UPGRADE OF THE OXFORD HIGH-SPEED LINEAR CASCADE (HSLC) FACILITY

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ABSTRACT

The High-Speed Linear Cascade (HSLC) blowdown facility at the University of Oxford has been used extensively to study over-tip leakage flows in High Pressure Turbine (HPT), including both aerodynamics and thermal performance (e.g. Mutekwa et al. [1]). This paper describes a recent upgrade of the facility, featuring an entirely new test section, control system, and data acquisition hardware. The primary requirement for the test section redesign is to enable variations in inlet angle, blade profile and pitch-to-chord. A modular approach incorporating interchangeable cassettes has been developed. Further physical improvements have been made to the tip clearance setting mechanism, bleed systems, periodicity, accessibility, inlet flow conditioning, and measurement capabilities. A CO_2 coolant feed system has also been commissioned. New DAQ and control systems have been implemented, enabling improved logic for safety, better stability of operating setpoint, and integration of all measurements and data logging into a single LabVIEW program. Commissioning data is compared to key results from the previous test section, including aerodynamic measurements of the downstream flow field, Film Cooling Effectiveness (FCE) and Heat Transfer Coefficients (HTC).

INTRODUCTION

In gas turbines, the tip region of the High-Pressure Turbine (HPT) blades is a primary life limiter because they tend to suffer thermal degradation from hot combustor exit gas leaking over the tip. This degradation typically limits combustor exit temperatures and therefore cycle thermal efficiency. Thus, there is a pressing need to develop better tip cooling schemes, while mitigating the loss of HPT aerodynamic efficiency from the tip leakage flow. The HSLC is a medium-duration (90-120 second runtime) blowdown facility which operates at representative Mach and Reynolds numbers, with independent coolant feeds. While the cascade cannot replicate the relative motion of the blade, this approach offers an excellent balance of rapid test capability, measurement accessibility and well-conditioned flow.

VARIABLE BLADE GOEMETRY

The blade tip sections of HSLC are rapidly interchangeable, but the root blade profile and inlet angle of the previous test section were fixed and could only be changed by full rebuild of the test section (e.g. O'Dowd [2] vs. Saul [3]). The HSLC upgrade is primarily designed to increase flexibility, allowing different blade section and flow angles to be studied, for example to investigate alternative aeroengine architectures such as geared turbofans. The upgrade (Fig. 1.a) allows the inlet angle to be varied between 0°-50°, and a modular cassette design allows for changes in blade profile, pitch and tip geometry. These cassettes are designed with built-in tip clearance adjustment. In addition, the new test section incorporates an improved modular variable-porosity grid upstream, to control both total pressure and turbulence profiles. The entire test section sits on linear guide shafts which allow it to be pulled to the edge of the test section tank for greater accessibility. The design of the facility was informed throughout by Computational Fluid Dynamics, Finite Element Analysis, and analytical models.

BLOWDOWN CONTROL SYSTEM

The facility inlet total pressure, and thus exit Mach number, is controlled by an upstream valve, which must progressively open as the feed tanks drain. The previous control system used a simple Proportional-Integral-Differential (PID) controller, which had to be manually tuned for each set point. The new control system features a calibrated Feed-Forward (FF) control in tandem with a PID, which only needs to make small corrections to achieve the setpoint. The FF system uses a system map of setpoint pressure vs. tank pressure vs. valve position and can be used to minimize the effect of transients on the operating condition, as can occur during the operation of the upstream heater mesh (see below). This approach allows reliable, automatic control across a range of exit Mach numbers from ~0.4 to transonic.

AERODYNAMIC AND THERMAL MEASUREMENTS

Aerodynamic pressure, velocity and flow angle are measured with four-hole probe area surveys at half an axial chord downstream of the trailing edge (e.g. sample total pressure loss traverse on the right of Fig. 1.b). The probe is calibrated for a pitch and yaw angle range of ±40° and Mach numbers between 0.4 and 1.3.

FCE on the blade tip is measured using a Binary Pressure Sensitive Paint (PSP) technique (e.g. sample tip FCE distribution on the top left of Fig. 1.b). The three central blades are fed with up to three coolant lines of oxygen-depleted gas. In the past this used N_2, but this system has been upgraded to use CO_2 to better represent coolant to mainstream density ratios. The luminescence emitted by the binary PSP varies due to oxygen quenching when the paint is excited by an ultraviolet (UV) light source. The PSP formulation also includes a temperature-sensitive component that emits at a different phosphorescent wavelength, enabling correction for surface-temperature [4]. A foreign gas, such as CO_2 or N_2, displaces the air close to the surface and forms a near-wall film. This reduces the local oxygen partial pressure and therefore increases the emitted light intensity, I, from the PSP. Once the tunnel has reached steady-state, a BigEye charge-coupled device camera records 30 frames for both the red PSP band at 610±10 nm, and the green PSP band at 560±10 nm. The PSP intensity is calibrated over a pressure range of 0.25–2 bar and at temperatures of 15°C, 20°C, 30°C, and 40°C to cover the conditions encountered in the tunnel.

The tip HTCs are calculated with Oldfield's impulse-response 1D flux reconstruction method for heat flux [2] by providing a 15°C step change in mainstream temperature via an upstream heater mesh (e.g. sample tip HTC distribution on the bottom left of Fig. 1.b). The tip is coated with a high-emissivity black paint, and the temperature change is measured with a FLIR AC655SC infrared camera through a Germanium window. Discrete deconvolution and Fourier transforms are used to obtain the filter impulse responses. The acquired temperature data are calibrated in-situ using a thermocouple mounted on the blade surface. This method assumes one-dimensional, semi-infinite heat conduction, which is justifiable with the current low-conductivity plastic blade tips. The HTC is subsequently calculated for each pixel using a regression analysis of the heat flux against the surface temperature measured by the IR camera. The slope of this regression gives the HTC, while the x-intercept corresponds to the adiabatic wall temperature, T_{ad}.

The full paper will give detailed information on the new facility periodicity, inlet conditions, and compare these key measurements to the previous build.

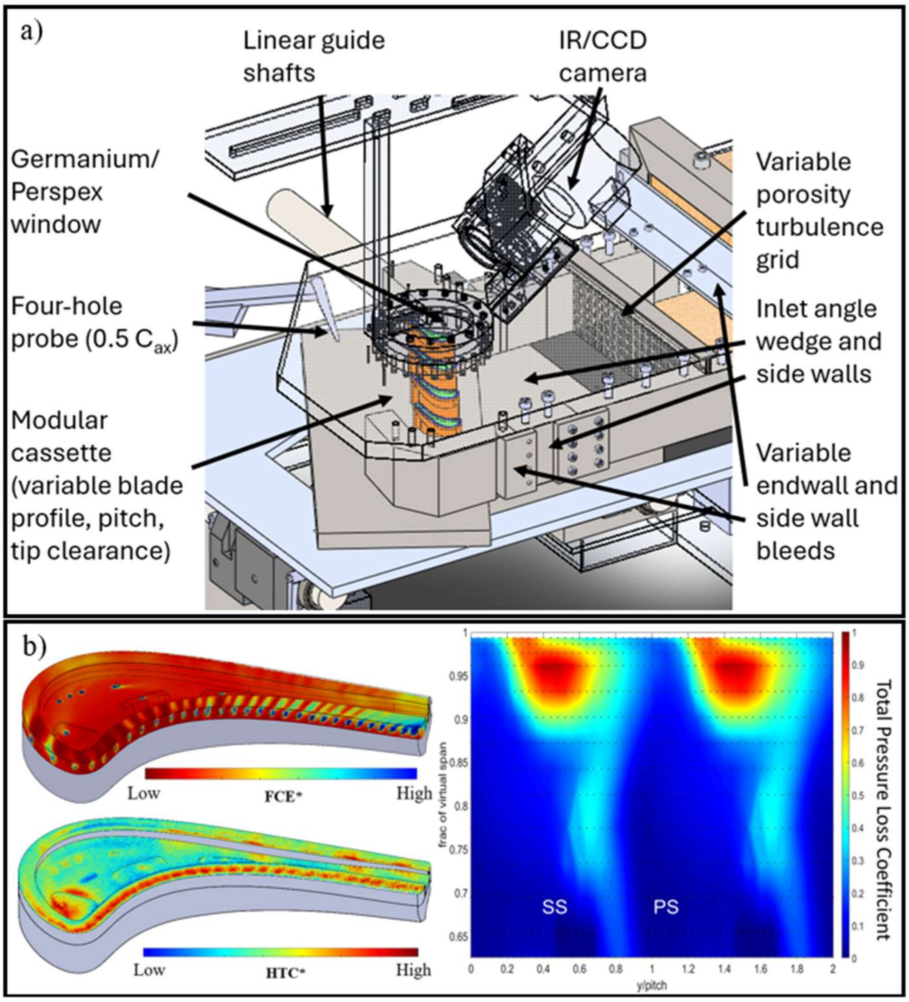

Figure 1. (a) High-Speed Linear Cascade Upgrade Design, and (b) Sample Results for FCE and HTC (Left), and Total Pressure Loss (Right) [6]

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