Fluid Flow and Heat Transfer within the Rotating Internal Cooling Air System of Gas Turbines (ICAS-GT2)

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European gas turbine manufacturers operate in an extremely competitive market sector.

The requirement to make efficient use of non-renewable resources and to minimise environmental impact of gas turbine operation is well recognised.

Traditionally, improvements in gas turbine performance have achieved by piece-wise optimisation of individual components.

More recently, the need to optimise gas turbines on a much broader front – including their secondary air systems – has been recognised.
In gas turbines secondary system air is drawn off from compressor stages to cool critical components, seal internal cavities and manage end loads.

This secondary air consumption makes no direct contribution to engine thrust and therefore exacts a penalty on cycle efficiency.

It therefore follows that efficiency gains can be accessed through more effective use of this air.

The ICAS-GT and ICAS-GT2 Projects were initiated to advance gas turbine secondary air systems technology – an area that had previously received relatively little attention from the engineering community.
Gas Turbine Secondary Air System
The ICAS-GT2 Consortium

- The ICAS-GT2 Project combined the resources of 10-major European gas turbine manufactures and 4-major Universities.

- Consortium was composed of:
  
  Rolls-Royce plc  
  Snecma  
  MTU  
  Rolls-Royce Deutschland  
  Volvo Aero Corp.  
  Turbomeca  
  Siemens  
  Alstom UK  
  Alstom CH  
  ITP  
  Sussex University  
  Surrey University  
  Aachen University  
  Karlsruhe University

Rolls-Royce
The ICAS-GT2 Task Scope

To advance gas turbine internal cooling air system design in five distinct – but related – areas:

- WP1: Turbine rim seal flow and heat transfer
- WP2: Rotating cavity flow and heat transfer
- WP3: Turbine stator well flow and heat transfer
- WP4: Turbine pre-swirl system flow and heat transfer
- WP5: Windage and engine parts experiments

In each case the experimental testing was pursued in conjunction with numerical modelling to derive design correlations and validated best practice analysis methods for use in front-line engine design.
Work Package 1, led by Alstom (CH) and supported by Aachen University, MTU and Volvo.

ICAS-GT advanced understanding of ingestion, but significant disparity remained between predictions and measurements of ingestion – particularly at low sealing flow rates.

The presence of low frequency structures (LFS) had been detected experimentally, but their relevance to ingestion was not understood.
WP1: Turbine Rim Seal Flow and Heat Transfer - 2

- Quasi-3D unsteady LDA measurements obtained at the rim seal.
- LFSs were subsequently captured using 360° unsteady CFD.
- Rotationally periodic sector models are adequate at high sealing flow rates.
- New sealing correlation derived to capture the results obtained.
- ICAS-GT2 modelling methods used to design an “optimum” rim seal – tested at Aachen and demonstrated to significantly outperform similar seals tested in ICAS-GT.
WP2: Rotating Cavity Flow and Heat Transfer - 1

- Work Package 2, led by Volvo and supported by ITP, RRD, Surrey and Sussex Universities.

- Rotating cavity flows are relevant to the flow within compressor & turbine disc stacks and are recognised as an extremely challenging application.

- ICAS-GT identified the existence of rotating structures within disc cavities.

- Prediction of buoyancy-dominated flow and heat transfer remained problematical.
First 3-component velocity measurements obtained in the Sussex multi-cavity rig.

Reynolds averaged Navier-Stokes (RANS) solvers used extensively to simulate rotating cavity flows – yielding modelling best practices.

First use of large eddy simulation (LES) at Surrey in rotating cavity flows – results obtained far superior to RANS.

Application of this modelling will permit better control of tip clearance providing corresponding reductions in SFC ~0.25%.
WP3: Turbine Stator Well Flow and Heat Transfer - 1

- Work Package 3 led by Rolls-Royce, supported by Alstom UK, ITP, Turbomeca & Sussex University.

- Rotating flow rig used to investigate shortened & extended foot on inter-stage seal.

- Wind tunnel rig used to investigate the effects of lock plate leakage.

- 3-D Unsteady CFD methods developed to support analysis.
Best design practice identified (superior sealing and cooling of the f’w’d cavity) for inter-stage seal configuration.

Novel rear disc cooling strategy identified (R-R patent) – which is also applicable to HP & IP turbine discs.

Computational methods significantly advanced and CFD best practices documented.
WP4: Turbine Pre-Swirl Flow and Heat Transfer - 1

- Work Package 4 led by MTU, supported by Alstom CH, Karlsruhe University and Siemens.

- Testing undertaken on an updated pre-swirl facility at Karlsruhe, including Cd, heat transfer and particle separation tests.

- CFD modelling undertaken using quasi-steady & unsteady methods on a range of CFD codes (FLUENT, CFX, TASCFLOW)
WP4: Turbine Pre-Swirl Flow and Heat Transfer - 2

- Verified CFD methods for simulating turbine pre-swirl systems.
- CFD best practices – including evaluation of quasi-steady methods.
- 1-D pre-swirl model for use in front-line system design.
- Separation functionality of pre-swirl systems was demonstrated.
Work Package 5 led by Snecma, supported by ITP, RRD, Sussex University.

Windage losses generated by protrusions in rotating cavities.

Engine parts experiments
- LDA measurements in actual engine cavities
- Shutdown transients

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Windage losses measured relative to plain disc and a range of static and rotating protrusions studied and correlated.

Some throughflow-dominated configurations develop less windage than plane disc.

Windage correlation suite will provide more accurate estimates of windage losses, providing the incentive for more aerodynamic cavity designs.
Value of the Programme - SFC

- Target reduction of 1% SFC
  - Turbine rim sealing -0.3% ✓
    - improved understanding and modelling of ingestion.
  - Turbine stator wells -0.25% ✓
    - design best practice advanced & new disc cooling strategy.
  - Pre-swirl systems -0.3% ✓
    - improved understanding and modelling methods.
  - Others -0.15% ✓
    - More rigorous appreciation of windage SFC exchange rate => more aerodynamic cavities -0.075%.
    - LES => improved tip clearances applicable to IP & HP compressor & LP turbine could translate to -0.25%.
Value of the Programme – Design Cycle

- Target to reduce design cycle times towards 24-months
  - CFD modelling best practice guidelines
    - valid range for rim seal sector models
    - use of LES in rotating cavity flows
    - quasi-steady simulation of turbine stator wells
    - quasi-steady simulation of pre-swirl systems
  - Characterisation of complex flow and heat transfer
    - 1-D seal model developed & demonstrated by Alstom (CH)
    - rotating cavity shroud heat transfer correlations
    - 1-D pre-swirl model
    - windage correlation suite
The ICAS-GT2 Consortium worked together throughout the Project in an exemplary manner - at times in adverse circumstances!

This has resulted in strong inter-organisational & multi-national bonds being made and maintained between the Partners.

Mobilisation of the Consortium’s the combined resources allowed the research to progress at a much faster pace and over wider scope than could have been achieved by any of the individual Partners.
Current Status and Way Forward

- Project results disseminated via conferences.
- EC will distribute e-TIP via CORDIS

- Examples of areas for further ICAS-GT2 Exploitation
  - wider LES application.
  - development & testing of improved TSW cooling strategies.
  - further consolidation of pre-swirl design technology.
  - use of windage data to support the design of more aerodynamic cavities, e.g. shielding of service pipes etc.
  - heat transfer augmentation in rotating cavities.

- Primary-secondary interactions/spoiling will be investigated within the 4-year MAGPI programme (*spiritual successor to ICAS-GT2*).
Acknowledgement & Questions

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