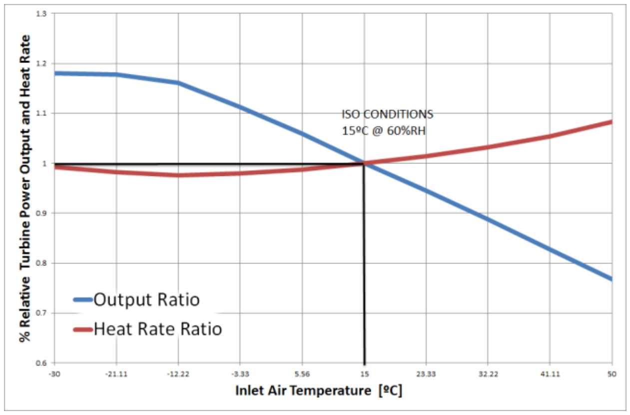

Figure 22: Sensitivity of Inlet Air Temperature on Output Power of Gas Turbine

Fogging

Finely atomized water (fog) is sprayed into the inlet airflow of a gas turbine engine. The water droplets evaporate quickly, which cools the air and increases the power output of the turbine. Demineralized water is typically pressurized to 138 bar (2100psi) then injected into the inlet air duct through an array of stainless steel fog nozzles. Demineralized water is used to prevent fouling of the compressor blades that would occur if water with mineral content were evaporated in the airflow. Inlet fog systems are simple and easy to install and operate. Inlet fogging is the least expensive gas turbine inlet air cooling option and has low operating costs, particularly when one accounts for the fact that fog systems impose only a negligible pressure drop on the inlet airflow when compared to media-type evaporative coolers. However, the cost for producing demineralized water shall be accounted for. It shall be noted that inlet fogging could be less effective in humid environments.

Fog nozzles manifolds are typically located in the inlet air duct just downstream of the final filters. Depending on the design of the inlet duct and the intended use of the fog systems, fog nozzles can be located at different positions in the inlet air system. Availability of water in arid climates and water consumption rates could be an issue, although performance enhancement would be significant.

On the other hand, inlet fogging reduces emissions of nitrogen oxide (NOx) because the additional water vapor quenches hot spots in the combustors of the gas turbine.

Wet Compression

Wet compression uses the same layout as fogging but with this system more power can be produced than being obtained by evaporative cooling alone. More fog will be sprayed as required to fully saturate the inlet air. The excess fog droplets are carried into the gas turbine compressor where they evaporate and produce an intercooling effect, which results in a further power boost.

Evaporative cooling

The evaporative cooler is a wetted rigid media where water is distributed throughout the header and where air passes through the wet porous surface. Part of the water is evaporated, absorbing the sensible heat from the air and increasing its relative humidity. The air dry-bulb temperature is decreased but the wet-bulb temperature is not affected. Like the fogging system, the theoretical limit is the wet bulb temperature, but performance of the evaporative cooler is usually around 80%. Water consumption is less than half of fogging cooling.

Vapour compression chiller

Chilling coil heat exchanger is installed in the filter house downstream the filtering stage. Downstream from the coil, a droplet catcher is installed to collect moisture and water drops. The mechanical chiller method can increase the turbine output and performance better than wetted technologies since inlet air can be chilled below the wet bulb temperature, indifferent to the weather conditions. Compression chiller equipment has higher electricity consumption than evaporative systems, accordingly the net efficiency in power generation applications shall consider consumed power by the mechanical chiller versus the enhanced power output from the gas turbine. Initial cost is also higher; however, turbine power augmentation and efficiency is maximized, and the extra-cost is amortized due to increased output power.

Vapour-absorption chiller

In this type of technology thermal energy is being used to produce cooling instead of mechanical energy. The heat source is usually leftover steam coming from combined cycle, and it is bypassed to drive the cooling system. Compared to mechanical chillers, absorption chillers have a low coefficient or performance, however, it should be taken into consideration that this chiller usually uses waste heat, which decreases the operational cost.

Gas Turbine Enclosure

Gas turbines are normally installed inside noise enclosures to minimize noise emissions levels to the plant. Enclosures can be negative or positive pressurized. The criteria to choose between an negative versus positive pressure enclosures are done according to area classification criterion where the gas turbine is located (although sometimes only one of options could be available for a certain gas turbine model) . If the gas turbine is located in safe area then usually the enclosure is under negative pressure so that direction of air leakage could be from outside to inside. Gas turbine enclosures are considered as an unmanned area; nevertheless, ventilation system shall be provided and properly sized to eliminate the risk of gas accumulation (number of air changes/hours) and maintain the temperature inside the enclosure within the limits of instrumentation and electronic components design temperature. Typical arrangement of enclosure ventilation systems is with two redundant fans.

Adequate fire & gas detection system shall be provided inside gas turbine enclosures. Either CO_2 or water mist systems are commonly used for fire suppression, but INERGEN could also be selected. Sparing philosophy of bottle racks (CO2 or water/ N2 bottles) and release time are covered by the applicable code. NFPA 750 for water mist (with 30 minutes' release time) and NFPA 12 for CO2 fire extinguishing system are two examples of international standards code for design of fire extinguishing system. Manufacturer usually perform computational fluid dynamics analysis to evaluate and validate the temperature distribution in the enclosure as well as air speed contours.

Figure 23: SGT 700 (Courtesy of Siemens)

Starting System

Ignition in gas turbines require a certain amount of air mass flow rate which is ensured by initial rotation of the axial compressor. This initial rotation is actuated by the starting system. The starting system driver design is customized according to project context; although the core part that is connected to the gas turbine remains standard. For heavy-duty gas turbines; which are mostly single-shaft machines, the starting systems could be electrical motor, diesel engine, steam turbine or hydraulic motor. For aero-derivative gas turbines the starting system is much smaller (less inertia) and integrated within the main skid. It rotates the Gas Generator (GG) and it is usually of hydraulic type. Aero-derivative gas turbines require about 200-300 kW (268 – 402 hp) as starting power; while for single-shaft gas turbine > 20 MW (26820 hp) of starting power could be required taking into consideration the size and characteristics of the associated driven equipment (ex: when a compressor is starting from settle-out pressure (SOP).

Exhaust System

Gas turbine exhaust system is required to disperse flue gases; which are at very high temperature > 400ºC (752 ºF), from the exhaust of the gas turbine to safe area. Those gases shall not be released at gas turbine exhaust without dedicated ducting allowing a proper dispersion at an elevation that is determined by the environmental dispersion studies. Exhaust stacks could reach 50 meters of height. Gas Turbine exhaust plenum is connected with the exhaust stack through a transition piece. In addition to ducting, exhaust stacks are composed of several other components such as expansion joints to cater for thermal expansion (and axial displacements in offshore floating applications) and silencers to mitigate the noise levels (normally > 90 dBA sound pressure level). Exhaust stacks are usually equipped with sampling points for Continuous Emissions Monitoring System (CEMS). In many cases; depending on the application, gas turbine exhaust stacks could be equipped with WHRU or HRSG to recover heat energy and improve the overall efficiency of the plant.

Figure 24: Exhaust Stacks (Courtesy of Braden Manufacturing LLC)

Washing System

Water washing systems are used to recover performance degradation in gas turbines and thus enhance the time-bound overall plant productivity. Performance degradation is usually a result of fouling in gas turbines due to deposit of particles on axial compressor blades of the gas turbine & guide vanes profiles. Gas turbine washing is achieved by periodically injecting a mixture of water and a detergent in an atomized condition either offline while the gas turbine is not in operation but in cranking mode or online at close to operating speed of the axial compressor. Some gas turbines are not suitable for online washing. In all cases, the best way to avoid regular washing is to properly select the air combustion filtration system.

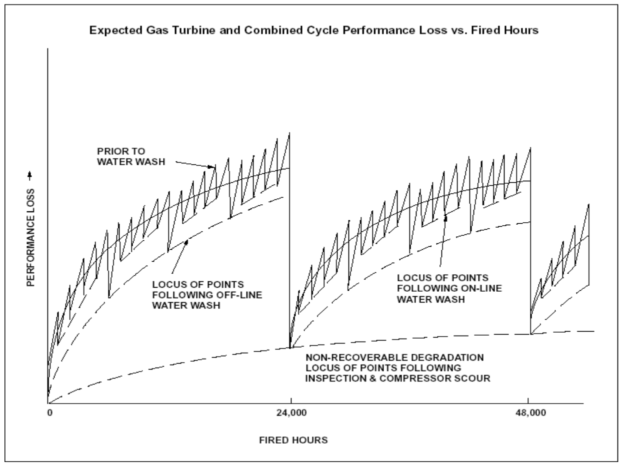

Figure 25: Typical Effect of Gas Turbine Washing Online/ Offline

Lubrication and Control Oil System

Lubrication oil for gas turbines could be either mineral or synthetic. Mineral oil is normally used with hydrodynamic bearings, while synthetic oil is required for rolling element bearings. Synthetic oil can withstand higher temperatures and shearing forces. Whether it is mineral oil or synthetic oil, both systems shall follow a lube oil system design that is almost standardized with minimal differences from project to project. The lubrication and cooling oil system shall be equipped with oil circulating pumps, coolers, filters, pressure regulators, accumulators …etc., in addition to oil vapor separator. Lubrication oil system for gas turbines may comply with the API 614 standard. However, for synthetic oil console, manufacturers' standard design is acceptable.

PRACTICAL ISSUES IN GAS TURBINE SYSTEMS

Gas Turbine Fuel

Gas turbines are mainly intended to use fuel gas for combustion, however dual fuel gas turbine allowing operation with both gas and liquid fuels are developed. Dual fuel gas turbines might be required for the following cases:

- Plant where a black start of plant shall be done by gas turbine (so no fuel gas available at start-up);
- Gas turbine to be commissioned at yard where no gas operation is available or envisaged;

Fuel conditioning skids are required to ensure the right conditions of fuel (gas and/ or liquid) at the gas turbine battery limit.

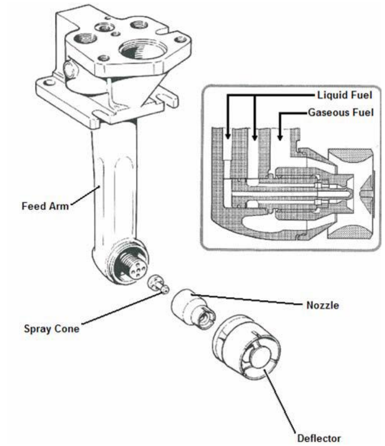

Figure 26: Duel Fuel Burner (Courtesy of Butterworth Heinemann)

Fuel gas

Fuel gas system plays an important role on gas turbine performance in terms of delivered power, emissions levels and on planned maintenance interval. For each gas turbine, several parameters shall be considered:

- Composition & Heating Value;
- Dew Point;
- Pressure;
- Filtration;

Composition & Heating Value

Gas turbines are designed to deliver the best performance with 100% natural gas. Practically gas turbines will operate with different fuel gas compositions, depending on the fuel gas available at site. Fuel gas composition variety shall be reviewed and agreed with the gas turbine manufacturer at an early stage of the project. The presence of one of the undesirable substances (sulphur, sodium and potassium, vanadium) will affect the turbine components' life; in addition to gas turbine performance. Gas Turbine emission could be equally affected. Heavy-duty gas turbines are flexible in burning wide range of fuel gas composition. Flexibility of gas turbine in terms of range of fuel gas is expressed through Wobbe index (WI) which corresponds to fuel gas high heating value divided by the square root of the fuel gas specific gravity. Gas Chromatograph (GC) is used for determining the exact gas composition. Heating value could also be determined from GC, but much faster using a Wobbe Index meter.

Dew Point

Fuel Gas temperature is a critical parameter. In some cases, it might be required to heat-up the fuel gas up to the required superheat temperature. This value is generally not less than 25-30 °C delta temperature above the fuel gas dew point.

Pressure

Fuel gas (and liquid fuel) pressure are required to be above some lower limits; as specified by the gas turbine supplier. If the pressure drops lower than required, then the gas turbine may not be able to sustain the base load. Gas turbines fuel gas systems are usually protected by pressure safety valves (PSVs) against high pressure which would exceed the fuel gas system design pressure in case of dynamic upset in the plant fuel gas network.

Filtration

Fuel gas filtration shall be achieved upstream the gas turbine battery limit to prevent particles from entering the combustion chamber and damaging the gas turbine components in the long term. The maximum allowable particle size depends on the materials and design of components inside the gas turbine and shall be indicated by the gas turbine manufacturer. It is also recommended that fuel gas piping downstream the gas filter be made of stainless steel to avoid particles resulting from erosion.

Liquid Fuel

Sodium and vanadium in liquid fuels shall be eliminated or brought below the acceptable limits. Liquid fuel storage tanks are typically located close to liquid fuel conditioning skids. Its size depends on the project specificity and expected duration of operation.

Plot Requirements for Gas Turbine Auxiliaries.

Gas turbines auxiliary systems need to be well positioned (relative locations) in the plot in line with the technical constraints to ensure proper functioning of those systems altogether. Not considering those constraints might result in abnormal operating parameters leading to trips.

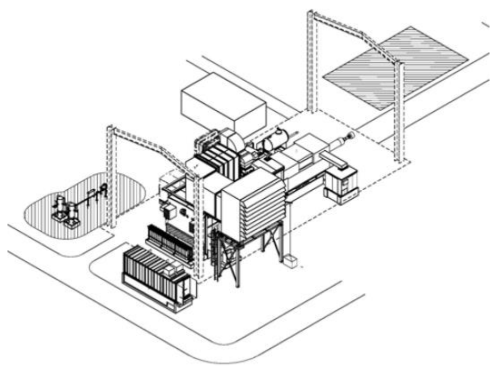

Figure 27: Typical Gas Turbine Generator Arrangement

Inlet Air Filter House

The face of the inlet air house shall be obstacle-free within a space-cone that is defined by the supplier of the equipment. The air flow to the inlet air filter house shall be clean air to extend the life of the filter elements. Cleanliness of inlet air needs to be verified by dispersion studies of flue emitters in the plant (ex: exhaust of diesel generators) or outside the plant (ex: trucks, offloading ships …etc.)

Enclosure Outlet Ventilation Duct

Enclosure Ventilation outlet air is normally at high temperature (could reach 90ºC (194 ºF) in some cases). In addition, that ventilation outlet air could be ionized and/or contaminated with other impurities. Accordingly, the outlet ventilation duct routing shall be extended to ensure no discharge air is crossing pathways or maintenance areas. In modular design, vertical dispersion to upper decks need to be also checked, especially in the case where deck plates do not exist.

Oil Vapor Separator

Due to high speed and temperature in the bearings of gas turbine, fine droplets of lubrication/ cooling oil might be entrained by air when the air console is breathing, creating oil vapor. Oil shall be separated and recovered, and the cleared air shall be vented. This is done in the oil vapor separator. The oil vapor separator shall be positioned above the gas turbine centerline; however, it shall not be located so high above the gas turbine centreline to respect the maximum allowable back pressure value.

Fuel Gas System

The fuel gas system maximum pressure drop requirements mandate an optimum routing of the fuel gas piping. In addition, fuel gas piping downstream the fuel gas filters shall be made of stainless steel to avoid particles in the pipes that are generated by erosion such as in carbon steel piping. Accordingly, it is recommended to position the fuel gas filters as close as possible to the gas turbine battery limits to minimize the amount of stainless piping.

Gas Chromatograph & Wobbe Index Meter

The relative location (& piping routing) from the sampling points (tapping on the fuel gas header) from which gas samples are sent to the GC and WI with respect to the gas turbine location shall be considered as to estimate the travel time of gas. This will ensure that the analysed gas sample represents exactly the actual gas that is arriving at the combustion chamber of the gas turbine. In case of multiple gas turbines are served by the same GC and WI, differences in travel time will have to be individually considered and programmed for each gas turbine control system.

Fuel Gas Flow Meters

Fuel Gas Flow meters shall be positioned relatively close to the gas turbine battery limits, so that the minimum interconnecting piping volume downstream the value up to the fuel gas shut-off valves is minimized. This is to ensure representability of fuel gas flow measurements.

Run Down Tank

Rundown tanks may be required if an emergency pump powered by a separate electric source such as DC batteries or compressed gas (air of fuel gas) is not available. Rundown tanks provide a natural flow (by gravity force) of lubricating oil to the hydrodynamic bearings of rotating equipment in case of loss of lube oil pressure and trip. This is to avoid damaging the hydrodynamic bearings and shafts during coast down from operating speed to zero speed. Run down tanks may be applicable to two-shafts gas turbines that are equipped with a free power turbine which are supplied with hydrodynamic bearings and to some industrial gas turbines.

The elevation of the run-down tank shall be maintained at an elevation range of minimum and maximum values from the centerline of the gas turbine. This is to ensure the proper oil pressure supply and duration (which is also determined by the volume of oil in the tank) of oil flow for the full duration of coast down from full speed to zero speed. The minimum and maximum elevation values are confirmed by performing dynamic simulation of the lube oil system.

Water Mist Fire Fighting Systems

The equivalent length of the interconnecting tubing/ piping between the water mist firefighting system and gas turbine enclosure need to be considered not to exceed the allowable pressure drop in the line which is also part of the system certification. Interconnecting piping between the bottle rack cabinet and gas turbine enclosure shall be properly routed (no pocket, slope could be specified by gas turbine manufacturer) to ensure proper alimentation of firefighting distributing pipe. When water mist is used, according to site minimum ambient temperature heat tracing or heat insulation could be needed to avoid icing inside pipe.

Gas Detection System

For safe operation of gas turbines, gas detectors shall be installed to trip the machine in case of confirmed gas detection. Gas detection is normally provided around the gas turbine package in the plant by the Contractor. However, the gas turbine shall also have its own gas detection system. Gas detectors shall be positioned at the air combustion inlet, the enclosure ventilation air inlet and inside the enclosure or at the ventilation air outlet. Gas detected at the inlet ventilation corresponds to a gas source from outside the enclosure, while gas detected only inside enclosure or at the ventilation outlet corresponds to gas source from inside the gas turbine enclosure. The equivalent tubing length from the gas detector to the gas detection rack shall respect a minimum value; accordingly, if the gas detector rack is very close the tubing could be routed in a spiral way to achieve the minimum required length.

Continuous Emissions Monitoring System (CEMS)

The permanent sampling points for the CEMS shall be positioned in the exhaust stack within a minimum upstream and downstream equivalent diameter to ensure laminarity and smooth readings by the relevant instruments. Access platforms shall be provided to access the permanent sampling points and to access the adjacent temporary sampling points that are used by regulators to ensure (with a portable analysing device) compliance with local rules and regulations and validate the data provided by the CEMS.

Specificities for Offshore

Offshore projects are characterized by requirements that are not encountered in onshore projects. Such issues shall be well considered in the design of gas turbines and their auxiliary systems. Described below are some of those conditions.

Motions and Accelerations

Floating offshore projects such as FPSOs, FLNGs and tension-leg platforms (TLP) …etc. are subject to sea motions and accelerations for which vary in level of severity. Gas turbines shall be able to safely operate at 1-year severity sea condition (a storm condition with a probability of occurrence once per year). However, gas turbines shall withstand 100-Year sea condition shut-down and be ready to restart without the necessity of major checks and inspections. For the 10,000-Year condition, gas turbines shall withstand the sea conditions in shut-down state without being damaged, although inspections shall be undertaken before restart. Those various sea conditions shall be applicable of the gas turbine, on-skid auxiliaries and off-skid auxiliaries. Other considerations shall be considered due to normal sea motions and accelerations such as:

Fatigue

Oil and gas projects are usually designed for 25 years of plant life. The repetitive sea motion with wave periods of 12 seconds (or less), the total number of cycles could exceed 100 million. Accordingly, careful attention shall be made to ensure that the items that are subject to those cyclic movements and loads have the endurance to withstand the induced fatigue. For example, expansion joints that are subject to horizontal and transversal movements (due to decks relative movements) and are made of metallic material will have to be verified for the induced fatigue; however, fabric-made expansion joints are less vulnerable to fatigue.

Shaftline Orientation

The orientation of the gas turbine shaftline; longitudinal vs transversal with respect to the major axis of the vessel, is also an important issue that is specific to offshore floating projects. If the shaftline is perpendicular to the axis of the vessel then the vessel movements shall be mapped such that the roll of the vessel is considered as pitch for the gas turbine shaftline. From a dynamics perspective, it is more favourable to have the shaftline parallel to the vessel axis than to have it perpendicular to it.

Alignment

Due to weight distribution on decks and acceleration forces, the deck on which the gas turbine main skid is installed will be subject to continuous deflections. Such deflections will be transmitted to the gas turbine skid to some extent (partially absorbed by the 3-point mount design) and would induce misalignment. This condition need to be checked. FEA study is usually performed to gas turbine skids to ensure the skid integrity as well as the effects on shaftline misalignment.

Slope for Oil Return Line & Oil Slushing

Lubrication and control oil systems for gas turbines are usually designed to have the oil return from bearings to oil tank by gravity. In case the oil tank is installed on the main skid and below the gas turbine, then oil will flow freely back to the tank regardless of the sea motion (pitch and roll). This might not be the case with driven equipment supplied with oil from the gas turbine lube oil equipment.

However, for separate oil console (especially if located on the same deck level with the gas turbine main skid) the oil return line shall be slopped to ensure the flow of oil in the return line even in the worst pitch and/or roll conditions. If this slopping requirement is not satisfied then scavange pumps shall be used. Another issue is the oil slushing inside the oil tank due to sea motions and accelerations. Oil slushing will create false readings of oil level in the tank and could cause unnecessary trips. Accordingly, the oil tanks shall be designed to prevent oil slushing for the worst scenario of operating sea conditions.

Modular Design

Offshore projects are characterized by modular design where several decks are built at yard, then the equipment are installed before having the full module lifted and/ or transported to the vessel or platform. Some of the modular design characteristics and constraints are listed below:

Deck Deflections

Modules for offshore applications are made of steel which is flexible and subject to deflections due to weight loads. Different deck deflections are anticipated at the installation phase due to erection activities and final removal of temporary supports. Deck deflections are also envisaged during normal operation at site due to sea motions and accelerations. The common practice is to de-couple (or at least minimize) the gas turbine main skid (relatively long skid) from the effects of deck deflections by having a 3-points mount. For the 3-points mount two options are available; either Anti-Vibration mounts (AVMs) or gimbals. The choice between AVMs or gimbals depends on several factors. For instance, in case the gas turbine is required to be isolated from the deck vibrations or the gas turbine main skid is located close to manned areas then AVMs would be a suitable solution. Whereas gimbals are better than AVMs in absorbing higher angular misalignments and thus are recommended for larger skids and higher levels of sea motions and accelerations.

Mechanical Handling

Designing mechanical handling remains a true challenge in modular design. Where the mechanical handling routes and the hatches need to be sized as required by the maintenance volumes of the gas turbine. Accessibility of mobile cranes could not be straight forward and in many cases monorails become the adopted solution. However, limitation on monorails may be induced by the steel structure beams in the module.

Figure 28: Gas Turbine Offshore Modular Arrangement

Compactness and Weight

Aero-derivative and light industrial gas turbines are lighter and more compact than their heavy-duty gas turbine counterpart. This is a highly critical aspect that is very well considered in offshore projects which favours the selection of the aero-derivative and light industrial gas turbines. Efforts are made by equipment suppliers to have also the auxiliary items smaller in volume and lighter in weight, such as for the inlet air filter system. Integration is one of the solutions that is implemented for gas turbine oil system where the oil console is integrated within the main gas turbine skid beneath the gas turbine.

Mirror Arrangement

In applications where parallel trains are included, the two gas turbine shaft lines that are operating in parallel shall have the face of the inlet air system facing the exterior of the vessel. In addition, maintenance corridor is usually designed in the middle of the vessel, so mirrored configuration would be indeed necessary for heavy mechanical handing of gas turbines. Mirror arrangements also facilitates the symmetry of the plant fuel gas piping and line items.

Saline & Humid Environment

Saline and humid environment is applicable to floating, and non-floating offshore applications such as for fixed-leg platforms (FLP) and gravity-based structures (GBS). The painting and coating systems shall be suitable for such condition.

Painting, Coating & Material Selection

Painting and coating are critical to prevent corrosion of equipment and piping in offshore applications. It is recommended to paint stainless steel and to have bolting galvanized (or coated with corrosion resistant material) for saline environment. Tubing material shall also be selected carefully to avoid failures due to corrosion problems.

De-humidifiers

During shut-down periods, gas turbine enclosure will be subject to stagnant and humid air that would induce corrosion problems for the gas turbine components. It is recommended to have space heaters inside the gas turbine enclosure for towing phase and for extended shut down periods at site.

Commissioning

Gas turbines are usually commissioned offshore at site due to non-availability of fuel gas at the installation yard. Offshore commissioning is very expensive and could cost multiples compared to being done onshore at the installation yard. It might be recommended for some projects to consider having the gas turbines of dual fuel capacity (fuel gas and liquid fuel) for commissioning at yard (among other reasons such as capability of black start for gas turbine generators). It shall be noted that running with liquid fuel could accelerate the wear on some gas turbine parts, accordingly eventual impact and/or limitation from its use should be checked with gas turbine manufacturer.

Cooling Water Return Temperature

Due to limitations on the maximum allowable return water temperature that will be rejected back to the sea that are regulated to minimize the effects on the marine eco-system, and also due to limited space for air cooling in offshore applications, either coolers will have to be increased in size or water circulation pumps need to circulate higher flow rate of cooling water.

Classification and Certification

Gas turbines in floating offshore applications are subject to either classification or certification requirements by a classification society. For certified equipment, the classification society reviews and validates the compliance of the equipment to the applicable international codes and standards. While for classified equipment additional rules and requirements that are mandated by the classification society are checked and verified. The objectives of certification and classification is to ensure the safety and operability of the floating unit, which are necessary requirements for insurers.

Gas turbines; for both onshore and offshore projects, shall also be anticipated to withstand the sea transport motions and accelerations. In aero-derivative gas turbines, GG(s) are shipped loose in special containers with special shock absorbers (not installed within the gas turbine enclosure) to withstand the G-forces during sea transport. Sea fastening; including rotor locking, is also required for gas turbine systems to minimize the risk of damage during transportation by sea.

TESTING & INSPECTION

Gas turbines and their auxiliary systems are subject to individual shop inspection and testing; eventually and before final delivery the full package should preferably be subject to a complete unit test where all job auxiliaries could be tested together for integrated functionality with the gas turbine shaftline running at either full load, partial load or no load. For practicality reasons, some shop auxiliaries might be allowed to be used during the complete unit test; such as fuel gas filters. Gas turbines which are new introduced to the market shall be subject to a qualification process that includes testing which is more extensive and different than the usual shop tests.

During the individual testing campaign, some major components of the gas turbine could be verified for mechanical integrity and/ or performance. For instance, the power turbine of an aero-derivative gas turbine will be subject to mechanical run test (MRT) to verify the vibrations levels. While the gas generator would undergo performance test to verify the operating parameters are within the acceptable ranges/ limits. The performance of the whole gas turbine assembly is performed according to the procedure of the ASME PTC22. On the other hand, all auxiliary systems would be tested at the sub-suppliers' shops for full functionality.

For the complete unit test, the supplier and the contractor/ end-user shall mutually agree on the steps that need to be performed during this integrated test. Depending on the project context and test bed limitations a choice between full load full speed, partial load or no load complete unit test could be made, however it is recommended to always have the shaftline running at full speed.

During the complete unit test (or string test – if not involving off-skid auxiliaries), vibration levels should be measured and verified according to the applicable international codes and standards. The torsional behaviour of the coupled shaftline may be verified during the complete unit test, and the overall noise level of the package should be measured during the complete unit test.

In addition, the integrated functionalities and sequences of all the auxiliary systems together is validated. Guarantees on utility consumptions are checked. Pressure drop in the inlet air system is also checked; similarly, in the exhaust system, both having effects on the gas turbine output power. The ventilation system of the gas turbine is also verified and the pressure inside the enclosure is measured. Finally, the fire and gas system is tested by activating it inside the gas turbine enclosure. The complete unit test could be also an occasion to demonstrate some major mechanical procedures such as the replacement of a gas generator.

Although full load complete unit tests are expensive, could cost several millions of euros, and would require few months of preparations; however, complete unit test reduces the execution risks in projects, especially for sites which are offshore and/or at remote location.

INSTALLATION PRECOMMISSIONING & COMMISSIONING

Installation

In offshore applications, gas turbine drivers may be mounted on a common 3-point mount skid with the driven equipment. In some cases, the 3-points mounting might create a heavy point load on the structure, mandating a strong structural beam to accommodate the load and precise shimming preparations then need to be done accordingly. For the 3-points mount installations, shimming under each point should be done based on the reference level of the complete skid. For floating applications, this can only be performed onshore to ensure that the levelling is not impacted by the sea movement. It is important that the skid remains stress-free during the installation sequence. A full welding on each mounting point can be performed (after the skid has been positioned and levelled within minimal tolerances) according to supplier's requirements. Flatness & levelness requirements on the interface between the gimbals and structure shall also be respected. Full Non-destructive examination (NDE) will then be applied to control the quality of the weld. For offshore projects where modular design is implemented, gas turbines main skids shall be provided with jacking pads to lift the skid if necessary during the installation adjustments when the use of the crane with slings crossing the decks above is impossible.
Auxiliaries such as ventilation ducts, inlet air filter house inlet air duct and exhaust stack will then have to be erected in a predefined sequence; starting from bottom to top. The expansion joints on all the ducting will allow to have some installation tolerances. Silencers will have to be installed (for example in the exhaust stack) as defined by the supplier (sometimes using special guiding tools). To facilitate the build-up/ erection of the ducting, some parts of the ducts will have to be assembled/ connected horizontally at ground and then tilted and lifted for final installation.

Pre-commissioning & Commissioning

Pre-commissioning

In the pre-commissioning phase, all instruments and electrical auxiliaries shall be verified for proper operability. A complete loop check on all instruments mounted in the gas turbine package (including auxiliaries) must be performed. Additional calibration may be needed to confirm the reliability of the instrument. All motors solo runs should be performed (with pump/fan uncoupled) to verify the cable connection and motor rotation. As much as possible, all piping networks around the gas turbine and its auxiliaries should be cleaned. For the oil line, a full oil flushing process must be performed. Lube oil pump of the oil console could be used to perform such flushing. Filters with fine mesh according to gas turbine manufacturer requirements should be installed on the return lines to capture solid particles and other oil contaminants. To perform such oil flushing, gas turbine oil lines are disconnected and bearings are by-passed. Boroscopic inspections for the gas turbine shall also be done at the pre-commissioning phases. A final check shall be done to ensure that the physical equipment is in full compatibility with the engineering documents, such as Piping & Instrumentation Diagram (PID) and hook-up drawings …etc.

Commissioning

Gas turbines are normally commissioned using site fuel gas; unless the gas turbine is dual fuel then commissioning could be done using liquid fuel (ex: diesel). Before starting any test runs of the gas turbine, all the auxiliary systems (including control and power panels) shall be commissioned and proved to be fully functional. Commissioning instructions are always provided by the gas turbine supplier in the commissioning manual, and shall be followed precisely by the commissioning team. Each auxiliary system shall be commissioned by itself. The fire and gas system (F&G) shall be the first system to be commissioned; including the enclosure systems such as fire dampers …etc., to ensure safety throughout the commissioning process. The commissioning of all permissive-to-start shall be then performed.

The sequence of systems that should be commissioned could be:

1. Unit Control and Power Panels;
2. F&G System;
3. Lube Oil Systems (Mineral & Synthetic);
4. Starting System;
5. Enclosure Ventilation System;
6. Fuel Gas System;
7. Inlet Air Filter System;
8. Gas turbine cracking/ motoring system;

then;

9. Systems relevant to the driven equipment.

Once the gas turbine is in running mode, the first step is to test the emergency trip system:

- Test of the emergency push button installed outside the gas turbine enclosure;
- Test of the remote trip signal;

Vibration control shall be performed to ensure a well stabilization after some running time. When vibration is stabilized within an acceptable range, then the gas turbine is considered ready for start-up.

CONCLUSIONS

This tutorial provided an overview from a contractor's perspective about gas turbines and their associated auxiliaries. The tutorial is intended to be an introductory presentation of knowledge on the subject. It is thought that this tutorial would help junior engineers understand various gas turbine auxiliary systems, their options, constraints, and why are they needed. This tutorial also supports experienced engineers to refresh on the topic. The tutorial presented useful insights which are important to tackle while preparing specifications for gas turbine drivers; according to the project context and in line with the project specific requirements, and during the detailed engineering phase of EPC projects where compliance need to be assured, and interfaces with the plant need to be well managed.

NOMENCLATURE

API	= American Petroleum Institute
AVM	= Anti-Vibration Mounts
CEMS	= Continuous Emissions Monitoring System
CFD	= Computational Fluid Dynamics
CGC	= Cracked Gas Compressor
CO	= Carbon Monoxide
DLE	= Dry Low Emission
DLN	= Dry Low NOx
EPA	= Efficiency Particle Air
EPC	= Engineering, Procurement and Construction
F&G	= Fire & Gas
FEA	= Finite Element Analysis
FEED	= Front-end Engineering Design
FLNG	= Floating Liquefied Natural Gas
FLP	= Fixed-leg Platform
FPSO	= Floating, Production, Storage & Offloading
GBS	= Gravity Based Structure
GC	= Gas Chromatograph
GG	= Gas Generator
GT	= Gas Turbine
HEI	= Heat Exchange Institute
HEPA	= High-efficiency Particle Air
HP	= High Pressure
HPT	= High Pressure Turbine
HRSG	= Heat Recovery Steam Generator
HSE	= Health, Safety & Environment
IMECHE	= Institution of Mechanical Engineers
ISO	= The International Organization for Standardization
LHV	= Lower Heating Value
LNG	= Liquefied Natural Gas
LNG	= Liquefied Natural Gas
LP	= Low Pressure
LPT	= Low Pressure Turbine
MCS	= Maximum Operating Speed
MOS	= Minimum Operating Speed
MRT	= Mechanical Run Test
MW	= Megawatts
NDE	= Non-destructive Examination
NFPA	= National Fire Protection Agency
NH_3	= Ammonia
NO_x	= Nitrogen Oxide
O_2	= Oxygen
PID	= Piping & Instrumentation Diagram
ppm	= Parts per Million
PSV	= Pressure Safety Valve
PSV	= Pressure Safety Valve
PT	= Power Turbine
PTC	= Performance Test Code
SCR	= Selective Catalyst Reduction
SOP	= Settle-out Pressure
TCV	= Thermal Control Valve
TLP	= Tension-leg Platform
UHC	= Un-burned Hydrocarbons
ULPA	= Ultra-low Particle Air

WHRU = Waste Heat Recovery Unit
WI = Wobbe Index

FIGURES

REFERENCES

API 671; 4th Edithion (2010). *Special Purpose Couplings for Petroleum, Chemical and Gas Industry Services*.
API 686, 2nd Edition. (2009). *Recommended Practice for Machinery Installation and Installation Design*. American Petroleum Institute.
API Standard 616; 5th Edition (2010). *Gas Turbines for Petroleum, Chemcial and Gas Industry Services.*
ASME - PTC 22: 2014. Performance Test Code- Gas Turbines.
Boyce, M. P. (2012). Gas Turbine Engineering Handbook, 4th Edition. Elesevier Inc., USA.
Brun, K., & Moore, J. (2006). API Specification Review for Gas Turbine Driven Compressors. *35th Turbomachinery Symposium,* (pp. 145-154). Houston.
Brun, K., Foiles, W. C., Grimley, T., & Kurz, R. (2013). Experimental Evaluation of the Effectiveness of Online Water-Washing in Gas Turbine Compressors. *42nd Turbomachinery Symposium*.
Brun, K., Thorp, J., Kurz, R., & Winkelmann, B. (2016). Gas Turbine Packaging Options and Features. *45th Turbomachinery Symposium.* Houston.
Bustos, E., & Mossolly, M. (2015). Improved Energy Efficiency in LNG Plants through the propoer Selection of Turbo-machinery. *World Gas Conference* – Paris.
Bustos, E., & Mossolly, M. (2015). Shop Testing of Major Turbomachinery in Oil & Gas EPC Projects - Cost Savings & Schedule Impact. *International Petroelum Technology Conference*, (pp. IPTC-18391-MS). Doha.
Giampaolo, A. (2006). Gas Turbine Handbook – Principles and Practices. 3rd Edition. The fairmont Press., USA.
Haught, J. (2010). Aero-derivative, Industrial and Light Industrial Gas Turbines – A Comparison. *39th Turbomachinery Symposium*, (pp. 189 - 192).
ISO 10816-3: 2009. Mechanical vibration — Evaluation of machine vibration by measurements on non-rotating parts — Part 3: Industrial machines with nominal power above 15 kW and nominal speeds between 120 r/min and 15 000 r/min when measured in

situ.
ISO 21789:2009, Gas turbine applications – Safety.
ISO 9614-1/2/3. Acoustics - Determination of Sound Power Levels of Noise Sources using Sound Intesity.
Kurz, R. & Brun, K. (1997). Field Testing of Gas Turbien Driven Centrifugal Compressor Packages – Test Procedures and Measurement Uncertainties . *26th Turbomachinery Symposium*, (pp. 19 - 34).
Kurz, R. (2005). Gas Turbine Performance. *34th Turbomachinery Symposium*, (pp. 131 - 146).
Kurz, R., Brun, K., Meher-Homji, C., Moore, J., & Gonzalez, F. (2013). Gas Turbine Performance and Maintenance. *42nd Turbomachinery Symposium*, (pp. 1 - 32).
McCloskey, T. (1995). Troubleshooting Bearings and Lube Oil System Problems. *24th Turbomachinery Symposium*, (pp. 147-166). Houston.
Meher-Homji, C. B., Matthews, T., Pelagotti, A., & Weyermann, H. (2007). Gas Turbines and Turbocompressors for LNG Service. *36th Turbomachinery Symposium*, (pp. 115 - 148).
Meher-Homji, C., Zachary, J. & Bromly, A. F. (2010). Gas Turbine Fuels – System Design, Combustion and Operability. *39th Turbomachinery Symposium*, (pp. 155 - 186).
Melissa, W., Kurz, R. & Brun, K. (2011). Successful Selection and Operation of Gas Turbine Inlet Filtration Systems. *40th Turbomachinery Symposium*, (pp. 254 - 267).
Mossolly, M. & Remy, P. (2015). Realization of over half a Billion USD worth Centrifugal Compressors for Mega Oil & Gas EPC Projects. *Abu Dhabi International Petroleum Exhibition & Conference.* Society of Petroleum Engineers. SPE-15ADIP-P-996-MS.
Patwardhan, S., Weatherwax, M., Meher-Homji, F., Cappetti, D., Musardo, A., & Iannuzzi, G. (2016). Full Speed String Test on LM6000PF Gas Turbine Driven Refrigeration Compressors. *45th Turbomachinery Symposium*.
Reddy, R. (1972). Commissioning of a Gas Turbine – Compressor of Single Lift Package for Offshore Gas Reinjection Application. *1st Turbomachinery Symposium*, (pp. 26 - 38).

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