

**ADVANCED DESIGN METHODOLOGY USING COMBINED
COMPUTATIONAL/EXPERIMENTAL TECHNIQUES FOR
GAS TURBINE FILM COOLING**

Final Report

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Experiment” Methods for Rapid Design Evaluation. Each task contains closely coupled, fully integrated series of computational simulations and laboratory experiments which yield two-way comparison of results. In most cases, other measurements found in the open literature are brought in to make three-way comparisons in order to validate the newly developed techniques at Clemson. Every task and sub-task in the proposed research has been addressed and completed successfully. Significant progress was made in understanding the interaction between cold jets and hot crossflow which is at the heart of film cooling. This is evidenced by a large number of refereed technical papers published by the Clemson Team. The major accomplishments include the following:

- A comprehensive computational methodology was developed and refined to yield consistently accurate results with impressive internal consistency. This methodology was shown to predict the relative performance of film cooling configurations reliably thus demonstrating its potential to become an effective design tool.
- A new experimental technique was developed based on a combined use of thermochromic liquid crystals and foreign gas injection. The method, which was shown to reproduce data obtained by more conventional measurements, is capable of providing continuous data (not just at discrete points) for both η and h .
- A novel vorticity based data processing technique is introduced in the post-processing stage which has proved to be extremely effective in capturing the combined effects of a large number of geometric and flow parameters influencing the behavior of coolant jets.
- Lessons learned in the study of all the fundamental configurations were brought together to form a set of design guidelines to help the practicing engineer to reduce the design cycle time and cost. Sufficient information is provided to enable film cooling designers dial-in the coolant behavior desired in practical applications through vorticity control.

This final report provides a complete documentation of all the activities carried out in the course of this research project. Five major sections following the Executive Summary contain detailed explanations of every task promised in the original proposal. Brief explanation of the highlights in each of these sections is provided next.

Section 1 is devoted to all the computational development activities combined with slot-jet and discrete-jet film cooling studies involving a row of cylindrical holes with streamwise injection. A proper modeling technique found to be especially effective in film cooling is established first. Next, a NURBS based geometry capturing approach which enables realistic configurations to be replicated in computer simulations is provide. A grid generation methodology which is capable of filling a complex domain with high quality finite volumes is

established in this section and expanded on other sections for different film cooling configurations. Finally, the role of the first-and second-order accurate discretization schemes is established and turbulence modeling issues for closure are addressed. Essentially, this section captures the original set of “trail blazing” operations involving 2-D slot and 3-D cylindrical jets. Important conclusions reached in the studies associated with this task are:

- The simultaneous inclusion of supply coolant plenum, film-hole, and crossflow regions is of critical importance in the accurate treatment of this class of problems;
- The counter-rotating vortex structure downstream of the coolant injection site is the most significant mechanisms affecting the film-cooling performance in the streamwise injection cases;
- Vorticity contained in the boundary layers within the film-hole is the origin of the mechanism responsible for the counter-rotating vortices.

Section 2 is designed to describe the experimental methodology development effort in much the same as Section 1. Both slot-jet and discrete-jet cases are used to demonstrate the relevant aspects of a unique measurement technique. The test section design and preparation for liquid crystal application along with the data acquisition and processing systems are explained in detailed. A very large volume of measured results are included to expand the existing database and to provide code validation quality data.

Section 3 isolates the effects of compound angle (Φ) on adiabatic effectiveness and heat transfer coefficient distributions downstream of a row of round holes. For the first time in the open literature, detailed surface and field results are included to explain the complex interaction and fundamental alterations as Φ varies between 0 and 90 degrees. The well-known symmetric counter-rotating vortex structure associated with streamwise injected jets becomes increasingly asymmetric as Φ deviates from 0° and becomes a single dominant vortex at $\Phi=90^\circ$;

Section 4 is devoted to the study of the effects of shaped holes with streamwise injection. A special sub-section is dedicated to an isolated look at the influence of inlet an exit region shaping in slot-jets. This is followed by a row of shaped holes with lateral (LDIFF) and /or streamwise (FDIFF) diffusion. LDIF provides the best coverage and adiabatic effectiveness of the five film cooling configurations. FDIFF performs well along the centerline, but does not spread well in the lateral direction. Coolant lift-off in the reference case (round holed with streamwise injection) described in Section 1 is effectively eliminated in LDIFF and FDIFF. Mechanisms responsible for all the result are explained fully.

Section 5 describes a study that combines the effects of compound angle injection with hole shaping. It is believed that a novel configuration can be generated by taking advantage of the positive aspects of both compounding and shaping. This combination proved to be highly non-linear. Flow features not seen in compound angle round hole (Section 3) and streamwise injected shaped hole. (Section4) studies appeared for the first time in the compound-angled shaped holes. Also, flow conditions at the coolant jet exit plane are even more non-uniform than those observed in studies conducted in previous tasks.

The methodologies developed in the present research creates effective design tools to screen out film cooling configurations with good potential. All aspects of the computational approach should be readily available to the turbine heat transfer designers. Given the extremely detailed description in this report, which is necessary for simulations to be successful, the end users should be able to make full use of the useful practices developed here. The present effort shows that computational methods, with great care and attention to minute details, can generate consistent results and give reliable information regarding relative performance of many film cooling configurations of interest to designers. Similarly, the fast turnaround time experiments make it possible to receive feedback on effectiveness of film cooling designs. The technique developed here eliminates two well-known stumbling blocks in experimental approach, namely, the long time requirement and overall cost issues. It is recommended that a combined computational experimental approach be followed to optimize the design process.