Paper No: 03-IAGT-204

15TH SYMPOSIUM ON INDUSTRIAL APPLICATIONS OF GAS TURBINES

UPGRADE OF GAS TURBINE CLEANING TECHNOLOGY

by

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Presented at the 15th Symposium on Industrial Application of Gas Turbines
Banff, Alberta, Canada - October 13 - 17, 2003
The IAGT Committee is sponsored by the Canadian Gas Association.

Biography Session 2.4

Peter Asplund
Worked with gas turbines since 1974, first with FINNAIR then with SAAB Aircraft on propulsion systems, latter as manager of the Power Plant Test Section, Flight and Systems Test Department. Aero engineer power plant systems, graduated 1979. ASME member. Awarded the design price in Sweden 1994 by H.M. the King of Sweden Carl XVI Gustaf for "excellent environmental qualities on new developed cleaning system for gas turbines". Now President of GAS TURBINE EFFICIENCY Ltd. With worldwide sell of the GTE-systems.

Abstract

The high pressure wash system was developed after findings that such a system could improve off-line as well as on-line cleaning of gas turbine compressors. Key features of the high pressure system is a cleaner compressor as well as less liquid used, less risk for damage by erosion and more simple installation by fewer nozzles.

Bench tests with the high pressure system were conducted on a LM 2500 at Kvaerner Energy test cell at Ågotnes, Norway. The test program included on-line washing as well as crank washing. Visual evaluation by borescope inspections showed significant improvements in compressor cleanliness after washings. A positive effect was that both sides of the compressor blades were equally cleaned. Numerical evaluation of logged engine running data confirmed that engine performance did improve after washing.

Field experience with the high pressure system on LM 2500 on North Sea platforms confirms good performance for both daily on-line washing and crank washing. An interesting feature with the high pressure system is that the use of detergent has been omitted at on-line washes, making the wash procedure more simple and saving costs. However, the most appreciated gain reported by the operators is that the interval for crank wash could be extended from 1500 hours to 4000 hours.

Introduction

Gas turbines consume large quantities of air. The air constitutes not only of gaseous molecules but also pollutants. As the air enters the compressor, these pollutants can have a tendency to stick to surfaces in the gas turbines gas path, especially the stator and rotor blades of the compressor. The contaminants degrade the aerodynamic performance by roughening the surface and causes operational losses. The only known way to manage these contaminants is to remove them by cleaning.

By a simple analysis of cost and profit one can easily find that every lost % in power output equals a huge amount of lost dollars. Modern gas turbine installations equipped with condition monitoring systems can easily display the performance degradation. Yet there are many gas turbines in the field that are not cleaned at all or have a poor cleaning system. Therefore it is surprising that so little attention has been paid to develop efficient cleaning systems.

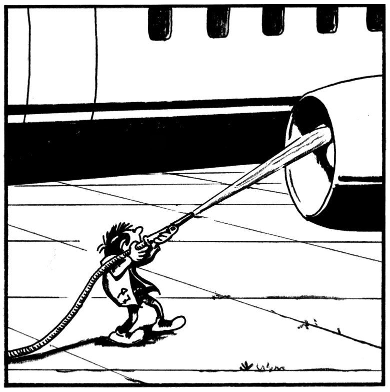

Fig. 1. How it all started

In the beginning cleaning was done by taking a simple garden hose and spraying a jet of water into the compressor air intake as shown by the Fig 1 cartoon. This was of course very simplistic and had limited success. However it must be credited for the low cost of the equipment. Since then the development of washing methodology and equipment has evolved into higher sophistication. A modern wash skid comprises a pump, regulator, detergent tank, rinsing water tank, heaters, wash cycle program, etc.

Washing Technology prior to Update

Prior to the upgrade of cleaning technology described in this paper, cleaning was preferably done at a time of engine shut down. This “off-line” or “crank wash” method is proven by operators to be effective. A cleaning fluid consisting of water or a mixture of water and detergents is injected through a large number of nozzles installed up-stream of the compressor inlet while running the gas turbine on its starter motor. Good wetting of the gas path components is accomplished by the mechanical movement of the rotor together with the chemical action of the detergents. At favorable conditions almost 100% of the engines lost power can be recovered.

The drawback with the crank wash method is that it can only be conducted when the gas turbine is out of service. From daily trend monitoring of engine performance data one can conclude that washing should be done much more frequent. For example, if daily washing could be conducted the loss level would be maintained constant simply by the compressor would hardly get a chance to build up any harmful contamination. However daily washes mean that washing must be conducted on-line. The on-line washing method faces numerous technical challenges. For example, injecting liquid into the high velocity air stream may result in only a portion of the liquid actually entering the compressor. Further there is the problem of erosion caused by too large droplets. There are engine manufacturers who do not recommend on-line washing.

Updating the Washing Technology

The fact that there is a need for an improved washing system opened the door to a research program. The research program was to include theoretical work, bench testing and field testing.

The theoretical work set the following requirements on the new system:

- the droplets must be small as not to cause erosion
- the droplets must be large enough to impact the blade surface and not follow the air stream
- too little liquid will evaporate and not wet the blades
- too much liquid will be centrifuged to the casing by the rotors rotation and not participate in the cleaning process
- too much liquid may stress material
- the liquid must strike a proposed target point at the compressor inlet else wetting of the compressor components will not be appropriate
- The liquid should strike the target point at both crank and on-line washing

A somewhat surprising outcome of the theoretical work was that the new wash system should work at 70 bar pressure which is a much higher pressure than the 3-8 bar used by old systems. Below are the features of the upgraded washing system:

- the high liquid pressure result in a high spray momentum which more effectively penetrates into the core air stream
- the high liquid pressure result in a high nozzle capacity whereby fewer injection nozzles are required
- fewer nozzles result in cheaper installation and lower maintenance cost
- the high pressure system became more of a “direct injection” system indicating less liquid wasted and thereby less liquid to be injected
- the same nozzles would be used for both crank washing and on-line washing
- the high pressure atomization result in smaller and less harmful droplet sizes

Fig. 2 LM2500 - same nozzles used for crank wash and on-line washing

The installation in practice on a gas turbine like the LM2500 is shown in Fig 2. Only 5 nozzles in total are required, installed between the struts. To assure an optimum spray pattern and liquid flow rate, the nozzles are tailor made for the turbine type and the site specific conditions.

The final proof of concept was done by Computerized Fluid Dynamics (CFD) simulation. CFD techniques has evolved rapidly in recent years allowing exploration of new fields of science and engineering at very reasonable costs. We conducted a CFD simulation of the air flow of the LM2500 compressor inlet and the liquid spray.

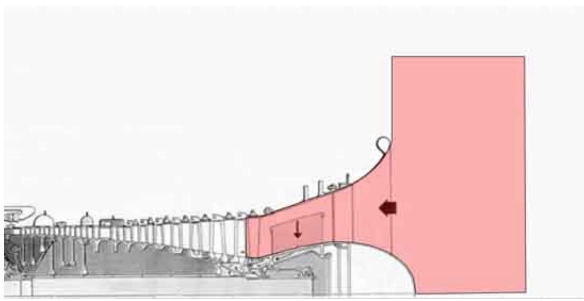

Fig 3. LM2500 compressor and computational domain (red shadow)

Fig 3 shows a cross section of the LM2500 compressor. The computational domain is shown by red shadow. Air enters the domain at the right vertical line and exits the left vertical line. The exit corresponds to the tailing end of the IGV. The CFD model is rotationally symmetric around the engine shaft thereby assuring a correct three dimensional flow.

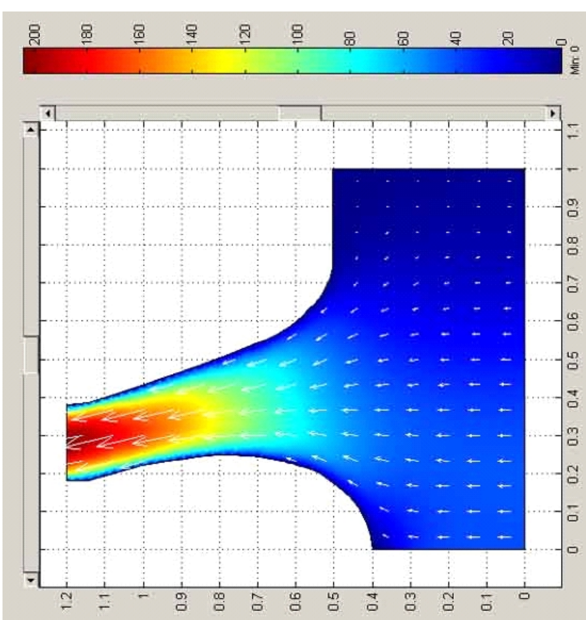

Fig 4 velocity profile

Fig 4 shows the CFD computed velocity profile for the LM2500 engine running at base load. By help of the color scale on the top we can see how the air accelerates from the right to the left. At the IGV we find peak velocities as high as 200 m/s. This image well illustrates the conditions prevailing at on-line washing. At cranking speed we get basically the same velocity profile but much lower velocities, typically 10 m/s at the IGV.

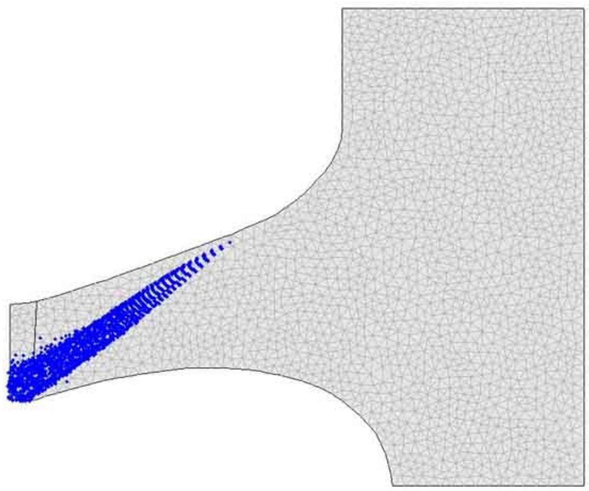

Fig 5 Spray pattern (blue) at cranking speed

With the help of computer techniques it is now possible to inject particles into the air stream and study the trajectories. By simultaneously injecting numerous particles at a high frequency we make up a complete spray. Particles are of the same density as the washing fluid. Particle diameter is the same as from the nozzle atomization. Fig 5 show the spray pattern for the cranking case. The nozzle is intentionally directed a little bit towards the root of the IGV. An additional feature of the computational techniques is that the number of particle that passes the IGV target line can be counted and compared to the total number of particles injected. This then gives an indication of how much liquid that enters the compressor and how much that hits the walls of the bellmouth and nacelle.

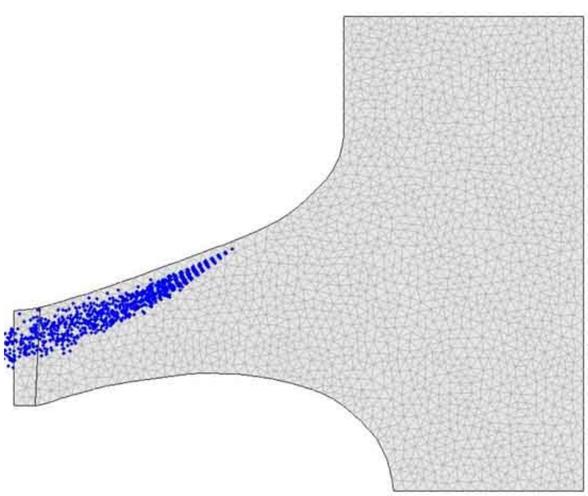

Fig 6 Spray pattern (blue) at base load

Fig 6 shows the spray pattern at base load. We can see that the spray is now being torn apart caused by the violent turbulence of the high velocity air stream. From the Fig 5 image we saw the spray striking a bit upwards from the root of the IGV. In Fig 6 we find the spray hitting higher which is caused by the air stream pushing the spray upwards. However, the key result from Fig 5 and 6 is that essentially all the liquid enters the compressor. This was one of the objectives with this development program. Both the Fig 5 and 6 spray patterns comply well with video images taken during the Ågotnes bench test as described below.

Bench test at Kvaerner Energy

Testing of the high pressure Direct Injection System took pace in November 1998 at Kvaerner Energy's test cell at Ågotnes outside Bergen, Norway [1]. Test object was a LM2500 gas generator that was due for overhaul. The gas generator came from a North Sea platform with a dirty compressor. The compressor had accumulated contaminants from 1350 hours of operation.

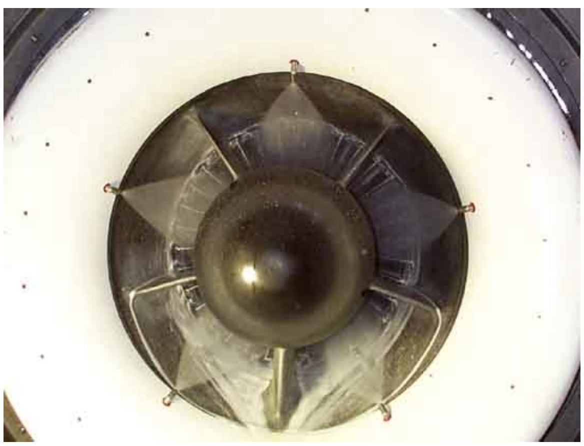

Fig. 7. LM 2500 at the test cell

The on engine washing equipment consists of 5 nozzles installed on the engine's bellmouth as shown in Fig. 7. Note the numerous holes on the bellmouth from the old washing system up-stream the current nozzles. A wash skid with two 80 liters tanks with heaters was used. The washing liquid/rinse water was heated to 65C prior to injection. Liquid supply pressure was 70 bar. A commercial cleaning liquid was used. The gas generator was rigged with Kvaerners standard test equipment for performance test.

Documentation of the test included:

- Video taped borescope inspections prior to and after each wash cycle in the program.

- A video camera installed in the front of the engine to record the spray pattern from the wash nozzles.
- Detailed vibration monitoring and analysis.
- Performance tests, performed prior to and after each wash cycle in the program. All obtained data was run through General Electric’s test cell performance computer program.

The tests were conducted 10-11 November 1998 according to the test program in Table 1:

Table 1. Wash Test Program

A. As received inspection
B. On-line wash (1 minute)
C. On-line wash (3 minutes)
D. Idle wash (3 minutes)
E. Crank wash (3 minutes)
F. Artificially fouling the compressor by oil/carbon injection
G. On-line wash (3 minutes)
H. On-line wash (3 minutes)
I. Idle wash

The tests commenced with two on-line washings, the first at 1 minute liquid injection time (test B.) and the second at 3 minutes liquid injection time (test C.). These two runs are the most interesting as the compressor at this time had been fouled with contaminants from 1350 hours of operation on a North Sea platform. The washing was done at close to 100% normal operating load.

<u>Evaluation by borescope inspections</u>

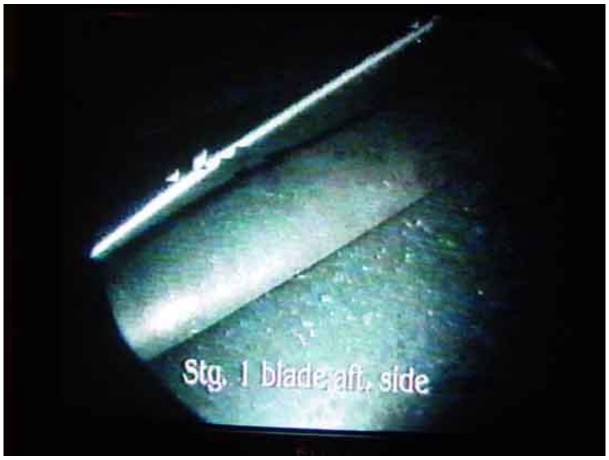

Fig. 8 Borescope image

Borescope inspection, Fig. 8, prior to test gave the general impression that the blades from stage 1 to 5 had a layer of black grease like deposit. The dirt buildup was heavier on the back side than on the front side. In addition to this there was also a salt build-up. At the rear end of the compressor stage 15 did not look dirty but had clearly visible salt deposits.

Borescope inspection after the first run (test B; on-line wash for 1 min.) showed that blades on stage 1 to 5 clearly looked cleaner than before. However there are still streaks of dirt along the blades. All traces of salt are gone. At the rear end of the compressor there has been some improvement but not much.

Borescope inspection after the second run (test C; on-line wash for 3 min.) blades on stage 1 to 5 showed that things are now starting to look very good. The blades are beginning to get a nice shiny appearance on both sides. However there are still some weak dirt streaks to be seen. But the overall impression is a definite improvement, and not missing much to be completely clean. At the rear end of the compressor things are looking very much the same as after the first run.

The next run was performed at idle speed (test D.). The test confirmed that washing at low speed was very effective although the observed improvement was small as the compressor was already fairly well cleaned after the on-line washes. Blades on stage 1 to 5 are getting close to completely clean. Some minor streaks (or shadows) can still be observed. The general impression is that it is marginally better than after the second run. At the rear end of the compressor less salt deposits were observed. This would indicate that the washing liquid is penetrating the complete compressor.

Fig. 9 Total gas path penetration

The next run was Crank wash (test E.) Now the liquid is definitely penetrating the complete gas turbine as shown by Fig 9. Blades on stage 1 to 5 would be considered close to or 100% clean. A very positive effect was that both sides of the compressor blades were equally cleaned. At the rear end of the compressor part of the blades show no salt deposits while other parts still has some salt.

This ended the first part of the test program. The compressor was now artificially fouled by injecting a mixture of turbine oil and carbon copy power. The continued testing with on-line washes (test G and H) and idle wash (test I) did not reveal anything new but confirmed the observations made during the previous tests A to E.

During all test runs vibration monitoring was done for the purpose of checking that non-symmetric distribution of liquid did not cause harmful vibrations. No severe vibrations were recorded.

Numerical evaluation

The test cell computer code would enable comparison between the various performance points in the program. However a test of this nature with the goal to measure marginal performance improvements was found to be difficult. From field installed gas turbines the effect of washing can be monitored from the corrected power output. This was not possible at Ågotnes as this was a bench test with no power load.

It is known that washing improves compressor performance in three ways; increased mass flow, higher pressure ratio and increased efficiency. Out of the three, the mass flow parameter has the strongest impact on engine output. However, mass flow rate is not measurable by the use of a probe or sensor. Mass flow has to be estimated. The estimate is a two step process starting with a thermodynamic model of the engine at its design point and then an aero-thermal model to predict off-design performance. This method was shown not to be successful at these trails. The next parameter, the improved pressure ratio, could in theory be easy to measure by simply reading the pressure at the compressor inlet and outlet. However, the outlet pressure has to be put in context of many variables such as air bleed-off, mass flow, speed, etc. This made this method not feasible on this turbine. Finally, the compressor efficiency. This has the least impact on gas turbine performance of the three. The efficiency can be estimated by a few measurements and the formula for isentropic process according to equation 1 and 2 below [2].

$$\frac{T3isen}{T2} = \left(\frac{P3}{P2}\right)^{\frac{K-1}{K}} \qquad \text{Eq. 1}$$

$$ETAisen = \frac{T3isen - T2}{T3 - T2} \qquad \text{Eq. 2}$$

T2 = inlet temperature
T3isen = outlet temperature at constant entropy
T3 = outlet temperature
P2 = inlet pressure
P3 = outlet pressure
K = specific heat ratio
ETAisen = isentropic efficiency

The method has the advantage of not involving mass flow. The method is very accurate in itself. But for an accurate result also the measurements must be accurate. The sensors installed at the test cell facility were field standard while laboratory instrumentation would be preferred. The result from computing the isentropic efficiency based on equations 1 and 2 is shown in Table 2. Readings were taken before and after test.

Table 2. Computed compressor isentropic efficiency

	Before	After	Change
B. On-line wash (1 minute)	0.8531	0.8534	0.0003
C. On-line wash (3 minutes)	0.8530	0.8539	0.0010
D. Idle wash (3 minutes)	0.8539	0.8619	0.0079
E. Crank wash (3 minutes)	0.8619	0.8610	-0.0009
F. Artificially fouling the compressor by oil/carbon injection			
G. On-line wash (3 minutes)	0.8582	0.8615	0.0033
H. On-line wash (3 minutes)	0.8590	0.8622	0.0032
I. Idle wash	0.8622	0.8589	-0.0033

Table 2 indicates that compressor washing improves efficiency. However, it must be kept in mind that we are looking at very small numbers as the compressor efficiency improvement is the least powerful of the three parameters.

Field experience

High pressure washing systems have been installed on aero-derivative gas turbines on North Sea platforms since 1999. The first installation was for a trail on a LM2500 on the Sleipner platform in March – September 1999. In June 2000 a permanent installation was done on a LM2500 on the Siri platform. This LM 2500 runs at 12 MW output which reduces air mass flow with about 25%. In October 2001 the operator of Siri reported the following [3]:

- Daily on-line washes were conducted from June 2000 till January 2001. 3 min wash cycle with detergent followed by 3 min rinsing. At periods crank washing was performed with 1500 hrs interval.

- Stage 1-2 relatively clean. Stage 4-6 with some deposits. Stage 15-16 with white "beard" on leading edge.

- Switch to on-line washing with pure water. Current procedure is daily on-line washes for 3 min with water only. Crank wash after 4000 hrs.

- The turbine was stopped for inspection on October 12 after 3200 hrs with water washing only. Borescope inspection revealed that the compressor was so clean that no crank wash was needed.

- The operators at Siri are very pleased with the wash equipment. No operational problems. Ion exchange filter needs to be replaced every 3 months.

In May 2003 the operator reported:

- The turbine had run for 5000 hours with on-line washes only before it was stopped. Borescope inspection showed some soot on the first stages however the turbine was fully operational. The soot was believed to come from intensified ship activities at the platform side.

- The operators experience that achieving long operating periods between stops requires on-line washes and a good inlet filter.

Summary and Conclusions

The high pressure wash system was developed after findings that such a system could improve washing of gas turbines. The bench test at Ågotnes and field experience from the Siri platform confirms that the system also works in practice.

This report is focused around the LM 2500 aero derivative engine. The high pressure system is today proven successful on a large range of gas turbines. The system will be available for all gas turbines when engineering and testing is completed.

Reference

[1] ONLINE WATER WASH TEST, Kvaerner Energy a.s., 28 January 1999

[2] Basic Thermodynamics and Heat Transfer, D.H. Bacon, 1983

[3] Erfaringsutveksling, vasking av turbiner, Statoil, 31. Oktober 2001