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TITAN™ 250 GAS TURBINE DEVELOPMENT

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Abstract

This paper highlights the design advances that led to the design of the Titan 250 30000hp class industrial gas turbine. Any gas turbine is designed as a system, and in the particular case of the Titan 250, design features were defined after detailed evaluation of customer needs. In the oil and gas industry, features like high efficiency and low emissions have to be met, but a key requirement lies in achieving high availability, reliability and maintainability. In the paper, we will highlight specific, state of the art design procedures. Optimization strategies are discussed, as well as their verification with exhaustive testing.

Introduction

Solar's product development strategy follows a low-risk evolutionary approach of using proven design tools, materials, coatings, and gas turbine technologies. The *Titan™* 250 gas turbine leverages core technologies that have been developed and proven in many of *Solar's* gas turbines. These core technologies include a conservative design approach grounded in advanced aerodynamic, thermal and mechanical design tools and methodologies, thorough combustion system modeling, full-scale laboratory and in-field testing, and integrated fleet support planning.

For a given power class, the goal is to provide a product offering to potential users that make their operation successful. This includes features that allow for:

-High Reliability and Availability
-Low Emissions
-High Efficiency
-High Power Density
-Attractive first cost and operating cost
-High operational flexibility
-Life cycle support

As a result, Solar developed the Titan 250 industrial gas turbine, a two shaft, 30,000hp engine, well suited for mechanical drive and power generation applications (Figure 1).

Many of the considerations discussed also focus on integrating the gas turbine and its driven equipment into the overall system, be it a compressor station, an offshore platform, a pipeline system, or a power generation installation.

Figure 1: Titan 250 driving a C85 pipeline compressor

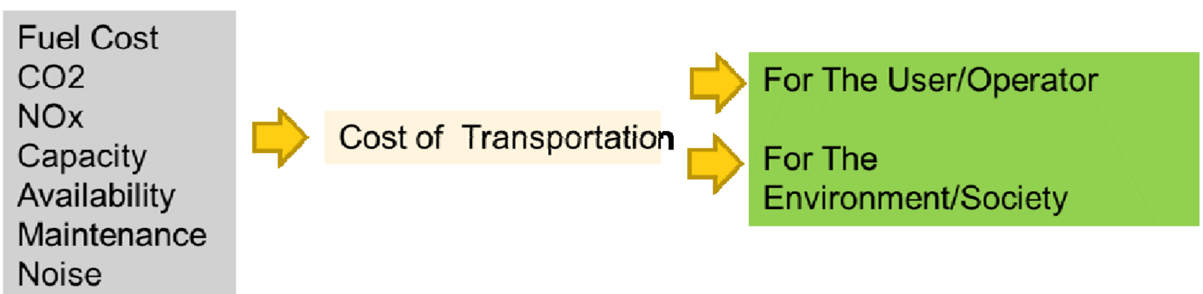

Figure 2: A wider definition of efficiency

In that context, we also have to allow a wider definition of efficiency (Figure 2), looking for example at the cost of transportation of natural gas in a pipeline, both to the owner/user/operator as well as to environment and society.

The application framework, especially in the oil and gas industry, exposes drivers to wider swings in operating conditions, gas and oil fields in a wide variety of sizes, or the requirement to integrate pipeline operation to follow significant swings in demand, especially when grids use significant amounts of renewables.

The Titan 250 is a low-risk hybrid design that combines proven technologies from three current gas turbine models: the Titan 130, Mars 100 and the Taurus 65. It provides 30000hp at ISO conditions, with a thermal efficiency of 40%.

It is a two shaft gas turbine with a 16 stage axial compressor driven by a 2 stage gas producer turbine. The power turbine is a three stage design (Figure 3) with a maximum operating speed of 7000 rpm. Both conventional and low NOx (SoLoNOx) combustion systems with dual fuel capability are available.

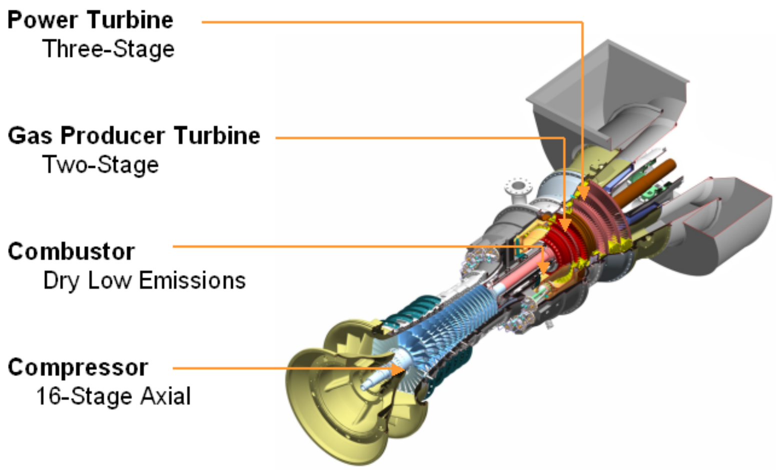

Figure 3: Titan 250 Components

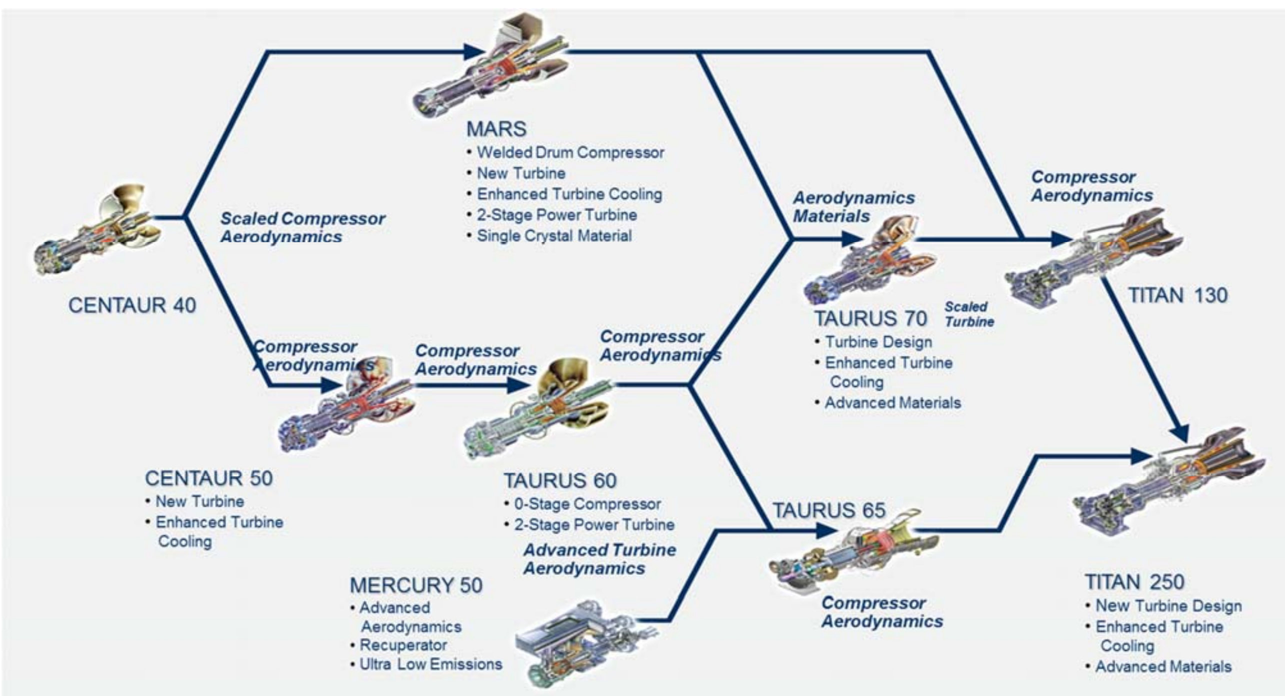

Figure 4: Titan 250 heritage

The *Titan 250* has a similar size and mechanical/structural design to the *Titan 130*. This platform and core technology was founded in the 1980's with *the Mars 100* model from which the *Titan 130* is largely derived from. The *Titan 250's* combustion system operates at the same firing temperature as the Taurus 65, which is only 10°C higher than the *Titan 130*.

All the key engine internal components are made of the same materials that are used on the *Titan 130*, *Mars 100* and *Taurus 65* product lines. The combustion system is derived from the Taurus 65 product line that fires at 1204° C (2200° F) TRIT, which is only 10C higher than the

Titan 130 product line. High efficiency airfoil design and ultra-low emissions technologies have been incorporated from the *Taurus 65* product line (Figure 4).

Like the Mars product line, the *Titan 250* is only available in a two-shaft design for all Oil and Gas and Power Generation applications for both onshore and offshore applications

Despite the higher output power, the *Titan 250* is less than 1 meter longer than the *Titan 130*, and shares a common, modular mechanical design (case, bearings, rotors, blades and combustion section) with the *Titan 130* and *Mars 100* models (Figure 5).

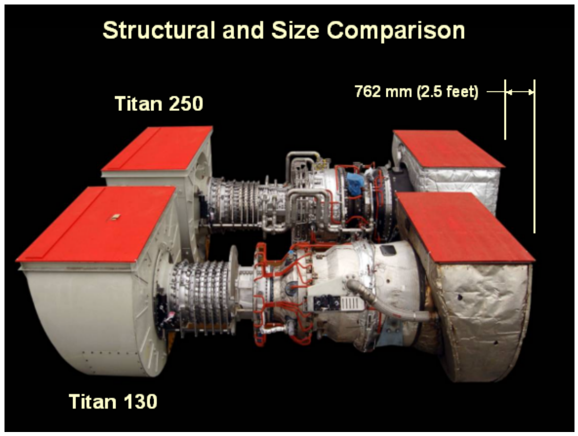

Figure 5: Size Comparison

On introduction, the engine went through rigorous factory and field evaluation campaigns to assure product maturity (Janssen et al [1])

Trade Offs

Engine development requires to evaluate the trade-off between competing requirements. One of the key trade-offs in engine design is therefore between engine life and engine performance, since both are tied to the question of process temperatures, and the resulting local material temperatures. Figure 6 illustrates one of these trade-offs: To increase efficiency and power density, higher engine firing temperatures, combined with as little use of cooling air in the hot section are desirable (Figure 7). However, this needs to be balanced with the detrimental effect of high metal temperatures on engine life and reliability. This can, and will be counteracted by material and coating choices, and, in particular, component cooling schemes. This is particularly true for the turbine nozzles and rotor blades.

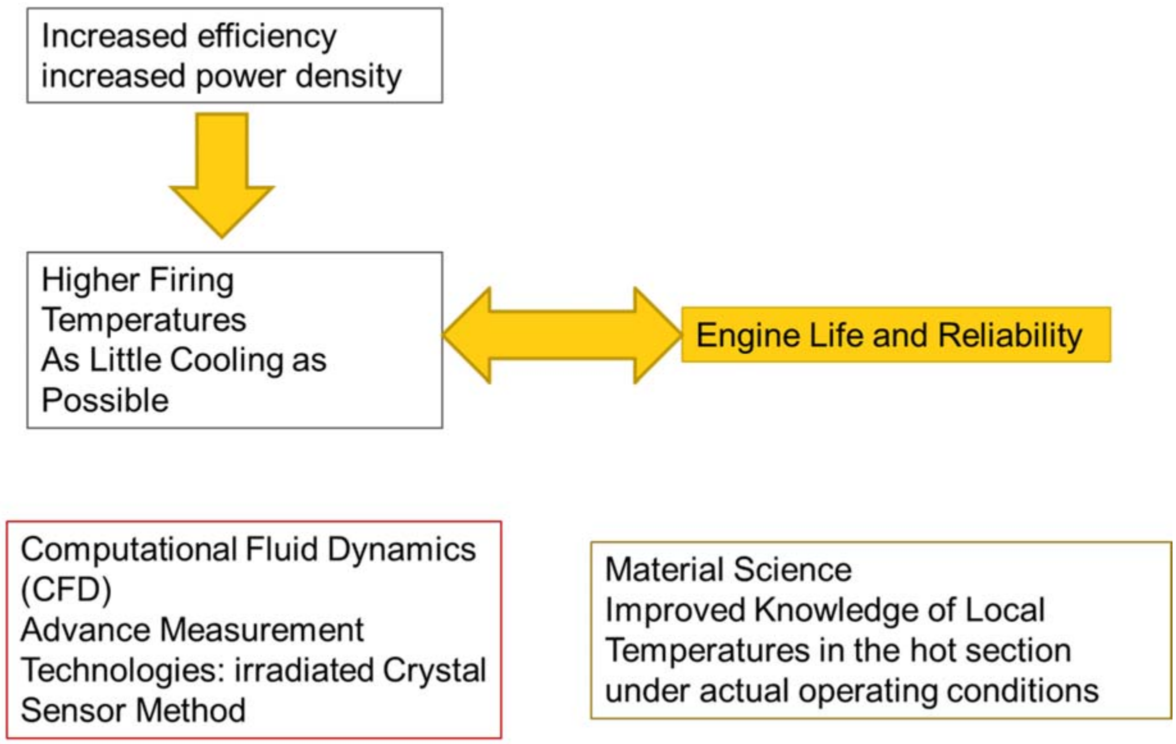

Figure 6: Trade-Offs

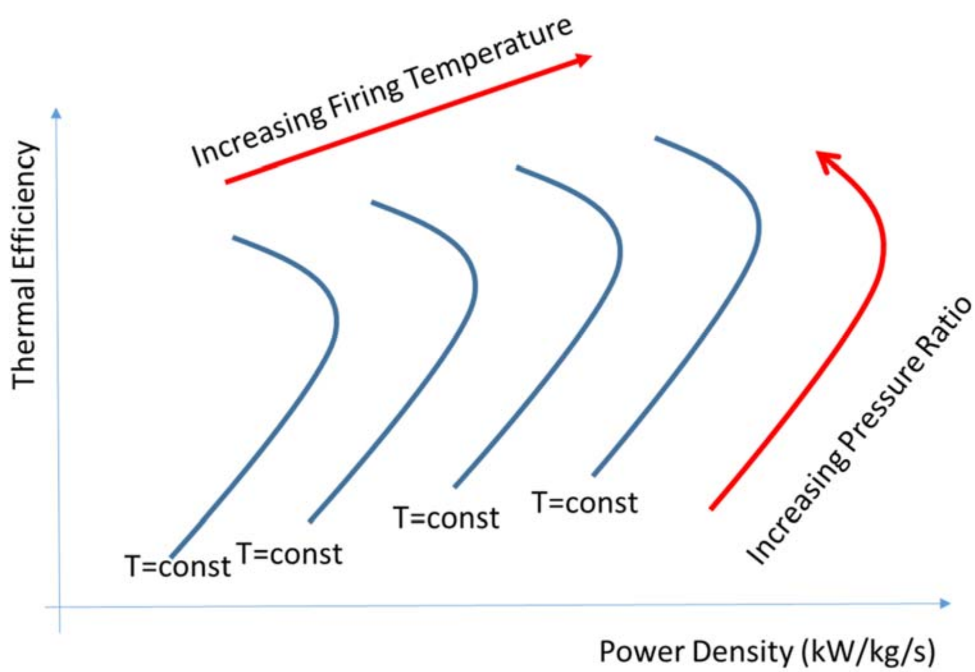

Figure 7: Key Cycle parameters.

Heat Transfer and Cooling

Different methods are used for component cooling (Figure 8). Generally there are two different methods:

1. Removing heat from the blade surface by vigorously cooling the inside of a hollow blade (Convection/impingement cooling)
2. Creating a layer of colder air between the blade surface and the hot gas (film cooling)

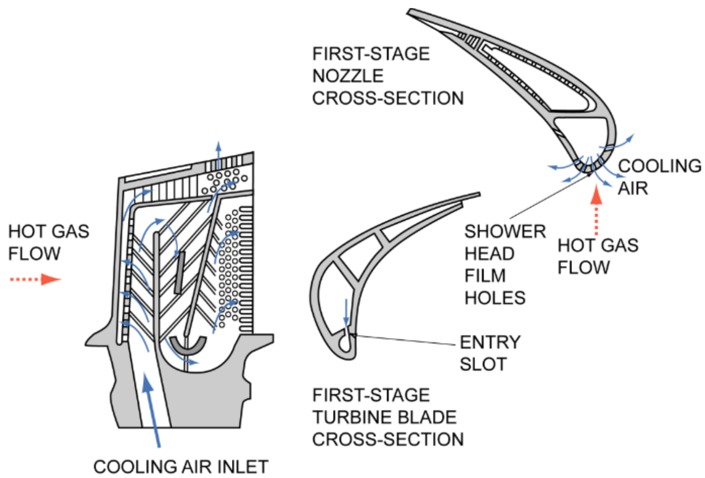

Figure 8: Practical Examples of Blade Cooling Concepts: Convection/Impingement Cooling (left), and film cooling (right)

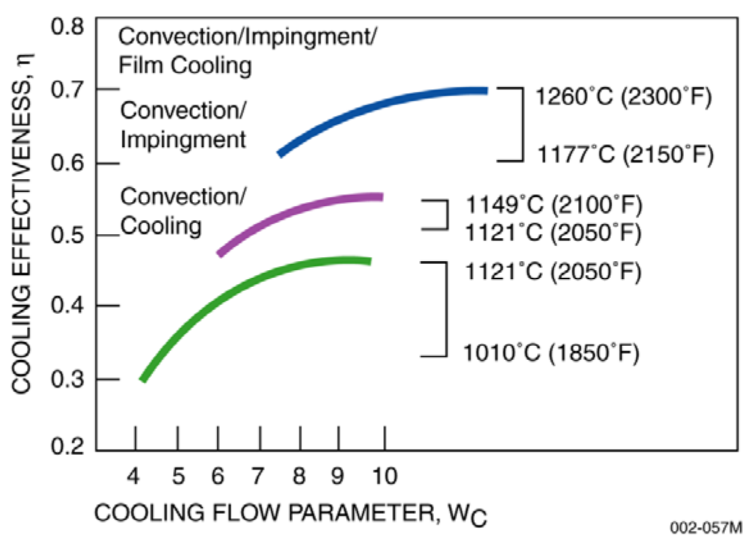

Figure 9: Blade Cooling Effectiveness

Depending on the cooling methods used, and the amount of cooling air expended (Figure 9), significant gas temperatures, and thus firing temperatures, can be allowed while meeting the durability goals of the blades.

Cooling air is a precious commodity, and the amount of cooling air required in itself impacts the performance of the engine. In approximate terms, reducing cooling flow by 1% may improve the power output of the engine by 3%, and its efficiency by 0.4%. Thus, the very precise knowledge of the local component surface temperature under actual operating conditions is necessary to make the best possible use of cooling air. For example, the heat transfer of the hot gas to the blade surface is very intricately linked to the state of the blade boundary layer. Heat transfer in a turbulent boundary layer is significantly higher than in a laminar boundary layer. Intricate 3 dimensional flow structures and vortices, and flow separation bubbles may prevent cooling flow layers from protecting the blade surface. Figure 10 shows the rapid increase in heat transfer when the blade boundary layer transitions to turbulent flow.

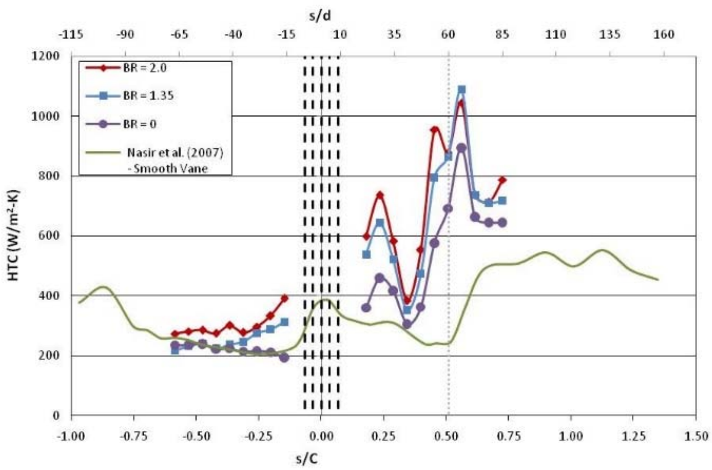

Figure 10: Heat Transfer (HTC) for a Turbine Nozzle along the surface (s/c=0 is the leading edge, positive s/c is the suction side, negative s/c is the pressure side of the airfoil).

The determination of heat transfer from the gas to the airfoil can be accomplished experimentally or with numerical calculations, or a combination of both.

At this point it should be acknowledged how far numerical simulation of gas flow has come in the past years (Figure 11).

From very humble beginnings, the capability to calculate flow behavior from simple one dimensional and two dimensional flows, to 3 dimensional calculations of individual airfoils, to the capability to calculate the flow through an entire compressor or turbine, across stationary and rotating components has provided incredible capabilities to understand and optimize the aerodynamic behavior of turbomachinery. Today, we can additionally determine the unsteady flow behavior, and the interaction of flow and structure in terms of heat transfer (conjugate heat transfer).

While in the past, the most sophisticated tools were limited to the use for the design of aircraft engines (especially for military aircraft), today the same tools are used for both aircraft gas turbines and industrial gas turbines. The capability to determine the three dimensional flow through entire components, coupled with conjugate heat transfer calculations, as well as structural and dynamic calculations is now state of the art (Figure 11). Today, it is possible to model entire compressors, and resolving unsteady flow . Modelling entire turbomachines (for example, the entire compressor of a gas turbine) has to overcome the difficulty that some components rotate, while others are stationary. For the rotating components, the flow from the stationary components appears unsteady, and for the stationary components, the flow from the rotating components appears unsteady. In other words, the code has to deal with unsteady flow (Figure 12). The capability to perform

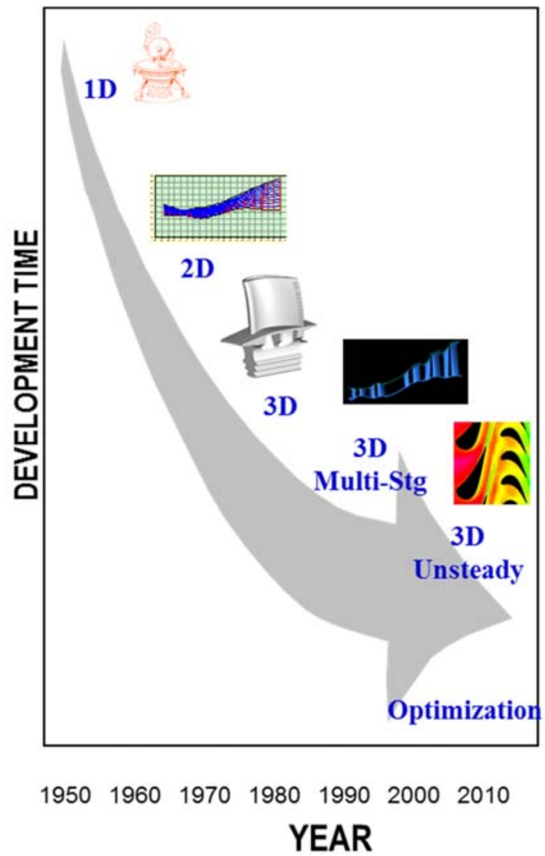

Figure 11: CFD improvements

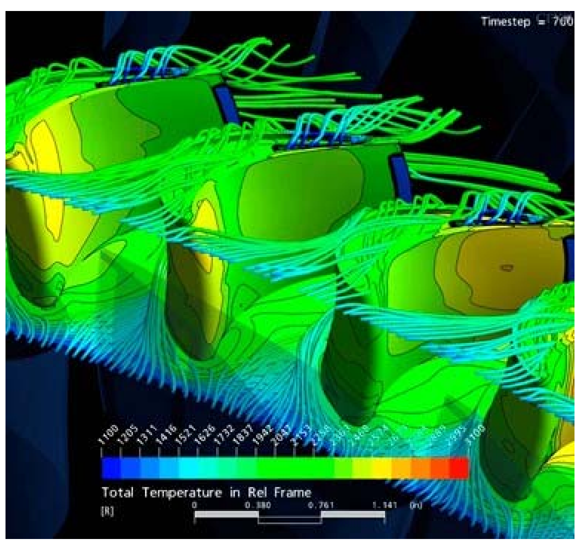

Figure 12: Computational Fluid Dynamic (CFD)
Analysis of the unsteady flow through a turbine rotor

conjugate heat transfer calculations, that is to calculate the heat transfer between a body (like an airfoil) and the gas flow, has great impact in optimizing engine life, cooling air usage, and engine performance. Other classes of problems are also solvable with great accuracy: Flows where chemical reactions occur, such is in the combustor of a gas turbine or gas flows with solid or liquid particles.

To optimize cooling methods, sophisticated CFD simulations have to be performed, that allow detailed studies of the aerodynamic behavior of airfoils and secondary systems.

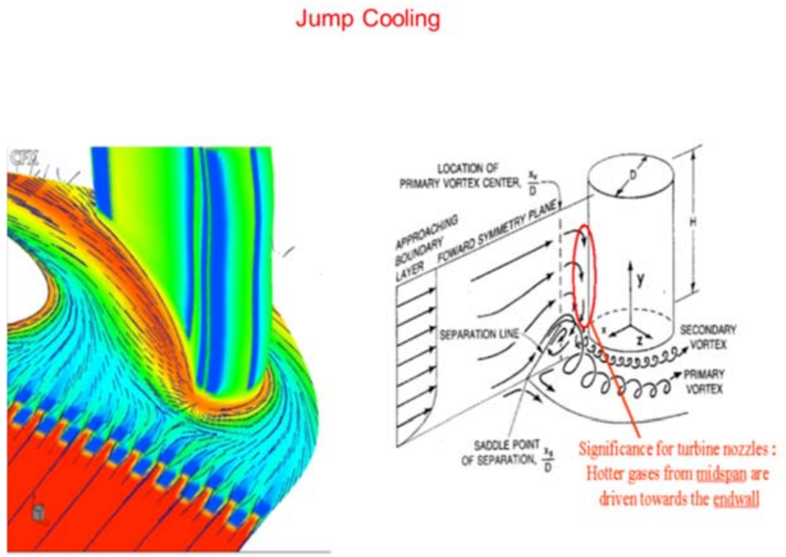

Figure 13: Jump Cooling

The capability to accurately model the three dimensional flow structures allows to tailor cooling flows precisely. Figure 13 shows how a so called horse shoe vortex forms immediately upstream of a turbine blade. Taking the behavior of this flow structure into account allows the use of jump cooling (Figure 13) as an effective way of reducing the exposure of the gas path to high gas temperatures. Figure 14 shows a detailed, numerical visualization of the cooling flows in a film cooled turbine blade.

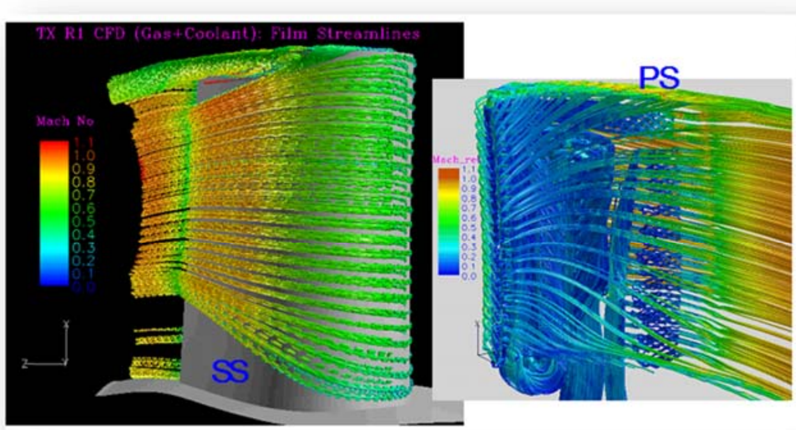

Figure 14: CFD simulation of Turbine section film cooling.

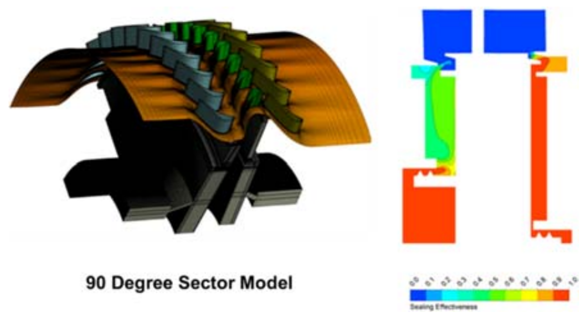

Figure 15: Numerical model to determine sealing effectiveness.

Similarly, the sealing effectiveness has to be optimized carefully (Figure 15). Seals are important within the engine for a number of reasons. Most obviously, seal leakage leads to a deterioration of performance. However, seals also protect engine components from being exposed to the high temperatures of the combustion gases, and they prevent lube oil from entering the gas path. Seal effectiveness, under all possible engine operating conditions is key to engine performance and life.

Experimental Methods

Nevertheless, simulations are only as good as the experimental verification of the results. To determine local temperatures in an engine while it is operating, a number of methods are available:

- -Thermal paint
- -Thermocouples
- -Temperature Plugs
- -Pyrometers
- -IMTK Crystals [2]

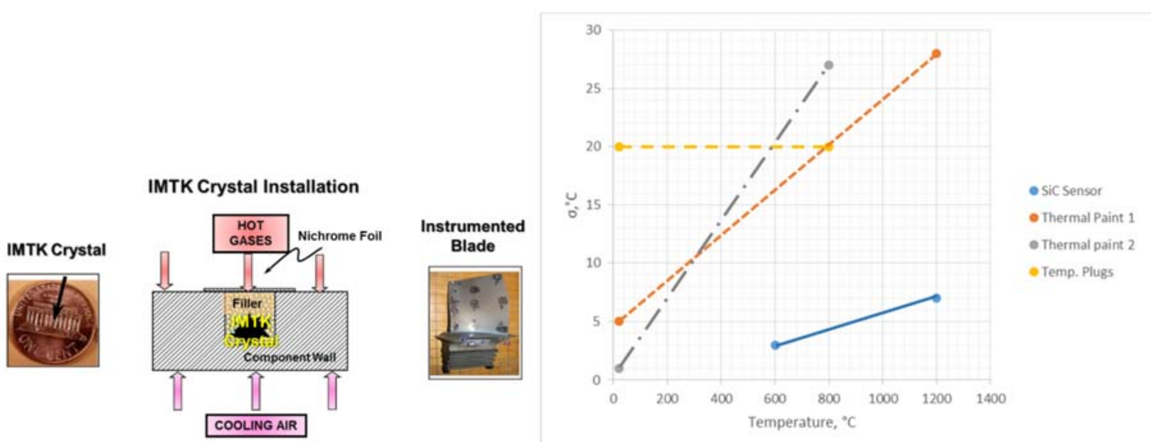

Figure 16: IMTK Crystals for blade surface temperature measurement: IMTK crystal, installation, instrumented blade, and measurement accuracy compared to other methods[2].

One of the key technologies to measure blade surface temperatures during engine operation is the use of radiated SiC crystals (IMTK Method, Figure 16). The crystal lattice is distorted by radiation prior to installing them on the blade surface. Exposure to high temperatures will remove the distortion gradually, depending on the local temperature. The strain can be measured by x-ray diffraction. This allows for temperature measurements in an engine during operation by taking advantage of the very small crystal size, and the fact that no leads have to be installed. Therefore the crystals can be used also in rotating parts. The method provides a significantly more accurate temperature measurement than thermal paint methods or temperature plug methods (Volonsky et al [2]), as outlined in Figure 16.

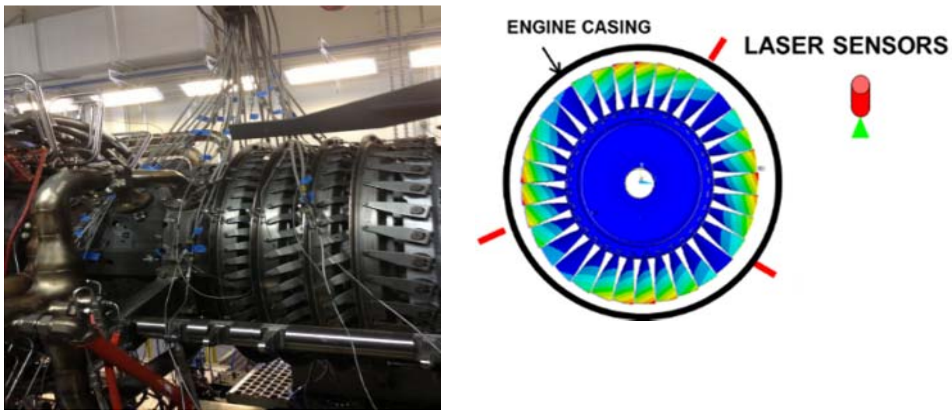

Figure 17: Non-Intrusive Stress Measurement System

Stress

Another important new tool involves the determination of blade vibration behavior in an operating engine. The Non-Intrusive Stress Measurement System, or NSMS, uses laser sensors for determining blade vibration behavior in an operating development engine. Real-time modal response of the rotor is evaluated using laser sensors and the stress level is measured for each blade in situ. This exciting new technique has quickly become a standard in our development process, and is a powerful tool for validating our predictive models, and ultimately improving durability (Figure 17)

Fuel Capability

A key requirement for industrial gas turbines is the capability to burn a variety of gas and liquid fuels. Often, low emission systems are required to meet local regulations. Lean-Premix combustion systems allow to lower NOx emissions significantly compared to conventional systems by premixing fuel and air before they enter the combustor (Figure 18).

One of the essential requirements for a low emission lean-premix system is proper mixing, as well as a thorough understanding of combustor aerodynamics (Figure 19).

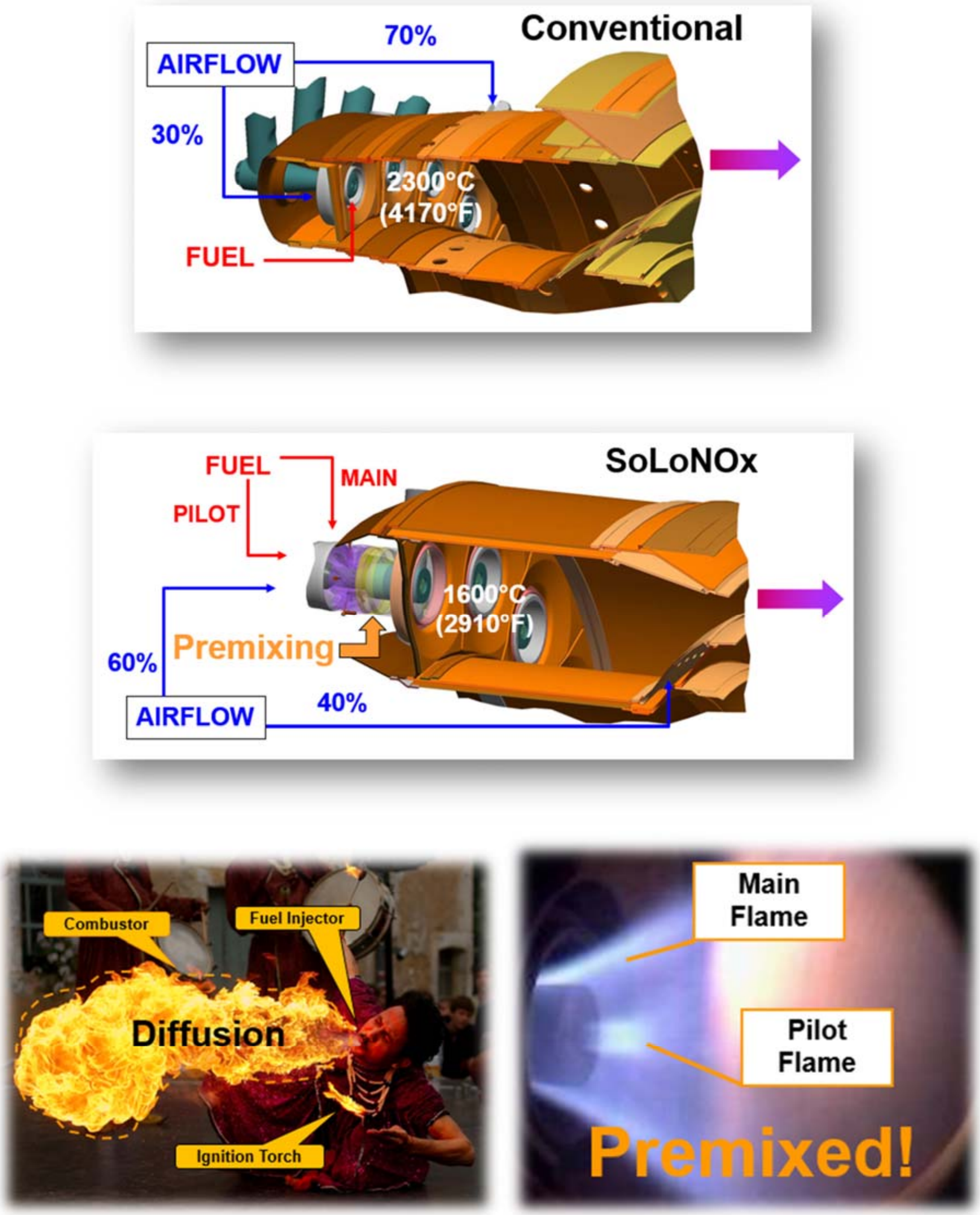

Figure 18: Lean-Premix and Conventional Combustion

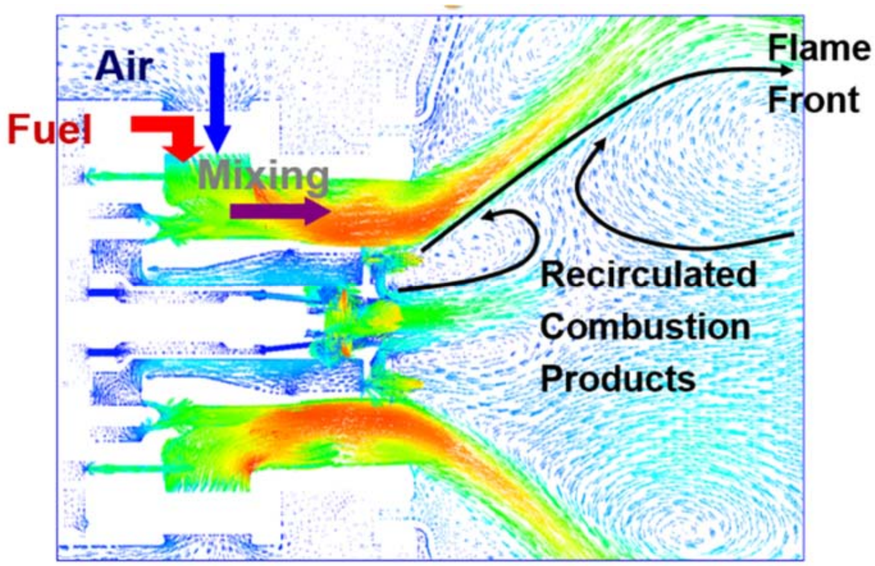

Figure 19: Combustor aerodynamics.

Conclusion

Ultimately, any product is only successful if it adds to the success of its users. Any technology advancements that are introduced need to be judged by this criteria. Therefore the question that has to be answered is: What do the technologies described offer the gas turbine operator?

Some of these are immediately obvious: If the emissions levels don't meet the regulators requirement, the engine cannot be operated.

Low fuel consumption, high power density, high availability and reliability, and low maintenance costs all add to the economic success of compression projects.

In a broader sense, in an increasingly competitive marketplace, user acceptance of gas turbine systems will be under increased scrutiny for economic and environmental benefit.

The use of state of the art and leading edge computational and experimental methods, together with the experience from over 15,000 gas turbines built, allowed to design and build a product that contributes to the success of its operators. Leading edge numerical and experimental methods allow to improve on all trade-offs mentioned in the paper.

References

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