SIEMENS SGT-800 INDUSTRIAL GAS TURBINE ENHANCED TO 47MW.
DESIGN MODIFICATIONS AND OPERATION EXPERIENCE

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ABSTRACT
Mid year of 2007 Siemens Oil & Gas and Industrial Applications introduced an enhanced SGT-800 gas turbine. The new power rating is 47MW at a 37.5% electrical efficiency in open cycle (ISO). Four components in the gas turbine are modified and are fully interchangeable between the existing 45MW and the 47MW rating. Improved cooling designs were introduced in the turbine stages #1 and #2 requiring no change to the casting design. The only modification is to the machining of the parts and to the guide vane cooling inserts and impingement screens. A re-stagger of the stage #1 compressor blade was made to give a slightly increase in the airflow. The combustor outlet temperature (COT) remains the same.

The first SGT-800 with 47MW rating was successfully tested during the autumn of 2006 and the expected performance figures were confirmed. This unit has, up to November 2007, accumulated 8 000 hours and a planned follow up inspection made after 4 000 hours by borescope of the hot section showed that the parts were in excellent condition.

This article presents some details of the design work carried out during the development of the enhancement from 45MW to the mature rating of 47MW and the operation experience from the first units.

INTRODUCTION
Launched in 1997 as a 43MW machine under the name GTX100, see [1], the SGT-800 up to date has been rated at 45MW with a 37% electrical efficiency (ISO) in open cycle and 64MW with a 53% efficiency in combined cycle with dual-pressure HRSG.

The SGT-800 core engine layout is presented in Figure 1. The engine, besides the inlet housing and outlet axial diffuser, consists of a 15-stage compressor, an annular combustor equipped with 30 DLE dual-fuel burners and a 3-stage axial turbine. The DLE system is simple and robust without any staging or advanced control with low NOx capability in the 50 to 100% load range.

More than 70 units have been sold up to November 2007 and the SGT-800 fleet has accumulated more than 600,000 EOH, all units are equipped with DLE system. The 12-month rolling average fleet reliability is 99.6% whilst the fleet leader has passed 50,000 EOH.

Figure 1: SGT-800 Engine layout

The SGT-800 enhancement is based on a proven operating record since commercial introduction as well as a comprehensive mapping of the hot section thermal state, carried out in August 2003 [2]. More than 1900 thermo-crystals were attached to the turbine vanes and blades, measuring the metal surface and hot gas temperatures.

Figure 2: SGT-800 Turbine Guide Vane 1 instrumentation

In addition, thermal paint on the first row guide vanes, thermocouples and pressure taps were used to verify the
temperatures and pressure distribution in the complete turbine section. The instrumentation used on the first guide vane can be seen in Figure 2.

Evaluation of the test results showed that the turbine cooling air could be redistributed in a way that the total air consumption will be reduced. This will also give a more uniform surface temperature distribution over the hot section components, hence reducing thermal stresses. The reduction of cooling air consumption, together with a 1.5% additional airflow from the compressor, was then used to increase power and improve efficiency.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Term</th>
<th>Description</th>
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<tbody>
<tr>
<td>APS</td>
<td>Air Plasma Spray</td>
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<tr>
<td>CFD</td>
<td>Computational Fluid Dynamics</td>
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<td>DLE</td>
<td>Dry Low Emissions</td>
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<tr>
<td>EB PVD</td>
<td>Electron Beam Physical Vapor Deposition</td>
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<tr>
<td>FEM</td>
<td>Finite Element Model</td>
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<tr>
<td>EOH</td>
<td>Equivalent Operation Hours</td>
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<tr>
<td>TBC</td>
<td>Thermal Barrier Coating</td>
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GAS TURBINE MODIFICATIONS

Compressor

The compressor section is shown in Figure 3. From the fifteen stage compressor the machine is getting almost 20 bar at the combustor inlet. The casing has a vertical split plane for easy access during on site maintenance. The first three rows have variable guide vanes and there are several bleed points to provide stable and effective operation in a wide range of load and ambient conditions.

The only modification in the compressor section for the 47 MW rating is at the first rotor blade. The blade has been re-staggered resulting in a more open profile in order to provide an increase of the air mass-flow through the engine. This modification contributes to the power increase as well as to improved total efficiency due to the increased pressure ratio.

The blade attachment geometry remains unchanged ensuring full retrofit ability with the existing 45MW rated units. The gas turbine inlet mass-flow has been raised by 1.4% and the compressor pressure ratio has increased from 19.5 to 20.2 as the first guide vane throat area in the turbine was kept unchanged.

Turbine

Figure 4 shows the principles of the turbine layout. The total-to-total pressure ratio is 17.6 distributed over the three stage turbine. The first stage blading is film and convective cooled and the second stage is convective cooled. The last turbine stage is un-cooled. The ISO Turbine Inlet Temperature is 1180°C for the 45MW rating and the turbine efficiency is dependant on a good aerodynamic design as well as on an effective use of cooling air from the compressor extractions. There is also a stator cooling arrangement for radial clearance control. The turbine rotor is of bolted design with a spigot fit to the compressor rotor. The turbine section is handled as a module during assembly or disassembly for high serviceability.

As mentioned the thermal state of the flow path components were mapped in detail using the thermo-crystal technique. The aim was together with the verification of existing component lifing models to investigate the potential for redistribution and a reduction of the total cooling air consumption. The information from more than 2 300 measuring points during the engine tests were used to verify the 3D Navier-Stokes aerodynamic model of the turbine and to calibrate a 3D thermal state model for each vane and blade. Finally these results were used for 3D-FEM mechanical integrity analyses of the hot section components.

The focus for the turbine section during the work in order to reach the new rating was to make small modifications to the cooling systems of the first two stages, without having to change the castings. The ability to retrofit existing units was an important target for the development.
Guide Vane #1

The first guide vane is a single airfoil design equipped with a two cavity airfoil cooling scheme. The front cavity has a shower head and is cooled mainly by a film arranged at the vane leading edge. The front cavity deflector works as a flow distributor along the span at the convex side rather than a flow area restrictor as the rear cavity insert does. The rear cavity is equipped with a lattice in the trailing edge region and an insert in the middle. The design utilizes a good combination of the convective and film cooling opportunities.

Both inner and outer platforms use an impingement type of cooling arranged by screens with air discharging through perforation holes along the platform sides. Since the SGT-800 combustor provides a relatively flat exit gas temperature profile along the channel height, an APS Thermal Barrier Coating (TBC) is applied on both inner and outer platforms to protect them from oxidation without the need to use an excessive amount of cooling air.

The thermo-crystal test showed that the leading edge was overcooled and confirmed some earlier noted hot areas in the existing design. By changing the film cooling holes distribution, density and angle to the cylindrical surface, the cooling air consumption at the leading edge could be reduced. Also, the impingement holes at the inner and outer platform screens and the distribution of the discharge holes at the inner and outer platform sides was optimized based on the detailed mapping of the temperature distribution from the crystal test. All changes could be implemented keeping the existing castings, just by a machining and insert modification. Figure 5 shows the temperature distribution on the modified vane and areas having the largest impact are indicated.

Blade #1

The blade #1 film-convective cooled design consists of a serpentine air path at the middle part of the airfoil, a lattice at the rear part and a leading edge channel feeding the shower head.

Since the combustor outlet gas temperature remains the same for the existing and the enhanced SGT-800 versions, a reduced amount of cooling air at the first stage guide vane will increase the gas temperature at the rotor inlet. This fact, acting in opposite to reducing the air consumption, had of course to be considered during the design of the modified blade.

Again, the outcome from the thermo-crystal surface temperature mapping was an overcooled leading edge region. Additionally some preliminary modifications of the shower head arrangements were investigated during the test to define the limitations in cooling air saving. The conclusion from test, supported by evaluation of blades that had been in operation for 20 000 EOH, was that a few film holes could be removed and the size of the remaining holes could be reduced by 0.1mm. After the modification, the size of film cooling holes became the same as on the leading edge of guide vane #1. It was also decided to introduce an EB-PVD TBC to further reduce the overall temperature level on airfoil and platform. Experience from this TBC system had previously been gained from operations in the existing design. A detailed 3D analysis confirmed that the temperature distribution now became more balanced and reducing thermal induced stresses.

At the blade tip on the concave side additional holes were added. The aim was to further reduce the risk of local oxidation at the tip which otherwise would contribute to a performance degradation.

Figure 5: Turbine Vane 1 surface temperature

A significant temperature drop in front of the pressure side film cooling holes was also achieved. This area was somewhat hot in the existing design. The improvement was the result of the re-distributed airfoil perforation positions together with the modification of the outer platform screen and rear cavity insert. The total saving of compressor air in the guide vane row #1 was 0.6%, relative to the compressor inlet flow. No increasing of the maximum temperature or reducing fatigue life of vane accomplished that saving.

Figure 6: Turbine Blade 1 surface temperature

Figure 6 above shows the temperature distribution on the modified vane and areas having the largest impact are indicated.
Evaluation of the extensive test program during 2003 also showed a potential to reduce the amount of ventilation air used in the rim cavity between blade #1 and vane #2. This was possible by tightening of the tangential gap and an improved sealing configuration between vane #2 inner platforms.

All together the high pressure cooling air savings at the blade #1 region was 0.8% relative to the compressor inlet flow. This was achieved without a change to the casting and with no increase in the maximum metal temperature in the blade. Furthermore, based on the temperature field in the modified design, numerical analysis showed a reduction in the thermal stresses.

**Guide Vane #2**

The convective cooled vane #2 is equipped with an airfoil insert. The insert is used for impingement cooling of the leading edge region and to provide a high air velocity in the cooling channels. It also transports the cooling air towards the inner platform and the connecting honeycomb box. Screens attached to the outer and the inner platforms provide an impingement cooling of the vane end-walls. The design configuration has a high cooling effectiveness and gives flexibility in terms of adjustments that sometimes can be needed. As used for the first stage vane, an APS TBC is applied to the upper and inner end-walls.

From the thermo-crystal test it was noticed that not only the leading edge was somewhat overcooled, but the trailing edge part of the airfoil was also. A potential for reduction of cooling air consumption and also of temperature gradients was clearly identified. The hole pattern of the airfoil insert and the platform impingement screens were changed to achieve the design target for the modified vane. A sealing at the lower end of the airfoil insert was also introduced to reduce the internal leakage.

A CFD analysis of the flow structure around the second stage guide vane row revealed a potential to reduce the leakage through the labyrinth seal between the vane inner platform box and the rotor. In addition to a tightening of the circumferential gaps between the vane platforms, a sealing plate was introduced just above of the honeycomb system. These actions not only reduce the risk of gas ingestion between the vanes, but also reduce the aerodynamic losses when the high momentum gas and the air leakage at the vane hub mix in front of the second stage blade.

The outcome of the guide vane #2 modifications was a total reduction of cooling air consumption by 0.7% relative to the compressor inlet flow. The surface temperature distribution for the modified vane #2 and the change in temperature compared to the existing vane at some points can be seen in Figure 7.

As for the previous two turbine components, the vane #2 machining has been modified but the casting remains the same.

![Figure 7: Turbine Vane 2 surface temperature](image)

Since the cycle pressure ratio has increased, air leakages in the turbine section has in general also increased. This effect was taken into account when the performance improvement for the enhanced SGT-800 was predicted. All blading components were evaluated by means of 3D thermal and stress-strain analysis. In spite of significant reductions of the turbine cooling air consumption, improved life expectancy could also be achieved.

All three modified turbine blading components are fully compatible with existing SGT-800 parts for retrofit ability of all existing units in the fleet.

**SGT-800 PERFORMANCE**

In Table 1 the new rating for the enhanced SGT-800 is summarized and shown in comparison with the existing 45 MW rating.

**Table 1: SGT-800 Performance summary**

<table>
<thead>
<tr>
<th>SGT-800 version</th>
<th>Existing</th>
<th>Enhanced</th>
</tr>
</thead>
<tbody>
<tr>
<td>GT output, MW</td>
<td>45.0</td>
<td>47.0</td>
</tr>
<tr>
<td>Combined Cycle output, MW</td>
<td>64.0</td>
<td>66.5</td>
</tr>
<tr>
<td>Thermal efficiency, SC, %</td>
<td>37.0</td>
<td>37.5</td>
</tr>
<tr>
<td>Thermal efficiency, CC, %</td>
<td>53.0</td>
<td>53.7</td>
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<tr>
<td>Compressor pressure ratio</td>
<td>19.5</td>
<td>20.2</td>
</tr>
<tr>
<td>Exhaust mass flow, kg/sec</td>
<td>130.0</td>
<td>131.8</td>
</tr>
<tr>
<td>ISO Turbine Inlet Temperature, °C</td>
<td>1180</td>
<td>1200</td>
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<tr>
<td>Exhaust temperature, °C</td>
<td>539</td>
<td>544</td>
</tr>
<tr>
<td>Emissions NOx, ppm</td>
<td>15</td>
<td>15</td>
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It can be seen from the table that in spite of the increased compressor pressure ratio and improved turbine efficiency, the exhaust temperature has increased due to the more than 2% reduction of turbine cooling air consumption. Together with the
increased exhaust mass flow this has given an additional improvement in combine cycle performance.

SGT-800 ENHANCED VERSION VALIDATION

The retrofit ability of existing units was an important requirement for the development of the enhancement. For the validation of the new rating, one of the existing SGT-800 engines was chosen. The modified components were installed into the compressor and turbine sections during a planned overhaul and the validation test was performed in autumn 2006. Besides a performance related parameters scanning, the secondary air system was studied by means of a number of thermocouples and pressure taps situated at the most sensitive places. Measuring points were chosen based on the extensive test program during 2003 in a way that a direct comparison could be made. This was done in addition to the standard high precision performance test equipment. All cooling paths were separately flow tested for all new components before installation to verify the expected cooling air consumption.

The measurements confirmed the predictions of the modifications in the secondary air system. The performance targets (47MW@37.5%) were also achieved, in spite the fact that this unit had several years of continuous operation at the time of the upgrade.

Since the official launch of the new rating during the Power-Gen Europe conference in Madrid in June 2007, two more units have been retrofitted to the 47MW rating. With both these engines, the performance has been in accordance with our expectations. Several new sales orders have also been signed and the 45MW rating is no longer offered to the market.

During a planned follow up inspection of the first 47MW rated unit the pictures, Figures 8 and 9, were taken after 4000 hours. All hot section components were found to be in excellent condition.

CONCLUSIONS

Continued improvements of the SGT-800 gas turbine have been performed since 1997 when the machine was launched. This paper has described the particular modifications making it possible to reach the new rating of 47MW with a 37.5% efficiency in open cycle and 66.5MW with a 53.7% efficiency in combined cycle.

The enhancement was achieved through a re-stagger of the compressor first blade and modifications of the cooling air arrangements in the two first turbine stages. Based on an extensive test program in 2003, involving a detailed temperature mapping of the turbine section using a thermo-crystal technique, the total cooling air consumption could be reduced by more than 2%. At the same time, thermal induced stresses could be reduced and life expectancy improved. The modifications could be introduced without changing blade or vane castings, only by machining and for the guide vanes also of the cooling inserts and impingement screens.

All modified components are fully interchangeable between the 45MW and the 47MW rating, giving the possibility for retrofitting all existing units. Up to November 2007, three units have been retrofitted confirming expected performance gain. The 47MW fleet leader has passed 8000 hours of operation and a follow up inspection made after 4000 hours showed that the parts were in excellent condition.

Siemens SGT-800 gas turbine with the new rating will reduce life cycle cost for open cycle, CHP and combined cycle plants. This enhancement is part of the Siemens product strategy for SGT-800 to maintain the leadership of industrial gas turbines in its class and to deliver reliable and environmentally friendly equipment to the world market.

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REFERENCES