DEVELOPMENT OF A LARGE-SCALE OPEN GEOMETRY FOR SQUEALER TIP COOLANT INJECTION RESEARCH

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ABSTRACT

Optimizations of coolant flow injection and squealer tip geometries have highlighted the importance of combined aerothermal effects on the overall efficiency of turbine tip design. In this work, a large-scale symmetric canonical axial turbine squealer tip model is developed, which allows for the investigation of incoming gas path flow interaction with coolant flow injected into the squealer cavity. The model is developed to investigate Reynolds numbers on the order of one million for their applicability to novel supercritical CO₂ cycles. Geometric parameters and instrumentation features are discussed to allow for replication and benchmarking of measurement techniques. Coolant is injected from a pressurized plenum, isolating the effects of the coolant injection development from the secondary air source. A backward-facing injection near the squealer rim at the leading edge along the centerline is studied with RANS, URANS, and IDDES models, and their results are compared.

KEYWORDS
URANS, IDDES, Supercritical CO₂, squealer tip, coolant injection

NOMENCLATURE
ALTP Atomic Layer Thermopile
IDDES Improved Delayed Detached Eddy Simulation
LEAF Linear Experimental Aerothermal Facility
M Mach Number
NPT National Pipe Thread
PETAL Purdue Experimental Turbine Aerothermal Laboratory
PIV Particle Image Velocimetry
Re Reynolds Number
TIGER LILY Tip Gap Experimental Research of Large-scale Injection Layouts
(U)RANS (Unsteady) Reynolds Averaged Navier-Stokes

INTRODUCTION
While the reduction of tip gap losses in turbines has improved over recent decades thanks to better numerical analysis and optimization tools, there still exists a difficulty in performing highly spatially and temporally resolved measurements of the over-tip flows and their interaction with coolant
injection. With the advent of advanced design cycles, like the semi-closed direct supercritical CO2 cycle (Allam, et al. 2013), gas densities are higher, machinery is more compact, and the impact of secondary flows and tip losses poses a risk to efficiency and component life if the underlying flow mechanisms are not adequately understood.

The scale of a production-sized airfoil in a cascade can make it challenging to perform spatially resolved measurements; that is not to say that experimental campaigns have not been undertaken to analyze over-tip flows. Data from Texas A&M University (Rezasoltani, Lu and Schobeiri 2015) numerical and experimental results for varying rotational speeds, blowing ratios, and tip configurations of a research turbine for which some geometric parameters are given. This turbine, however, has an aspect ratio of just above three and a reported Reynolds number of $Re = 220,000$.

For high Reynolds number design and analysis of squealer tip flows, computational investigations are the most often used tool, evidenced by recent optimizations (Wang, et al. 2015), (Ma, et al. 2017), (De Maesschalck, et al. 2019), and (Duan and He 2020). Many of these optimizations and in-depth analyses of squealer tip flows are done using RANS solvers, which are known to have diminished accuracy in the regime of globally unstable and separated flows, such as those seen in the tip gap of a turbine (Menter 2012). A comprehensive understanding of the following physical mechanisms is required to enable more efficient designs: the structures emanating from the separation over a squealer tip rail, the interaction with the rail, the interaction with tip cooling flow, and the propagation downstream in and out of the squealer cavity. Scale-resolving simulations and experimental data from a standardized model must be symbiotically utilized to advance understanding of these phenomena and how they can be manipulated for performance benefit. This work proposes a new canonical model for investigating high Reynolds number tip flows, which can be readily implemented into an axial wind tunnel test section, such as the Linear Experimental Aerothermal Facility (LEAF) at the Purdue Experimental Turbine Aerothermal Laboratory (PETAL) (Paniagua, et al. 2019).

**RESEARCH APPROACH**

The present work introduces the Tip Gap Experimental Research of Large-scale Injection Layouts (TIGER LILY) test article, which is designed to serve two major purposes:

1. Create a canonical test article capable of developing specific flow features characteristic to turbine tip cooling flows on a scale large enough to be investigated with optical techniques alongside traditional aerothermal measurements.

2. Investigate the high Reynolds number over-tip flow interaction with coolant injection near a squealer rail on the order of magnitude of Reynolds numbers in supercritical CO2 turbines.

The TIGER LILY model meets these purposes through a geometric combination of a cylinder of 250 mm diameter as the leading edge and a slightly modified NACA0012 profile of 250 mm in chord. This combination of shapes allows for a model that has specific qualities of a cylindrical blade: the large leading-edge radius allows for high Reynolds numbers; a horseshoe vortex develops at the leading edge and propagates down the passage along the airfoil body as secondary flows grow; whether by clocking of the test article or conditioning of the inflow, a pressure differential across the tip can be obtained if desired; and the trailing edge produces a wake. The investigation of coolant schemes is customizable, and the integral plenum allows for tailoring injection pressures and blowing ratios. TIGER LILY does not attempt to create a pressure distribution or loading profile across the body as would be seen in a typical turbine passage, and this is deliberately done to create a geometry
that can be easily scaled to fit into a linear wind tunnel for benchmarking purposes, where the reproduction of the flow features mentioned above is a way to verify measurement techniques. Further, the leading-edge shape and injection layout provides local flow similarity to what would be seen in a squealer tip, with the ability to change injection layouts to explore injection-rail interaction, injection-injection interaction, symmetric cooling effects, and non-symmetric cooling effects. The ability to vary these will enable researchers to benchmark measurement techniques, wind tunnels, and investigate fundamental flow phenomena that are generally present on scales too small to accurately spatially resolve.

Design Tools

The design of TIGER LILY is multi-faceted, pairing machine design considerations with the desired aerothermal goals. A driving factor of the design is that of the plenum and pressurization method. Multiple design iterations are investigated using Numeca’s unstructured CFD solver FINE/Open to evaluate the plenum pressurization source flow on the development of the flow through the coolant tubes and into the squealer cavity. Specifically, a pressurization method is desired, which prevents the pressurized jet from directly impinging on the coolant holes and leaves the flow as quiescent as possible so that the driving factor in coolant injection flow is the blowing ratio between the plenum and the over-tip flow.

Following the plenum and machine design of TIGER LILY, ANSYS Fluent is used to investigate the aerothermal qualities of a single backward-facing injection source near the squealer rim at the leading edge. Fluent is used for the RANS, URANS, and IDDES computations and post-processing contour plots. Routines are written in MATLAB for frequency analysis and comparison of pressure profiles across the model. All MATLAB routines use standard libraries, except for the pressure profile reconstruction of Figure 4, which uses a Kriging script freely available on the MathWorks File Exchange by (Schwanghart 2010).

DESIGN OF THE TEST ARTICLE

Main Design Parameters

Figure 1 displays a 3D view of the TIGER LILY model. The design model size is governed by the following constraint when considering the LEAF test section at PETAL: the model should not create transonic flow in the test section at an inlet Mach number of \( M = 0.25 \). The LEAF test section measures 230 mm wide by 170 mm tall, and the TIGER LILY model in the test section measures 80 mm wide by 165 mm tall, allowing for a 5 mm tip gap between the top of the squealer rail and the top of the LEAF test section and creating \( M \approx 0.55 \) flow around the sides of the airfoil shape with a total area blockage of 28.76%. Further geometric definitions for the main airfoil shape are included in the planform view in Figure 1. The airfoil leading edge is defined by a cylinder of diameter 250 mm. The NACA0012 non-cambered airfoil defines the sides of the airfoil shape. The NACA0012 profile is split into an upper and lower side and translated out 40 mm to meet the edge of the cylinder. The 80 mm total width results from the aforementioned area analysis to avoid transonic flow. Aft of the area of maximum thickness, the NACA0012 profile is slightly modified to ensure continuous curvature along the profile to meet a blunt trailing edge of width 15% of the maximum airfoil thickness. A circular trailing edge is created tangent to the blunt edge to form a continuous curvature airfoil with a total chord of 250 mm. The blending of the leading-edge cylinder shape into the NACA0012 body is facilitated to not cause flow separation around the airfoil body. A fillet that is 15% of the model thickness is employed between the two shapes, causing local flow acceleration around the model but no separation. Figure 2 shows a plot of wall shear stress versus streamwise coordinate for
a slice taken at the midspan of the model. Inset in the upper right corner is a surface contour plot scaled to [0, 1] Pa to show that along the surface of the airfoil, there is no negative wall shear stress indicating separation. Slight patches in the squealer cavity and at the hub secondary flow development show decreased shear stress, but it is readily seen in the graph that, though there is flow deceleration after the fillet peak, it is not so extreme as to cause flow separation.

Figure 1: TIGER LILY pieces (a) and entire 3D assembly (b)

Figure 2: Wall shear stress on model surface
TIGER LILY is comprised primarily of two pieces: a base airfoil (Figure 1(a) – grey body), which is mounted to a plate to be inserted into the test section; and a squealer rim cap (Figure 1(a) – green body), which is affixed to the base airfoil shape and creates the squealer cavity with injection hole geometry. Figure 1(b) shows a cross-section of the test article as it is to be mounted in the test section. This figure calls out ten critical features of the test article design:

1. Plenum, where secondary air is effused to create a pressurized system to drive coolant injection into the squealer cavity.
2. Instrumentation pathway, open to ambient conditions where pneumatic lines from the squealer cavity surface pressure taps are routed out to measurement systems.
3. Sintered bronze mufflers, which allow the secondary air’s effusion to pressurize the plenum without impinging on the cavity and affecting the coolant flow development.
4. Auxiliary quarter inch NPT plug, which allows for PIV seed to be piped directly into the plenum for optical diagnostics.
5. Coolant injection plug, which allows for flow from the plenum into the squealer cavity.
6. Coolant plug blank, which seals the cavity and does not allow coolant throughflow.
7. Atomic Layer Thermopile (ALTP) sensor housing within the footprint of the coolant injection plug, allowing for high-frequency heat flux measurements at the surface.
8. Precision spacers to adjust the tip gap of the model in the test section.
9. Mounting base plate, which allows TIGER LILY to be mounted in LEAF.
10. Sealing base plate, which seals the plenum to allow pressurization.

Feature seven is developed for the use of ALTP sensors (Huber, et al. 2023) but is not unique in its execution: any sensors with a small enough footprint can be housed inside a specially modified coolant plug to introduce new instrumentation without the need for re-machining and retrofitting of the base airfoil or squealer cap.

The two pieces of the TIGER LILY model are fit together using a raised rim around the base airfoil that located the cap with a 0.002” tolerance (Figure 1(a) – Feature 3). The pieces are then bolted together by M3 bolts, which fit into counterbores internal to the plenum to avoid interference of the flow due to raised bolt heads. On the squealer cavity cap, threaded inserts are used to prevent failure of the threads upon repeated assembly with stainless steel bolts. The bolts are sealed with O-rings to discourage plenum leakage into the interstitial space. An O-ring groove is featured around the base airfoil profile to deter flow from the test section freestream to the instrumentation passthrough (Figure 1(a) – Feature 2).

Though a major reason for the conceptualization of the TIGER LILY model is for the use of optical measurement techniques, there is instrumentation integral to the model, which includes a total of 28 surface pressure tap holes distributed throughout the squealer cavity floor and two surface pressure tap holes on the base sealing plate to monitor pressure within the plenum. Further instrumentation is possible through the use of the coolant injection plugs. For configurations in which not all coolant injection plugs are used, instrumentation can be fit into specially designed coolant plugs for further surface measurements, as previously discussed for an ALTP sensor.

The surface pressure tap features are designed with pressure signal time response in mind. The surface taps are 0.5 mm in diameter for a distance of 0.5 mm into the model. After 0.5 mm, the hole opens up to 1.5 mm to allow flexible pressure lines to be affixed to the model and routed out through the ambient cavity passthrough to the data acquisition system. PreMeSys is a tool for evaluating the time response of a pressure signal given lengths and diameters of lines, which is based on the work...
by (Bergh and Tijdeman 1965). This tool assesses the time response of three different diameters of tubes (Teflon, Urethane, and Stainless Steel) of varying length (from 300 mm to 1100 mm) plumbed from the airfoil model directly to a Scanivalve MPS 4264 unit for measurement. The Scanivalve MPS units are used to obtain time averaging pressure measurements. Based on the PreMeSys analysis, 1.5 mm urethane tubing plumbed directly to the surface pressure taps with a length of 500 mm has the best time response and allows for pressure lines to be interchanged with high frequency pressure transducers (Kulite XCQ) as necessary for performing high frequency testing as informed by numerical analysis. The results of the IDDES analysis serve to better inform where high frequency pressure transducers should be placed. Modification of the test article is simple, with the replacement of the pneumatic line with a Kulite in the same hole on the cavity affixed with a probe holder.

Beyond the two sections of the main airfoil model, the interface with the LEAF test section and sealing of the plenum requires additional consideration. This interface is created by use of three parts: the LEAF base plate (Figure 1(b) – Feature 10), the sealing base plate (Figure 1(b) – Feature 9), and the airfoil spacer (Figure 1(b) – Feature 8). The LEAF base plate bolts onto a frame for the LEAF test section, which is held into the wind tunnel via a windowpane bolted to the structure. The sealing base plate bolts to the TIGER LILY airfoil, sealing the plenum and allowing passthrough of instrumentation and then bolts onto the LEAF base plate via a second bolt pattern to situate the airfoil into the test section. The precision spacer plate sets the proper vertical alignment to ensure the desired tip gap. All interface parts are specified to be machined with MIC6 aluminum to ensure precise surface flatness of the elements and mounting construction.

Apart from the pressure taps on the sealing base plate, a quarter-inch NPT port is included to allow direct seeding of PIV oil such that seed concentration is maximized near the coolant injection without oversaturating the freestream flow, resulting in better resolved PIV measurements of the injection phenomena. Aft of the PIV seed port are two counterbored ports, which introduce the secondary air supply to the plenum. Eighth-inch sintered bronze mufflers with the tops sealed are affixed to the air supply to create diffuse pressurization of the plenum, mitigating jet impingement on the top face of the cavity. The porosity of the mufflers allowing diffusion of the injection air creates a near quiescent plenum flow.

On the LEAF base plate, four quarter-inch NPT ports are added to allow total pressure Kiel probes, thermocouples, and hotwire probes to be instrumented, allowing for upstream total pressure and temperature measurements for the characterization of the incoming flow. An additional four surface static pressure taps are included upstream of the TIGER LILY model on the LEAF base plate for calculation of inlet Mach number.

**Injection Schemes**

Between the base airfoil and the squealer rim cap, nine locations for injection holes are placed, three down the centerline, and three along the NACA 0012 profile on either side of the centerline (Figure 1(a) – Feature 1). Coolant is passed from the plenum into the squealer cavity employing additively manufactured coolant plugs, which feature a 3.175 mm coolant hole, first piped normal to the plenum and then angled at 62.5 degrees to the horizontal. The angled portion of this coolant channel has a length-to-diameter ratio of 4.25. For configurations in which no coolant is to be injected from a specific location, the 3.175 mm hole is not present, and a coolant plug “blank” is used in its place. Both versions of the coolant plug feature O-ring grooves on the top and bottom faces to seal the plenum side from leakage and the squealer cavity side from ingress. The plugs are located by three pin features for each plug on the top face of the bottom airfoil piece (Figure 1(a) – Feature 4).
The coolant injection plugs feature a mating hole for the pins at each cardinal direction and one patterned in each direction at +/- 15 degrees to allow for 12 different clocking positions.

**Plenum Analysis**

The plenum of the TIGER LILY model and the associated pressurization source are carefully considered to minimize the interaction of the pressurization air source with the development of flow through the coolant tubes. In initial inceptions, pressurization flow was plumbed straight into the plenum, which caused jet impingement on the top wall of the base airfoil and even into the aft-most coolant injection holes. To better diffuse the flow, sintered bronze mufflers are used. Various sizes and numbers were tried, and in the final iteration, two eighth-inch sintered bronze mufflers with the tops blocked to only allow flow diffusion circumferentially were chosen to pressurize the plenum. They are located on either side of the centerline in the aft portion of the plenum, longitudinally away from the coolant injection holes. The bronze muffler domain is a porous model according to the Carman-Kozeny formulation of the Darcy Law as implemented in FINE/Open. The porosity and specific area are defined based on the mechanical properties of sintered bronze as defined by filter grade with a reported size of 40 microns, correlating to a porosity value of 38%, according to (Neikov 2019). Figure 3 shows three views of the plenum flow analysis for the eighth-inch sintered bronze muffler pressurization. The top row of figures shows the Mach contours within the plenum, and the bottom row indicates a black line where the slice was taken on the model. This pressurization scheme uses 1.35 bar air fed into the plenum through the bronze mufflers resulting in the majority (except at the muffler and the contraction) of the flow below M = 0.01, which is 1-2% of the injection Mach into the squealer cavity and is a static to total pressure ratio of 0.999.

**Squealer Cavity Instrumentation**

The squealer cavity is instrumented with 28 surface pressure taps spaced symmetrically about the centerline. Six pressure taps sit on the centerline, with four evenly spaced axially from one another and the aft two spaced further downstream. On either side of the centerline between the injection holes, six pressure taps are placed following the curvature of the airfoil profile. Four taps are placed on each side along the outer edge of the squealer rim, between the injection holes and the squealer rail. Finally, two additional pressure taps are added near the rails around 70% of the chord.

The location of the pressure taps throughout the cavity serves to get a reasonable spatial sampling for the reconstruction of the pressure field while still leaving space on the underside of the squealer cap for the addition of electrical resistance heaters to evenly heat the model to obtain heat flux through IR thermography (Sousa, et al. 2014). Figure 4 shows the reconstruction of the pressure field in the squealer cavity using only data from the 28 pressure tap locations in the RANS run compared to the full extraction of data from all cells. The data is taken from the nominal design conditions of uniform inlet total pressure 1.2 bar, 300 Kelvin total temperature, and a coolant total pressure and temperature of 1.27 bar and 320 Kelvin. Figure 4(a) shows the pressure tap locations colored by pressure, with the outline of the squealer rail in black. Figure 4(b) shows the pressure field in the cavity directly output from the RANS simulation. Figure 4(c) shows the pressure field in the cavity as it is recreated from data of only the 28 pressure tap points extracted from CFD at the locations shown in Figure 4(a). Figure 4(d) compares this reconstructed field to the full CFD prediction [Figure 4 (b)], showing that from the 28 local pressures, it is possible to reconstruct the full cavity field to +/- 1% in 98.7% of the cavity. This information suggests that the cavity pressure distribution is well captured by the 28 discrete points, and in future comparison of experimental to numerical results, a reconstruction error of about 1% along the entire cavity can be expected from the Kriging reconstruction.
Figure 3: Plenum Mach contours for (a) lateral view through the sintered muffler, (b) top-down view midway through the muffler, and (c) just below injection contraction

Figure 4: Reconstruction of pressure field in the cavity from pressure tap data

COMPUTATIONAL INVESTIGATION AND ANALYSIS OF RESULTS

Domain Definition
The computational domain in this investigation is pictured in Figure 5. The cross-sectional area is true to the earlier reported dimensions of the LEAF test section. The domain is formulated with the inlet two chords upstream of the test article so that the incoming flow develops a boundary layer height of approximately five millimeters when it reaches the test article, consistent with boundary layer measurements previously taken. The test article is placed to have a tip gap of five millimeters between the top of the squealer rail and the top of the test section. The domain outlet is located two chords downstream to allow flow to mix out before reaching the pressure outlet.
Grid Refinement

A grid refinement study is conducted during the model design phase to ensure the adequacy of the spatial discretization, and the methodology follows that of (Roache 1994) for Richardson extrapolation based on a refinement factor of 1.3, approximately doubling the cell count for each successive mesh, which is applied uniformly to each area. The initial grid is created with three refinement zones: one for the plenum, one covering the tip area to the LEAF walls, and one covering the squealer cavity area. These refinements allow for a gradual and uniform transition of the grid from the inlet freestream to the area of interest and back to the outlet far-field. Table 1 shows the grid convergence index according to the squealer cavity static pressure profile.

The range of convergence for the three mesh sizes is near one, asserting confidence that the solution is within the asymptotic range and is well resolved spatially. For the present investigation, the focus is on the scale-resolving simulation of the model. Being in the asymptotic range means that further refining the grid for the IDDES and using that grid across the board lies within the scope of the study. The cell sizes and refinements for the IDDES grid are calculated based on the best practices for scale-resolving simulation meshes (Menter 2012). This leads to a cell size of 0.1 mm in the tip gap and coolant tube and a total cell count of 112 million cells. The local y+ values are kept at or below one with a first cell layer thickness of $1.5 \times 10^{-6}$ m.

Table 1: Grid convergence index

<table>
<thead>
<tr>
<th>Cavity Static Pressure</th>
<th>Grid Step</th>
<th>Refinement ratio</th>
<th>GCI</th>
<th>Range of Convergence</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>coarse-medium</td>
<td>2</td>
<td>1.0018%</td>
<td>1.0061</td>
</tr>
<tr>
<td></td>
<td>medium-fine</td>
<td>2</td>
<td>0.2403%</td>
<td></td>
</tr>
</tbody>
</table>

Figure 5: CFD domain definition
Unsteady Results

A RANS simulation is used for initializing the URANS and IDDES models and for the initial design and placement of pressure taps. In addition to a drop of three orders of magnitude in the residuals, convergence of the RANS simulation is judged through the evolution of lift, drag, and moment with respect to the base airfoil, and heat flux in the squealer cavity. When each of these quantities has developed an oscillatory behavior with an amplitude about the mean of 1% or less, the simulation is judged to be converged.

The URANS and IDDES computations have a time step of $\Delta t = 1.135 \times 10^{-5}$ seconds. The time step is chosen such that the residual drop for each time step is three orders of magnitude with 20 inner iterations for the URANS and 2.5 orders of magnitude for the IDDES, following the guidance of (Menter 2012). Both models use the SST formulation for turbulence close to the wall, and as noted by the grid refinement, the entire domain has $y^+ \sim 1$. The IDDES analysis uses a Third Order MUSCL scheme for spatial discretization along with bounded second order central implicit temporal discretization. A coupled scheme is used for pressure-velocity coupling and a Rhie-Chow momentum-based flux type is used. Limits to pressure and temperature are set to [20000, 200000] Pa and [150, 400] K respectively to prevent development of areas of erroneous pressure and temperature.

Figure 6 compares the static pressure in the squealer cavity and on the rim predicted by the RANS, URANS, and IDDES computations. This describes the difference in pressure field prediction between RANS, URANS, and IDDES simulations. The data is taken from the CFD computations at the same nominal design conditions as described in “Squealer Cavity Instrumentation”. For the URANS and IDDES, the field variables are averaged over 60 timesteps. The RANS simulation showed markedly higher pressures throughout the squealer cavity when compared to the URANS and IDDES. The RANS comparison to URANS varies on the order of +/- 5%, while the URANS and IDDES were nearly identical, with pressure fields varying within +/- 0.4%. As expected, the largest differences are seen near the leading edge and around the squealer rim, where separation and recirculation zones occur. In both cases, there is a noticeable difference directly behind the coolant injection, which spreads out to either side and into/onto the squealer rim. This is due to the bifurcation of the injected coolant jet as it impinges on the squealer rail and the top of the test section while the over-tip flow enters the domain. The coolant injection is split into two streams and advected downstream in the cavity, forming the two lobes seen in the comparison plot, Figure 6. This bifurcation is an expected result of case impingement and over-tip flow (Ma, et al. 2017).

Looking in the tip gap region at the pressure profiles over TIGER LILY for different axial positions reveals the difference in content captured by the three simulations. Figure 7(a)-(c) shows total pressure profiles for data taken midway between the squealer rail tip and the top of LEAF for three different axial positions corresponding to $x = 30$, 130, and 230 mm, as reported in the lower right corner. Each of the three subfigures contains the time-averaged profile (solid line), the 95% confidence interval for the time-averaged data based on multiple averaging intervals (dotted line with dark shading), and plus and minus one standard deviation from the mean profile (dashed line with light shading). For the RANS simulation, these values are computed from 500 iterations after the converged solution is reached. The standard deviation bands for the URANS and IDDES come from the pressure profiles over eight periods of injection flapping (discussed in the following section).

In Figure 7(a), the plane is located 15 mm behind the coolant injection, and in all three analyses, a deficit in total pressure is seen at the centerline and near the rails of the squealer on either side. The RANS and URANS peaks in total pressure do not align with the IDDES, nor is the URANS able to capture the full fluctuation of the pressure field as the IDDES can, evidenced by the smaller bands in standard deviation about the mean. Moving downstream to about halfway through the cavity, the
URANS and IDDES overlap along the entire profile, though the profiles on the right 50% of the model show different inflection. Similarly, the RANS profile has a sharp inflection at both squealer rails, and on the right 50% of the model, the profile sits outside the standard deviation bands for both the URANS and IDDES. Nearing the trailing edge, although the total fluctuation of pressure in time becomes more remarkable, the URANS and IDDES profiles match more closely than in the prior two positions. They still show conflicting inflection at the squealer rim though.

**Figure 6:** Percent difference of static pressure field of RANS to URANS and URANS to IDDES

**Figure 7:** Tip gap pressure profiles at different axial positions and uncertainty about the mean
**Coolant injection flapping frequency analysis**

The pressurization of the plenum and subsequent cooling injection is steady by design in that there is no input function of time governing the pressurization or injection. Regardless, the URANS and the IDDES results show a consistent unsteadiness in the coolant injection through the tube. Figure 8 shows a period of this instability, deemed “injection flapping”, with the URANS results on the left and the IDDES results on the right. The URANS and IDDES predict slightly different frequencies, with the URANS predicting a flapping frequency of 1572 Hz and the IDDES predicting 1468 Hz. In both simulations, the flapping frequency is characterized in the tip gap by four major flow features: first, there is an over-tip stream of relatively high Mach number flow separating over the squealer rim and suppressing the coolant jet injection as it travels over the coolant jet and into the squealer cavity from the tip gap; then the coolant jet breaks into and mixes with the over-tip stream, causing some recirculation behind the area of interaction; following that, the relatively high Mach number over-tip stream, which was initially suppressing the coolant injection, is contained to a small separation bubble on the squealer rim. In tandem, the coolant injection jet, which previously broke into and mixed with the over-tip flow, is diminished in strength above the squealer rim; finally, the periodic cycle recurs, with the incoming over-tip flow separating and suppressing the coolant injection jet, with some small recirculation behind the jet.

The instability of this coolant injection is due in part to the recirculation bubble caused by the geometric contraction from the plenum into the coolant tube and around the tube injection elbow. This recirculation bubble phenomenon was studied by (Wang, et al. 2019), who showed that there will always exist a recirculation in the corner of contracting channels. This bubble causes asymmetries in the flow development through the coolant tube, which manifests as asymmetries in the bifurcation of the injection, which is seen in the pressure profiles of Figure 7 and pressure contours in Figure 4. The size and development of the bubble are predicted differently for the URANS and IDDES; for the IDDES, the coolant tube mesh resolves turbulence away from the walls and in the squealer cavity. This contributes to the differences in the flapping period prediction and behavior of the injection throughout the period. In the URANS, the transition from breaking through the high Mach over-tip stream and causing a sequestered bubble at the squealer rail happens more quickly and lingers longer than in the IDDES (shown in Figure 8 – 0.216 ms and 0.420 ms for URANS; 0.227 ms and 0.454 ms for IDDES).

Cross-correlations and coherence analysis are performed on the pressure taps in the squealer cavity to assess the importance of the flapping frequency and uncover any related interactions downstream. Figure 9 shows the coherence plot for the pairs of pressure taps 9-19, 14-10, and 10-20. In all cases, there is a high coherence (above 0.9) signal in the 1400 Hz – 1650 Hz range, within the bounds of the flapping frequency identified by both URANS and IDDES. Figure 10 shows the raw pressure signals for pressure taps 14 and 10 (top) and their spectrograms (bottom) for a window of time from 0.1 s to 0.14 s. Circled in red is the correlated peak between the two taps. The cross-correlation for pressure taps 14 and 10 reveals a lag in the signal of tap 10 with respect to 14 of two timesteps, or $\Delta t = 2.27 \times 10^{-5}$ s. Given the axial spacing between them of 10.7 mm, the signal travels at 470 m/s, which aligns with the speed of sound plus the convective velocity in the squealer cavity. The cross-correlation, high coherence, and agreement of wave speed with inflow suggest an effect of the injection flapping frequency with the pressure signal in the squealer cavity. This result of the IDDES analysis suggests that high frequency pressure transducers must be used at these measurement points in the cavity to ensure capturing of the flow phenomena expected. To this end, in experimental work, the pneumatic lines of pressure taps 9, 10, 14, and 20 will be replaced with high frequency transducers.
Kulite pressure transducers to capture high frequency data for direct comparison of experimental to numerical results.

Figure 8: Flapping period of coolant injection for URANS (left) and IDDES (right)
Further, optical techniques such as PIV can be used to measure the velocity field in the tip gap and find the flapping frequency by focusing on the injection and propagation through the squealer cavity. Correlating the intermittency in the injection velocity field and the high frequency pressure tap data as done numerically gives the ability to compare experimental to numerical data. The setup of this model to perform in the LEAF test section at PETAL can hold Mach number constant for the duration of a two-minute test. During that time, the temperature of the test section will drop 15 Kelvin. Experimental analysis by (Roh and Park 2003) showed that from Re = 5920 to Re = 148,500, the development of vortical tip structures from a cylindrical body does not show major change. The ability to monitor and adjust plenum pressure and temperature allow for tuning the injection density ratio to stay constant throughout the test as well, allowing for the main conditions of interest to be controlled and reproduced within the test environment.

![Figure 9: Coherence plot for pressure tap pairings 9-19, 14-10, and 10-20](image)

Figure 11 shows a plot of the axial and spanwise velocities in the cavity and external flow. This plot reveals more clearly the separate lobes of the coolant stream resulting from the over-tip and case impingement bifurcation, which showed up in the squealer cavity static pressure contours comparisons of Figure 6. The bifurcated stream travels through the cavity on either side of the centerline and spills out of the cavity around 60% of the chord. On either side of the injection at the leading edge, recirculation is seen, resulting from the over-tip flow spilling into the cavity from the rail and becoming entrained by the bifurcated stream. Periodically with the flapping frequency, this flow tends to spill over the side and move downstream. Aft of 60% of the chord, there are large areas of negative axial velocity, which indicates flow from the freestream back into the squealer cavity. This flow tends to entrain in between the bifurcated coolant stream and influences the pressure signals mentioned earlier. The recirculation of the freestream combined hot gas and cooling injection flow causes lower effective heat transfer, which yields insight into the placement and shaping of cooling injection schemes.
CONCLUSIONS

A new canonical large-scale model for the investigation of over-tip flows and interaction with coolant injection is developed, presented, and shown to offer a way of isolating cooling flow injection from the cooling flow source, allowing for investigation of the mixing flow phenomena absent influence from the source. The model geometry is reported, and the off-the-shelf hardware is explained to make the model openly accessible. The instrumentation of the model shows the ability to reconstruct full pressure fields from 28 measurement locations in the squealer cavity with an error below 1% for 98.7% of the cavity.

An IDDES scale-resolving simulation is performed and compared to results from RANS and URANS analysis, showing the discrepancies of time-averaged profiles along the squealer cavity and the inability of the RANS model to consistently sit within the standard deviation bounds of the unsteady simulations. Unsteady simulation in the investigation of squealer tip flows is paramount to understanding the effects of instantaneous flow features compared to the time-averaged results.

The analysis of the unsteady simulations reveals a flapping frequency of the cooling injection even when the boundary condition is steady. This flapping is due to the recirculation bubbles in the
coolant channel from diametral contractions and changes in the direction of the channel. The flapping frequency is correlated with pressure signals in the downstream squealer cavity, which affects the heat transfer in the cavity and is information on necessary changes to cooling injection to more effectively cool the tip.

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