DESIGN CHARACTERISTICS AND OPERATING EXPERIENCE
OF NUOVO PIGNONE PGT 16 GAS TURBINE

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ABSTRACT

The paper outlines the main features of the PGT 16 gas turbine with its auxiliaries and summarizes the experiences made in the field with the first seven units put in service starting in the first quarter of 1992.

The PGT 16 gas turbine utilizes an aero-derivative gas generator, the LM 1600 manufactured by General Electric, coupled with a heavy-duty power turbine designed and manufactured by Nuovo Pignone. This power turbine is the same utilized for the 14000 HP heavy-duty gas turbine Nuovo Pignone PGT 10. The nominal shaft power is 18600 HP, with 36.4% efficiency.

The design shaft speed of 7900 rpm makes this unit particularly suitable for mechanical drive applications, matching the typical speed range of centrifugal compressors in its power range. At the same time the high efficiency makes this unit attractive for both simple cycle and combined cycle power generation plants.

The package design privileges maintenance requirements to minimize the downtime and to provide the highest possible degree of availability.

The first 5 units in service have been installed along the Transcanada Pipeline and drive pipeline booster compressors, FCL and BCL type; the other two units are in operation in a cogeneration facility in a paper-mill. At October 93 the seven units have totalled 60,000 fired hours and the fleet leader 13,000 fired hours approximately.

INTRODUCTION

Nuovo Pignone has been engineering gas turbines since the late 1960s.

During these years various turbine models have been designed, both as complete machines and as power turbine to be coupled with gas generators of aeronautical derivation.

In the development of these machines the experience acquired by Nuovo Pignone in designing and constructing other types of turbo machinery, such as process centrifugal and axial compressors and gas expanders, has been widely utilized.

Obviously, each gas turbine model must be developed on the basis of the specific requirements for that particular type of machine and power range.

In any case, all of the models of Nuovo Pignone gas turbines are designed to meet specific objectives:

- adequacy of structural design
- high reliability and availability
- easy maintainability
- versatility of auxiliary and operating systems

The PGT-16 has been designed to the same criteria, utilizing in particular the experience acquired in developing the 23MW power turbine of the PGT-25 (coupled to LM-2500 gas generator) and the 10MW PGT-10 industrial turbine.

BASIC CHARACTERISTICS

Concept of the machine

In the mid-80’s Nuovo Pignone developed the 10MW PGT-10 industrial gas turbine (1). Simultaneously and in parallel, General Electric was then developing the LM-1600, an industrial version of the aeronautical engine F-404.

The thermal and fluid-dynamic conditions at the LM-1600 gas generator discharge are similar to those at the PGT-10 gas generator discharge.

It was thus possible to develop a power turbine that could be coupled, without significant modifications, to either the PGT-10 gas generator or the LM-1600 (Fig. 1).

The Nuovo Pignone range of machines has thus been presented at the international Gas Turbine and Aeroengine Congress and Exposition.

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enhanced by a 14MW machine, at an intermediate level between the PGT-10 (10 MW) and the PGT-25 (23 MW).

This is made possible by the configuration of the PGT-10. Although the PGT-10 is a Heavy Duty turbine, its architectural structure is that of two clearly distinct modules, a high-pressure one (gas generator) and a low-pressure one (power turbine), which can be disassembled from each other and subjected to separate maintenance procedures.

The speed range of the power turbine (nominal speed 7900 RPM) allows direct coupling with gas pipeline compressors of this size, while generator drive obviously requires the use of a reduction gear.

Due to the mechanical and aerodynamic design of the power turbine, the speed can be varied within a wide range (from 50% to 105% of nominal speed) while maintaining high efficiency and operation not restricted by resonance in the blades or critical speeds of the rotor.

Turbine efficiency is 36%, among the highest for gas turbine of this power range. The performance curves are reported in Fig. 2.

It has thus been possible to design a machine which unites some of the typical characteristics of both the aeronautic derivation turbine and the heavy duty turbine:

- exceptional performance, especially as regards efficiency.
- overall compact, light structure.
- quick and easy installation.
- uncomplicated disassembly and replacement of gas generator.
- maintenance of gas generator based on the "On-condition" philosophy, to be carried out in specialized service shops.
- maintenance of the power turbine based on number of hours of operation, to be carried out either on site or in the service shop.

Power turbine

As previously stated, the power turbine of the PGT-16 is the same one utilized for the 10MW PGT-10 Heavy Duty turbine (see Fig. 3). The conditions of the hot gases at inlet and exhaust of the power turbine in the two cases are summarized in Table 1:

<table>
<thead>
<tr>
<th>INLET</th>
<th>EXHAUST</th>
</tr>
</thead>
<tbody>
<tr>
<td>PGT-10</td>
<td>PGT-16</td>
</tr>
<tr>
<td>Flow rate Kg/sec</td>
<td>41.88</td>
</tr>
<tr>
<td>Pressure BAR A</td>
<td>3.22</td>
</tr>
<tr>
<td>Temperature °C</td>
<td>705</td>
</tr>
</tbody>
</table>

Table 1
The fluid-dynamic, thermal and mechanical design has thus been developed from the very beginning to allow effective coupling with the two different gas generators. This has been made possible thanks to the power turbine first stage variable nozzles, which allow wide change of flow function with minimal change of efficiency.

The configuration and structural solutions of this power turbine, described below, are the typical ones, already thoroughly tested, of the Nuovo Pignone turbines.

**Gas generator/power turbine connection**

Mechanical connection is obtained through a casing which is not in contact with the hot gases and which connects at both ends the "hot" casings of the gas generator (>600°C) with the "cool" ones (<300°C) of the power turbine (see Fig. 4).

The material (Inconel 718+low-alloy steel) and the design of the casing are such as to minimize the resulting thermal stress.

The hot gases are conveyed through a transition piece made of Hastelloy X, supported by eight radial pins, made of Nimonic 105 instead of X-40 as in the PGT-10. This modification, one of the most important introduced in the development from PGT-10 to PGT-16, was necessary because of the higher temperatures and pressures of the hot gases.

The pins are traversed by air taken from the low pressure compressor discharge, which is used to cool the power turbine.

**Nozzles**

The 1st stage nozzles, with single airfoil, are built of FSX-414.

In the PGT-10 their opening is automatically regulated by the control system in coincidence with variations in speed, load, etc.

This continuous regulation has been eliminated in the PGT-16 since gas generators of aeronautic derivation are usually designed to be coupled at discharge with a turbine with constant flow function. It is however possible to effect, with the proper equipment, limited adjustments in the opening of the nozzles to optimize performance as ambient conditions vary (seasonal adjustment) or for coupling with possible future upgraded versions of the gas generator.

The 2nd stage nozzles, built of FSX-414, are constructed in segments of three airfoils.

Considering the thermal conditions involved, it is unnecessary to cool the airfoils for either of the two stages.

Fig. 5 shows both power turbine stages as assembled in the turbine casing.

Fig. 5 Details of power turbine shrouded blade tip sealing
Rotor Blades

The 1st stage blades are built of IN 738, the 2nd stage blades of Udimet 500, Fig. 6 and 7.

Both stages are equipped with "TIP SHROUD" for the purpose of stiffening the blades, eliminating possible vibration phenomena, and reducing leakage. For the same purpose, the stator part has "HONEY COMB" seals.

The blades have shanks between the airfoil and the roof connection which, in addition to having a dampening effect on vibrations, serve to limit heat conduction toward the disks. This results in high safety margins on the life of the disks, built of M-152 steel, and curtails thermal expansion on the disks themselves.

Due to this, as well as to control of thermal expansion in the casings, (relatively cool since they are not in direct contact with the hot gases), it is possible to have relatively narrow clearances between rotor and stator, thus minimizing leakage and maximizing efficiency.

The actual blades resonances have been examined during the PGT 10 design process.

The blade natural frequencies and the relevant modes have been detected either by tests carried out on isolated blades either on the assembled rotor during the full scale prototype test.

The results have confirmed the expected behaviour which means absence of resonances in the whole operating range.

The Campbell diagram in Fig. 8 shows the prototype test results.

Shaft assembly

The shaft is formed of a single forging made of low allow steel. Connection with the assembly of two disks and the spacer is achieved through a set of tie rods, while radial centering is ensured by proper fitting. Torque transmission takes place by friction between the radial surfaces without the need for a clutch or toothing.

The journal bearings and thrust bearing are of the tilting pad type. During the process of development of the PGT-10, extensive test campaigns were conducted to verify the dynamic behaviour of the rotor-bearings-casings assembly. As the PGT-16 has a system of support for the casings different from that of the PGT-10, additional verification of the mechanical impedance of the stationary parts was carried out during the development of the machine.

Subsequent tests on the turbine have confirmed the absence of critical speeds in the system throughout the entire operating range.

\[ F = 10 \, \text{N/mm}^2 \]

Fig. 7 Power turbine rotor ready for final balancing.

Fig. 8 Power turbine 1st stage blade Campbell diagram.
PACKAGE AND AUXILIARIES

In engineering the auxiliary systems of the PGT 16, the same philosophy as that applied for all of the turbines produced by N.P. has been followed: realization of a package system, making it possible to maximize assembly carried out in the manufacturer's shop, thus simultaneously reducing onsite erection time and upgrading the quality of the product. As final result of this approach, turbine installation consists merely of positioning two main skids, the turbine baseplate and the lube oil console, and a few other items of limited size.

All of the connections, both electrical and mechanical, are terminated at the edges of the skid, simplifying installation still further.

Supporting structure

The gas turbine, consisting of the gas generator and the power turbine, is installed on a steel baseplate built of welded beams. The baseplate houses the lube tank for lubrication of the power turbine and the bearings of the driven machine, the fuel valves (gas and/or liquid), the starting system, the power turbine and the bearings of the driven machine. It thus becomes necessary to support the assembly in the casings detrimental to the correct operation of the machine. Inclined at 45 degrees connected to the gas generator, is installed on a steel baseplate built of welded beams. Support structure

The junction boxes where all of the instruments installed on the skid terminate are also placed along the perimetral beams.

The baseplate supports, in addition to the turbine and the inlet plenum, the lube oil system for the gas generator, the manometer panel and the lagging.

The turbine is assembled with ball joints on 4 connection rods; two vertical ones connected to the power turbine and two inclined at 45 degrees connected to the gas generator.

A spherical thrust pin located under the power turbine, completes the isostatic scheme of the supporting system (see Fig. 9).

The assembly system described above is unusual and highly sophisticated, when compared to the supporting systems normally used for heavy duty gas turbines, although it is common for turbines of aeronautical derivation. This type of machine is in fact characterized by a light-weight, highly flexible structure. High external loads would cause deformation in the casings detrimental to the correct operation of the machine. It thus becomes necessary to support the assembly isostatically so as to eliminate reactions deriving from constraints in case of imperfect alignment and, above all, resulting from the thermal gradients to which the turbine is subjected during operation.

Lubrication system for power turbine and load

The power turbine utilizes hydrodynamic journal bearings and thrust bearings of the tilting pad type. Consequently, it can utilize a lubrication system in common with the driven machine.

The lube oil flow, 200 liters/min. at 1.7 barg for the PT, plus the amount required by the load, is provided by a tank with capacity of approx. 4000 liters housed, as previously mentioned, in the turbine baseplate in the zone below the inlet plenum. The system has two pumps, a main pump and an auxiliary pump, capable of providing 100% of the required flow, as well as an emergency pump driven by a DC motor used for shutdown and cool down of the power turbine bearings in case the other pumps are not available.

Gas generator lubrication system

The gas generator is equipped with rolling ball bearings and roller bearings. The oil used for lubrication is a synthetic oil which retains high lubricating capacity at high temperatures.

For lubrication of the jet, approximately 36 l/min of oil at 50°C is required, at a pressure which varies with the speed of the gas generator high-pressure shaft ranging from 3.5 to 5.5 barg.

The system consists of a tank with capacity of approx. 350 liters, one delivery pump and five scavenge pumps ejecting oil from the bearing housings zones, termed "sumps". All of the pumps are of the positive-displacement type, mechanically driven through the auxiliary gearbox installed on the gas generator itself. Both the delivery and the oil drainage lines are equipped with duplex filters. Due to the corrosive effects of the synthetic oil used, all of the components used in the system are made of stainless steel Series 300.

Hydraulic oil system

The three variable-geometry control systems with which the gas generator axial compressor is equipped require oil at high pressure (50-60 bar) for their actuation. This oil is supplied by a pump, also driven through the auxiliary gear box, which sends part of the oil treated by the lubrication pump back to the gas generator (approx 24 l/min).

Part of this oil is utilized also for actuation of the fuel control valves.

Starting system

For the starting system there are two possible configurations. One is pneumatic, consisting of an expansion turbine installed on a gas generator auxiliary gearbox, which through a clutch and a epicyclic gear transmits motion to the high pressure shaft; the other consists of an electro-hydraulic system including a motor/pump group, positioned on a separate skid, and a hydraulic motor installed on the gas generator auxiliary gearbox. The expansion turbine can be fed either by pressurized air or by pressurized fuel gas.

Turbine enclosure

The turbine skid is equipped with an enclosure built of soundproofing panels. The whole is designed to guarantee an acoustic pressure level lower than 90 dBA at a distance of one meter from the package.
The enclosure is equipped inside with a bridge crane for removal of the jet (see Fig. 10) and for disassembly of the hot parts of the power turbine. A large door allows these procedures to be carried out with ease. Moreover, the roof panels are bolted and thus easily removable to allow complete disassembly of the power turbine.

Inlet combustion air system

The inlet system consists of the filter system, interconnecting silenced duct and inlet plenum.

The filter has an important role in this type of installation, since gas turbines of the aeronautic type, equipped with very sophisticated cooling systems for the hot parts, require a high degree of air filtering. High efficiency filters, such as the self-cleaning media filters are thus necessary.

The axial compressor of the LM 1600 requires a very low distortion of the flow on inlet. The design of the inlet plenum is thus a crucial element for successful operation of the machine.

The design chosen for this component in the PGT 16 package has resulted from fluid-dynamic tests conducted on scale models, during which the gradients of total pressure, temperature and speed of flow to the inlet of the machine have been determined.

Exhaust system

The exhaust duct of the power turbine can be rotated 180 degrees by discrete steps of 22.5 degrees. In this way the exhaust duct can be easily adapted to the individual requirements of the plant.

Control system

The LM 1600 gas generator is representative of the state of the art in the jet engine field, but it also requires a state-of-the-art control system.

In fact, the extremely fast dynamics of this engine, along with the number of servo controls and analog loops necessary for its control, requires the utilization of control systems which are equally rapid and capable of processing a large number of inputs/outputs. For the installations made up to now, the PLC Netcon 5000 produced by Woodward has been utilized. General Electric is now studying the possibility of using the Speedtronic MK V control panel currently utilized for the entire range of G.E. gas turbines.

MAINTENANCE

The maintenance philosophy of the aero-derivative machines is quite different from that for heavy duty gas turbines. For the latter, inspections at regular intervals during operation are preferred. During these inspections disassembly procedures are carried out, ranging from simple removal of the combustion chamber to complete opening of the rotor.

For a turbine of aero-derivative type, it is sufficient to define the HSRI (Hot Section Repair Interval), estimated in relation to the type of fuel and type of service. For a machine such as the LM 1600 operating at base load with natural gas as fuel the HSRI is 25,000 hours. Overhaul is estimated at about 50,000 hours of operation. The HSRI is merely indicative of the possible life of the hot parts. In reality, maintenance is carried out "on condition". Through borescope inspection, performed every 6 months, it is decided whether or not repair is necessary. Consequently, inspection of the hot parts is not carried out at regular pre-established intervals.

In our case, where we have an aero-derivative gas generator combined with a power turbine of the industrial type, the same criterion of on condition maintenance has been adopted for the power turbine, for which the interval of overhaul, 36,000 hours has been specified. This value is to be considered introductory since an interval of 50,000 hours should be possible in the near future.

The life of the P.T. component such as blades and nozzles is estimated as high as twice the overhaul interval i.e. 72-100,000 hours, assuming 1 repair of the nozzles during the specified life.

Borescope inspection at intervals of 6 months is in this case extended to the power turbine which is equipped with suitable inspection holes. The availability of aero-derivative turbine plant is usually very high. For borescope inspections, in fact, 8 hours are sufficient, while for inspection of hot parts or overhaul, the jet can be replaced by a spare one within 8 hours, utilizing the disassembly equipment supplied with the enclosure. Repair procedures are carried out by specialized shops. The concept of the power turbine ensures that availability remains high allowing, in case of severe outages, complete replacement of the power turbine module in few days. In this case the removal must be accomplished utilizing lifting equipment external to the package.

Overhaul of the power turbine can be easily performed on site, as no special equipment is required. If the type of service is such that the plant can be shut down for the duration of the overhaul or if a spare module is unavailable, the overhaul procedure can be carried out without removing the module from the package.
Replacement of hot parts of the power turbine (connection duct between gas generator and power turbine, 1st and 2nd stage nozzles and blades) can be effected utilizing the lifting equipment supplied with the turbine enclosure. Inspection and disassembly of the thrust bearing and the outer journal bearing can be completed in few hours, since they are readily accessible. The maintenance of the auxiliary systems is very reduced. For example the lube oil system is sized in order to obtain lube oil filter cartridges life in excess of 1 year operation, while for the oil pumps and motors is expected a life in excess of 50,000 running hours.

OPERATING EXPERIENCE

The first PGT16 constructed by NP was the first of 5 produced for Transcanada Pipelines. The unit was tested at the Nuovo Pignone plant in Florence, Italy in the Summer of 1991. As of today, seven PGT 16 units are in operation. All of them are installed in Canada: five along the pipeline operated by TransCanada Pipelines, where they drive centrifugal compressors. The other two produce electric power and heat for cogeneration plant located at a jobsite managed by Cascades Inc. at Kingsey Falls, Quebec.

The first unit was commissioned in January 1992 at Deux Rivières for TOPL, the last in January 1993 at Kingsey Falls. The fleet leader has totalled approximately 13,000 hours as of October '93, while total operating hours exceed 60,000.

During this period of operation, no major technical problems have emerged either on the power turbine or on the auxiliaries/control system group. As the only variation in the original design, modification of the distribution manifold for cooling air to the power turbine is now being made to avoid the formation of cracks due to stress originating from thermal expansion of the assembly.

The reliability and availability of the power turbine/auxiliaries assembly has been nearly 100% in these first two years of operation, confirming the performance level predicted during design, and the experience accumulated on the power wheel coupled to the heavy duty PGT-10 gas generator. As of today, three units of this type have abudantly surpassed 30,000 hours of operation with no significant problems.

For the LM 1600 gas generator it should be noted that this is a new unit which has not yet acquired the development maturity that has ensured the high reliability of other models of the LM range such as the LM 2500 and the LM 5000.

During the last two years, in which the market has shown great interest in this unit, the design data have been confirmed in terms of HSRI as well as performance. Conversely, some mechanical problems have emerged requiring the help of the manufacturer.

Specifically, two structural resonances of the system, leading to abnormal wear of some accessories installed on the gas generator, have been observed. Modifications in the zone of extraction of bleed air from the low pressure compressor and in the design of the fuel gas pipes to the burner, necessary for resolving the problem, have already been finalized and should be made available by General Electric by the end of the year, or at most within mid-1994.

A further modification is under study in order to improve the high pressure rotor bore cooling. In fact, the bore cooling flow is severely affected by the backpressure generated by the power turbine at the gas generator exhaust flange. A redesign of the system is required in order to minimize the effects of different backpressure values due to engine-to-engine variations.

CONCLUSIONS

The validity of the project in general and the verification in particular of fluid-dynamic and mechanical match between the LM 1600 gas generator and the power turbine has been demonstrated through the operating experience accumulated, as well as the attainment of the expected levels of performance and reliability.

The package and auxiliaries, realized on the basis of the experience acquired in engineering industrial systems of high reliability, have shown themselves adequate to this type of service. In particular, the design developed with the aim of reducing to an absolute minimum down time for maintenance have been found extremely effective.

The PGT 16 thus confirms the possibility of industrial use of gas generators derived from sophisticated aeronautic engines of the latest generation with high performance levels.

Thus increasingly greater utilization of aero-derivative turbines is to be expected in the near future, for this power class also, especially for those applications requiring high efficiency and rapid maintainability.

REFERENCES
