# Unsteady flow visualisation takes the heat out of hot spots

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*The development of codes that can analyse unsteady flows and animation software that enables the visualisation of results has the potential to shave £millions off the cost of designing and operating turbomachinery*

Apart from the huge centripetal forces on turbine blades, hot spots around blades can peak at temperatures above 2,000 K, creating thermal fatigue that can ultimately lead to cracks that can cause blades to snap off. Made from special metals, turbine blades are generally the most expensive component in an engine. Since a set of blades for a large industrial gas turbine, for example, could cost £1 million, any developments aimed at increasing blade life are keenly monitored and assessed by designers and users alike.

Controlling the temperature across the blade can reduce creep significantly. Until now, manufacturers have had to take a very conservative approach to the design of such components and adopt a precautionary route to checking and replacing blades more frequently than may be necessary. This means taking the gas turbine out of service at a cost in excess of £250,000 per day for a large engine. Hence, accurately predicting the interval between inspections can have a massive effect on operational costs.

Hitherto, experimentation and simple CFD analysis have not provided sufficient insight into the flow conditions inside turbine engines, but now codes developed by the Turbomachinery Group of QinetiQ, combined with Fieldview visualisation software marketed and supported by simulation technology specialist Applied Computing & Engineering, enable engineers to visualise the development of hot spots.

In so doing they gain a better understanding of why and where hot spots occur and how to minimise their effects on turbine performance. With this knowledge design changes can be tested and recommendations made to extend blade life. Another benefit is that the turbine cooling air, which can still be at temperatures as high as 850 K, can be directed more accurately. This results in less wasted air which in turn enhances gas turbine efficiency.

If the CFD analysis of unsteady flows adds 50% to blade life and inspections are reduced, cost reductions in the order of £1 million are achievable, over and above any increase in efficiency. Such analysis could also dramatically reduce time to market. Applied Computing & Engineering estimates that conventional experimentation times can be cut by around one fifth. CFD analysis also allows “what if” scenarios to be undertaken before the detailed development work and subsequent manufacture.

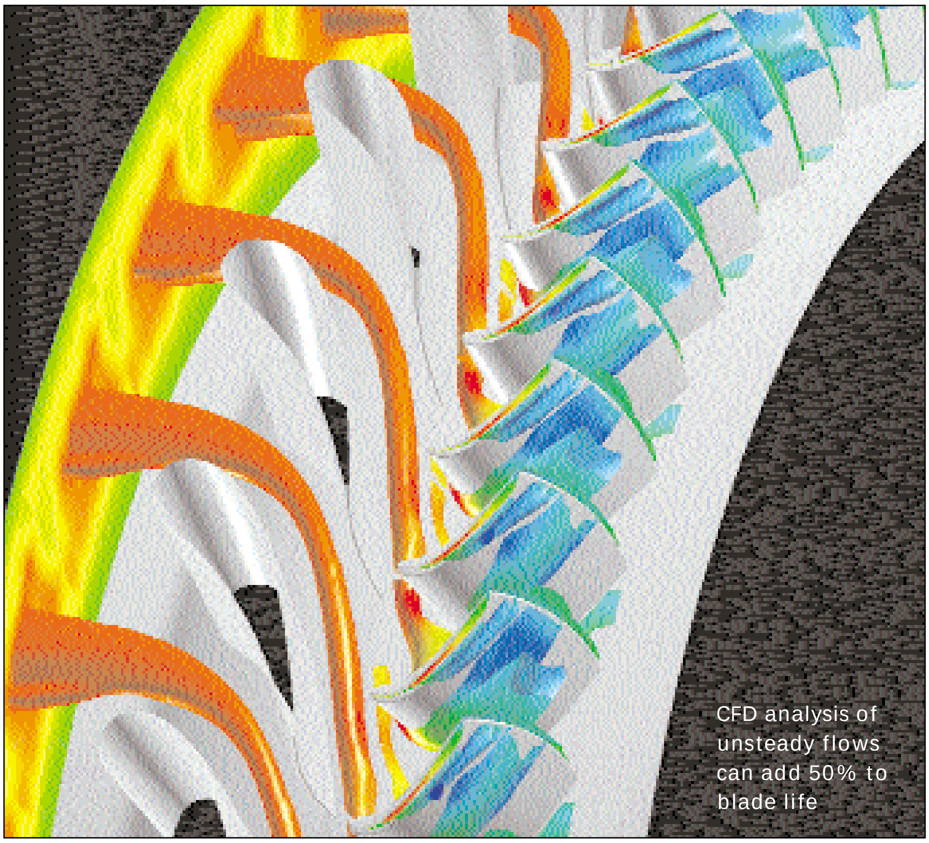
## Unsteady flows

In modern gas turbine engines the combustor exit flow has a non-uniform, temperature profile because of the discrete nature of the injection of fuel and dilution air, and the wall cooling flows. The effect of this non-uniform temperature profile on the aerodynamics and heat transfer rate of nozzle guide vanes (NGV) and turbine blades is difficult to predict; knowledge of this is important for estimating turbine component life and efficiency.

Most advances in gas turbine performance focus on increasing power to weight ratio and cycle efficiency and this tends to drive combustion temperatures upwards. Clearly, the maximum sustainable metal component temperature during operation of the engine limits cycle temperatures. Applications must also withstand components rotating at high speed, with centrifugal blade loadings equivalent to 50,000 times gravitational acceleration.

In such high stress environments creep may occur well below the melting point of the metal, and for engines in which extended service is an important issue, metal temperatures must be minimised. Typical turbine blade metal temperatures are around 1,350 K, while the combustor exit temperature may be as high as 2,100 K for advanced aerospace applications. For creep limited components an error of just 25 K in the predicted metal temperature can half the blade life.

One of the most difficult problems facing the turbine designer is that of predicting heat transfer rates and hence the temperatures of metal components. Temperatures are critical to life cycle and the overall thermodynamic cycle efficiency of the engine. An



CFD analysis of unsteady flows can add 50% to blade life improvement in cycle efficiency comes not just from allowing an increase in the turbine entry temperature but also from a reduction in cooling flows made possible by more accurate temperature predictions.

## Unsteady codes

The flow through a gas turbine engine is complex and unsteady. Alternate rows of stationary and rotating blades chop and redistribute the flow. The box on the facing page explains.

As the non-uniform flow passes through the turbine it is cut by the rotor and this generates an inherently unsteady temperature field. If the air that hits the blade surface is too hot then it will melt it unless the turbine is adequately cooled. Ideally, as little cooling air as possible should be used to optimise efficiency, so understanding where the hot gas impacts the blade surface is key to turbine design.

Conventional steady state CFD cannot model the true passage of these flow features through the turbine and an unsteady code is needed. To be successful in this analysis it is essential to be able to display and animate the results of the unsteady analysis. Although QinetiQ has had its unsteady code available for some time, success with unsteady analysis has only been possible by having powerful visualisation that can accurately animate the large quantities – several gigabytes of data – from such unsteady analyses.

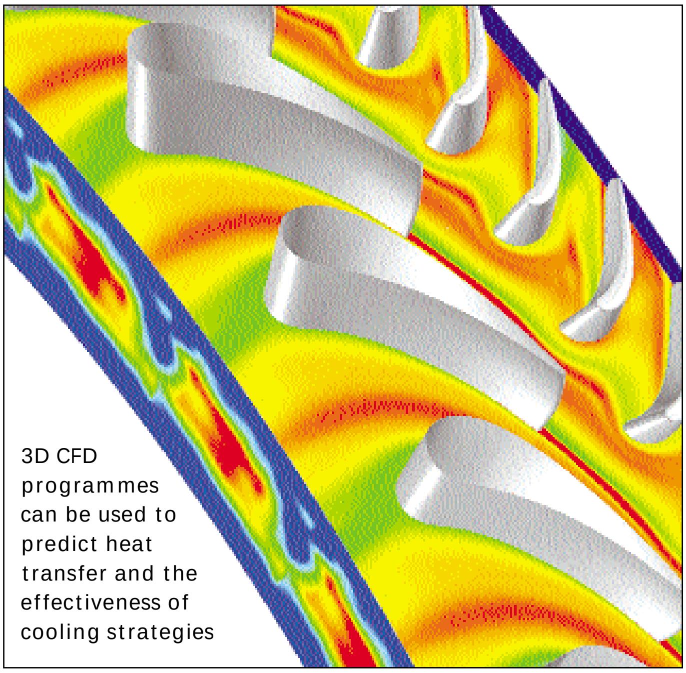
Features in the Fieldview visualisation package, such as particle tracking, are invaluable in tracing the path of fluid from different inlet regions through the turbine. The unsteady analysis coupled with new experimental data gives a better understanding of the flow field in the turbine and will enable future design improvements. The software package is highly flexible and enables engineers to customise, automate and optimise CFD, consolidate multi-step processes, capture formulas and reduce work to a single button.

Fieldview accepts data from in-house codes as well as managing generic file formats to accept data from in-house codes as well as most commercial solvers and is available on UNIX, Windows and Linux.

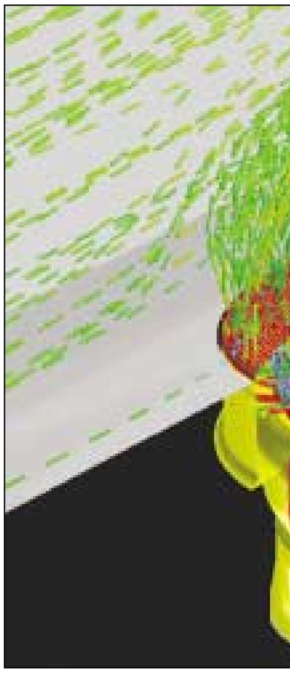
## Reducing costs

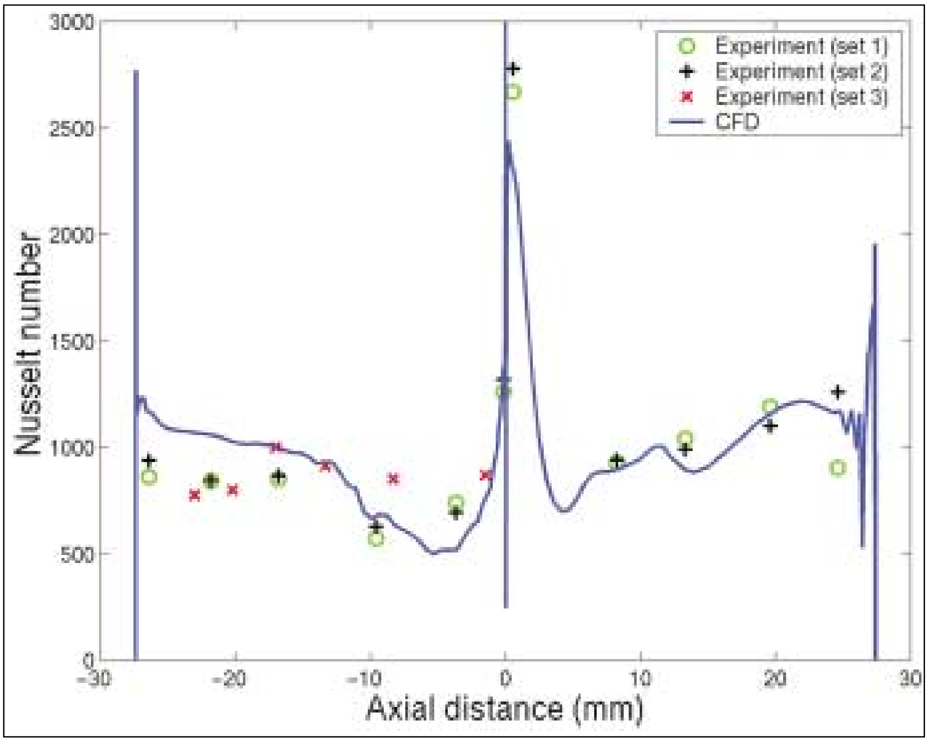
One of the main tasks of the QinetiQ Turbomachinery Group is to investigate ways to reduce component costs. This is often achieved by reducing the number of blades – if performance can be achieved with fewer blades then cost is reduced and manufacture is simplified.

QinetiQ has been using its in-house



3D CFD programmes can be used to predict heat transfer and the effectiveness of cooling strategies






TransCode unsteady CFD code to analyse the flow through a research turbine and Fieldview's unsteady capability allows detailed study of the 3D flow field, enabling changes in the pressure and temperature distributions to be viewed concurrently.

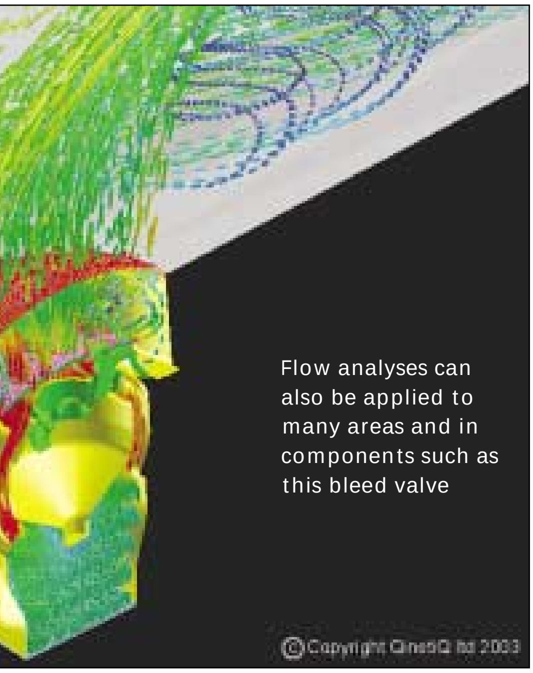
The group has in fact been developing TransCode for the past 15 years and has validated it against a wide range of turbomachinery test cases.

Following this work QinetiQ now offers a range of design and analysis services to industry using a number of in-house developed 1 and 2D design tools, a 3D viscous solver for turbomachinery, and a number of OEM supported 3D codes.

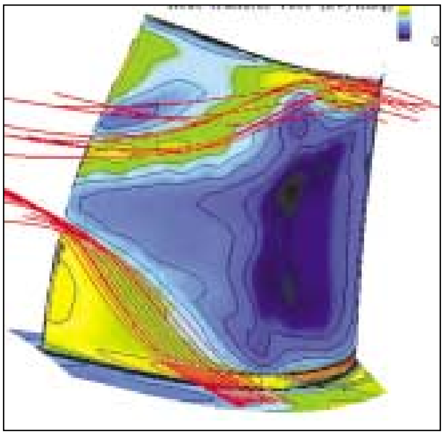
The group's work has led to considerable experience in design and analysis of 3D geometries that aims to reduce losses and increase the efficiencies of compressors and turbines.

Experience includes the modelling of seal and platform leakage flows of compressors as well as unsteady fan aerodynamics. This extends into turbine design where manufacturers need to achieve high aerodynamic loading, minimum heat, load and peak efficiencies.

At the leading edge of rotors and in regions of high turbulence its 3D CFD programmes can be used to predict heat transfer and the effectiveness of cooling strategies.




Flow analyses can also be applied to many areas and in components such as this bleed valve



Above and left: 3D visualisation of the high heat transfer at leading edge and in regions of high turbulence require large computational meshes

Flow analyses can also be applied to other components such as control and bleed valves, and in other areas such as aircraft jet velocity. Similarly, flow simulation can be used to test components. For example, to examine temperature distortion and cooling on turbine blades which can lead to more optimum material choice and possibly lower manufacturing costs through more easily worked metals such as aluminium for example.

QinetiQ's Turbomachinery Group performed the experimental work for TATEF: Turbine aero thermal external flows, a European Union Fourth Framework Programme, to understand the complex aero-thermal phenomena generated in high pressure, intermediate pressure or low pressure turbines. TATEF involved the majority of Europe's leading aerospace and industrial gas turbine manufacturers and aimed to build the associated data bases and to facilitate the validation of improved computational fluid dynamics (CFD) methods.

Ultimately the research will generate an understanding of the limitations of existing turbomachinery models and lead to more cost effective turbine design.

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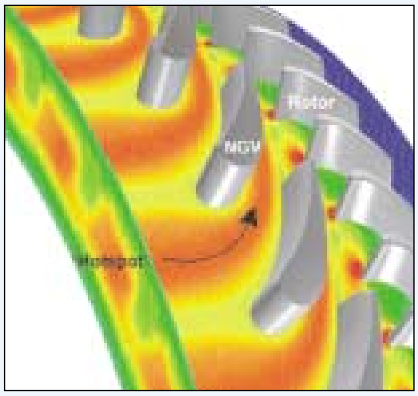
## Unsteady flow

The boundary layer separation at the trailing edge of a vane can cause localised regions of very high unsteadiness, which are generally rather more persistent in nature than the unsteadiness caused by combustor mixing or potential interaction of blade rows. These wakes slowly mix-out as they move downstream, and, because of the relative motion of succeeding blade rows, are chopped to form pockets of high unsteadiness in the exit flow of the succeeding blade row. The unsteadiness associated with secondary flow vortices may be significant for low aspect ratio blade rows. In the transonic turbine, trailing edge shock formation may cause further unsteadiness as shocks impinge on the downstream blade row, although this may be a relatively small affect for modest exit Mach numbers. These effects cause unsteadiness in the boundary layer, which can cause quite marked changes in the aerodynamics and heat transfer to a vane surface. A good model is therefore essential for satisfactory prediction of the aero-thermal behaviour of a vane.

A powerful CFD post-processor capable of handling several gigabytes of data enables users to visualize and understand results and identify important flow features quickly and easily from both steady and unsteady cases.

Display options available make it easy to produce diagrams that are helpful in explaining complicated flow features. An animation feature (below) allows the viewer to follow the flow through the model using coloured streamlines or to tour through the model watching how the flow field develops.

Technical note: all the images provided in this article are from Fieldview. However, for the unsteady analyses reported above, the QinetiQ technical personnel are able to work with full 3D animations of these images to appreciate and better understand the dynamic processes.




The flow around turbine blades in a gas turbine engine is highly unsteady. This is partly due to the forced periodic oscillations in the pressure field as blade rows move relative to each other, and thus occurs at the blade passing frequency