EFFECTS OF 'COOLED' COOLING AIR ON PRE-SWIRL NOZZLE DESIGN

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ABSTRACT

It is common practice to use Pre-Swirl Nozzles to facilitate getting the turbine blade cooling air onboard the rotating disk with minimum pressure loss and reduced temperature. Higher engine OPR's and expanded aircraft operating envelopes have pushed cooling air temperatures to the limits of current disk materials and are stressing the capability to cool the blade with practical levels of cooling air flow. Providing 'Cooled' Cooling Air is one approach being considered to overcome these limitations. This presentation looks at how the introduction of 'Cooled' Cooling Air impacts the design of the Pre-Swirl Nozzles, specifically in relation to the radial location of the nozzles.

The current generation of engines now entering production have pushed the operating temperatures to the limits of current disk materials. Cooling air temperatures are reaching levels that challenge the capability of the airfoil designers to cool the airfoils with practical levels of cooling flow. To meet the goals of the next generation, advanced engine will require higher OPR's and operate in expanded flight envelopes which will push operating temperatures to even higher levels. Advanced materials and improved cooling technologies are being pursued to achieve these goals.

Another approach being considered to overcome these limitations is to provide 'Cooled' Cooling Air to the temperature limited components. For example, typical trade studies show that while holding metal temperature constant and cooling the cooling air temperature by 100°F would allow the combustor exit temperature to be increased 200 °F or the blade cooling air to be reduced by 15% of the uncooled cooling air level. While cycle studies incorporating these types of benefits have been done previously we are just starting to look at some of the consequences to the actual design of the engine internal flow system. Discussion of the results from these cycle studies or of specific methods to cool the cooling air will not be covered today. Rather, this presentation will look at how the introduction of Cooled Cooling Air impacts the design of the Pre-Swirl Nozzles, specifically in relation to optimizing the radial location of the nozzles.

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AGENDA

- Statement of the Problem
- Past Solutions
  - Commercial
  - Military
- 'Cooled' Cooling Air Effects
  - Redefinition of the Problem
  - Effects on Existing Engine Design
  - Proposed Solution
- Summary

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It is common practice to use Pre-Swirl Nozzles to facilitate getting the turbine blade cooling air onboard the rotating turbine disk with minimum pressure loss and reduced temperature. In today's modern gas turbine engines the Pre-Swirl Nozzles, or 'Pre-Swirler' for short, is a annular vane cascade located just forward of the turbine disk. Some typical engine cross-sections are included later in the presentation. While it is intended to stick with the term "Pre-Swirler" throughout the presentation it is also noted that P&W nomenclature for the Pre- Swirler is to call it a "TOBI", which stands for Tangential Onboard Injector.

The agenda for the presentation is outlined for you here. We will start by looking at a basic statement of the problem faced by the secondary flow analyst when designing the Pre-Swirler including a review of the factors that influence the optimum radial location. Next we will look at how these factors have influenced past designs and why the solution has been traditionally different for commercial and military applications. Introducing the 'Cooled' Cooling Air into the Pre-Swirler design results in some redefinition of the problem. We will look how this redefinition influences an existing engine design and then how changing the design results in an improved solution. The presentation will be concluded with a summary of the main points that were covered.

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Statement of the Problem

- Problem : Design Pre-Swirler to Meet Blade Supply Pressure Requirement
- Givens : Rim Cavity Pressure, Radius of Blade Entrance , Rotor Speed, Pre-Swirler Supply Conditions (P&T)
- Variables: Radius of Pre-Swirler, Pressure Ratio, Pre-Swirler Aero

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The number one requirement to meet with the design of a Pre-Swirler is to assure that the supply pressure to the blade is always greater than or equal to the minimum level specified by the airfoil designer. As a minimum, not meeting this requirement results in higher operating temperatures, an increase in hot gas erosion and decreased airfoil life. If the pressure gets low enough then hot gas backflow into the airfoil can occur, leading to local burn-through and other conditions that dramatically decrease the airfoil's life.

In addition to the blade supply pressure requirement there are certain factors that influence the Pre-Swirler design that are essentially outside the control of the secondary flow analyst. These are the 'Givens' in the problem and include things like the rim cavity pressure, radius of the cooling air entrance into the blade, rotor speed, and the conditions of the air supplied to the Pre-Swirler. In conventional engines this air is usually supplied from the plenum around the combustor and inside the diffuser case. Therefore, the supply pressure and temperature are set by the high compressor exit conditions.

The variables of the problem include the radial location of the Pre-Swirler, at least within some range governed by packaging of other hardware, etc. The pressure ratio across the Pre-Swirler can also be varied somewhat with a minimum set by the rim cavity pressure. The aerodynamics of the Pre-Swirler vane cascade can be varied in terms how close the air exit angle is from being tangential, velocity coefficients, etc. Keeping with good aerodynamic design practice keeps the realistic range of varying the vane cascade small.

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Statement of the Problem (Continued)

- Process
  - Combine the Givens with selected values for the Variables to define the Pre-Swirler Exit Velocity(V_t). This velocity sets the Blade Cooling Air Temperature ($T_{c/a}$) and results in additional Pressure Losses getting onboard the rotating structure if not matched with the Disk Speed (V_d)

  $V_t = f(\text{Mach\#, angle, } C_v, \Delta P_t/P_t)$ where $\text{Mach\#} = f(P_r, T_{supply})$

  $T_{c/a} = T_{supply} + (V_{be}^2 - 2\eta V_d V_t) / (2 g_c J c_p)$ (Reference 92-GT-378)
- Goals:
  - Lowest Blade Cooling Air Temperature
  - Lowest Leakage - Minimum TSFC
  - Lowest Weight
  - Maximum Piston Area for Bearing Thrust Load Control

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Using simple compressible flow theory the given information can be combined with selected values of the variables to define the tangential exit velocity of the Pre-Swirler. Once the velocity is known the cooling air temperature to the blade can be determined with Euler relationships. If the velocity is not matched with the wheel speed of the rotating structure, where the air is brought onboard the disk, then additional pressure losses result which must be accounted for in the analysis.

Selecting different values for variables results in a matrix of solutions that can meet the blade supply pressure requirement. Selecting the optimum solution from this matrix depends on the relative importance of several additional goals in the particular engine design. These goals include supplying the blade with the lowest cooling air temperature to minimize the blade cooling air flow rate. This cooling air temperature is a key driver in the determining the blade attachment temperatures well. Keeping the Pre-Swirler exit pressure as low as possible minimizes leakage which increases turbine efficiency and minimizes TSFC. Keeping the weight down is always a goal. Lastly, the Pre-Swirler and associated seals form a piston area that is included in the bearing thrust load calculation. For most engines, maximizing this piston area, which is done by increasing the Pre-Swirler radius, is beneficial to overall thrust load control.

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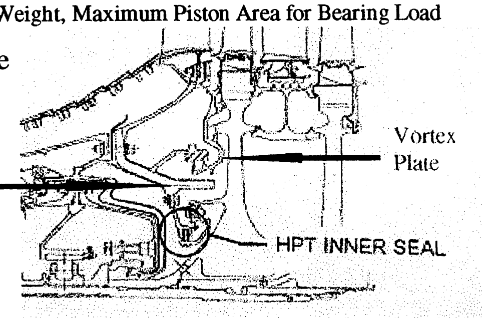
Past Solution - Commercial

- Primary Goals : Lowest Possible Leakage - Minimize TSFC
- Secondary Goals : Lowest Blade Cooling Air Temperature, Lowest Weight, Maximum Piston Area for Bearing Load
- Solution : Minimize Pre-Swirler Radius



Pre-Swirler

PW4168

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Here is a picture of the high turbine area of a fairly typical current generation commercial engine, specifically the PW4168. It can be seen that the Pre-Swirler is located fairly far radially inward in the available space forward of the turbine disk. This type of design results when the primary goal is to have the lowest possible leakage. The Pre-Swirler exit pressure is set to a level just above the front rim cavity pressure, minimizing the deltaP across the swirler cavity seals. A vortex plate is used to allow the oversped air to vortex outward, causing an increase in pressure, before it is captured by the slots between the HPT disk and the vortex plate.

The low leakage levels possible with this type of design results in better TSFC than alternatives that place the Pre-Swirler further out in radius. However, it also results in warmer blade cooling air temperature and smaller thrust load piston areas. In essence, these goals have been made secondary. The engine is probably heavier as well, for instance, other features have to be added or made more complex to control bearing thrust loads. It should be noted that later PW4000 models have moved the Pre-Swirler out in radius because the operating temperatures reached levels that would have resulted in blade cooling air temperatures that exceeding allowable limits for the blade attachment design with this 'low radius design'.

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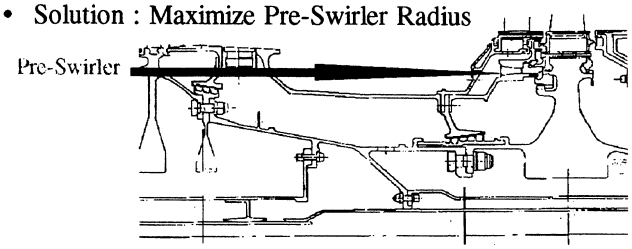
Past Solution - Military

- Primary Goals : Lowest Blade Cooling Air Temperature,
  Lowest Weight
- Secondary Goals : Maximum Piston Area for Bearing Load Control,
  Lowest Leakage - Minimum TSFC
- Solution : Maximize Pre-Swirler Radius



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Military engines on the other hand, have typically operated to flight Mach numbers that required the design to achieve the lowest possible cooling air temperature. Fighter engines are also more sensitive to weight than commercial engines. A design that emphasizes these goals leads to the Pre-Swirler being placed as far out in radius as possible within the available space. This engine cross-section is typical of this type of design. This design does maximize the thrust piston area but it isn't really a primary goal. Similarly, low leakage levels are desired to minimize TSFC but this will be compromised if necessary to achieve the primary goals. However, as the military adjusts to the post cold war world we are seeing TSFC concerns play more importance in design decisions.

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'Cooled' Cooling Air Effect on the Problem

- Problem : Design Pre-Swirler to Meet Blade Supply Pressure Requirement
- Givens : Rotor Speed, Rim Cavity Pressure, Radius of Blade Entrance
- Variables : Radius of Pre-Swirler, Pressure Ratio, Pre-Swirler Aero

  → Pre-Swirler Supply Conditions (P&T) ← Become a Variable

- Goals :
  - Lowest Blade Cooling Air Temperature
  - Lowest Leakage - Minimum TSFC
  - Lowest Weight
  - Maximum Piston Area for Bearing Thrust Load Control

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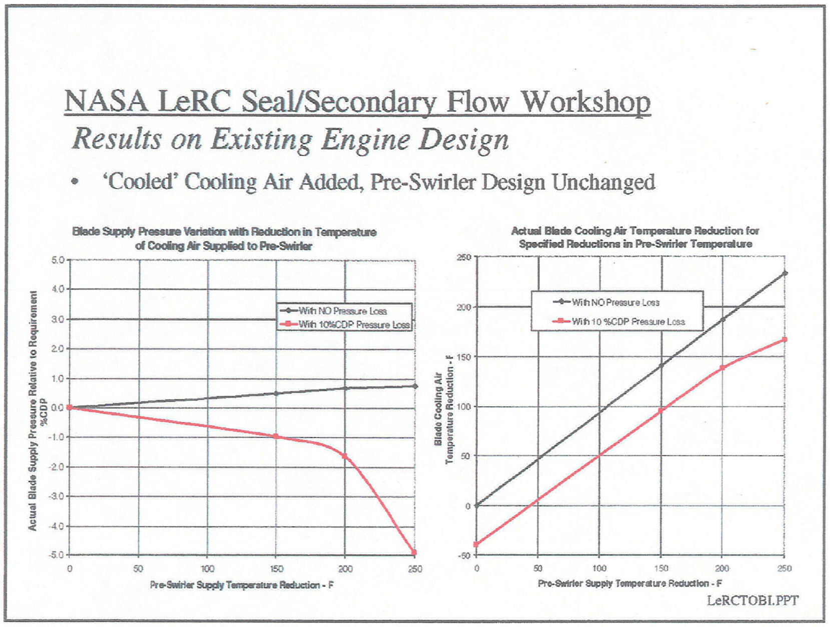
The primary effect of adding a Cooled Cooling Air system on the design problem is that the Pre-Swirler supply conditions are no longer a given and become a variable. Obviously the amount of temperature reduction by the system can be varied. The pressure loss through the cooling system can also be varied by designing with larger size pipes, heat exchangers and so on. Some cooling systems have even proposed auxiliary compressors to offset the plumbing losses but this is not considered likely in the near term. Therefore the supply pressure to the Pre-Swirler is going to be somewhat reduced due to these losses.

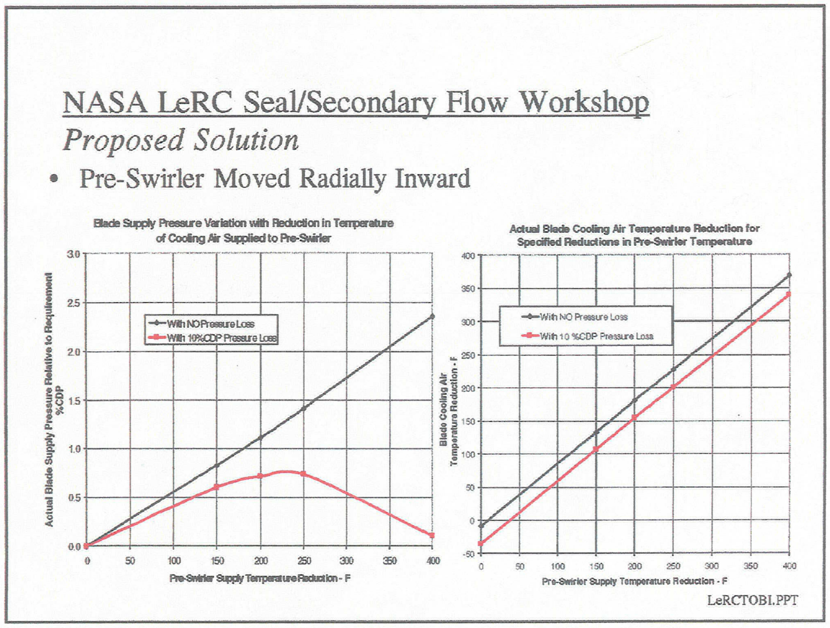
While these supply conditions can be varied there is a direct effect on the tangential velocity of the air exiting the Pre-Swirler. First, if nothing else changed the velocity would come down proportional to the square root of the reduction in temperature. Including the pressure losses reduces the pressure ratio and therefore the exit mach number causing even more reduction in velocity. This new exit velocity must be compared with the speed of the rotating structure and factored back into the cooling air temperature calculation and the pressure losses getting onboard the turbine disk.



This slide shows what happens to blade supply pressure and temperature when a cooled cooling air system is added to an existing engine and no other design changes are made. Looking at the chart on the left and assuming that the cooling air system had no pressure loss (black line) it can be seen that the blade supply pressure actually rises a slight amount as the temperature is reduced. This is because the base design actually overspeed the air exiting the Pre-Swirler, increasing the pressure loss getting onboard the disk, to drive the cooling air temperature to the lowest possible value. Therefore the lower velocity obtained by cooling the cooling air reduces the velocity mismatch thereby reducing the pressure loss due to it.

Including a pressure loss of 10% of the Compressor Discharge Pressure (CDP) for the plumbing losses of the cooling system gives quite a bit different result. The blade supply pressure falls gradually as the cooling air temperature is reduced up to about 175 °F. Cooling the air further causes a rapid fall in pressure because the pressure losses due to the velocity mismatch become the dominate factor in the system. This characteristic is considered to be unacceptable for an engine that has to operate over a wide range of operating conditions that is typical for a fighter engine.

The right-hand chart also reveals that the actual temperature reduction achieved at the blade entrance is significantly less than anticipated by looking at temperature reduction supplied to the Pre-Swirler. For instance, a cooling system sized to reduce the cooling air temperature by 200 °F would only achieve about 140 °F temperature reduction at the blade. Therefore, the cooling capacity of the system would have to be increased to achieve an actual 200 °F reduction at the blade entrance.



This slide provides the same two charts on blade supply pressure and temperature for a design where the Pre-Swirler has been moved radially inward. It can be seen that blade supply pressure is fairly constant over a wide range of supply temperature reduction when the 10% CDP pressure loss is included. The maximum pressure point represents a condition where the Pre-Swirler exit velocity equals the wheel speed of the rotating structure that brings the air onboard the disk. The actual radial location of the Pre-Swirler to get this type of characteristic for any engine is then driven by achieving this zero velocity mismatch condition with the desired amount of temperature reduction.

From the right hand chart the slight temperature penalty for moving the Pre-Swirler inboard is seen with no supply temperature reduction and no pressure loss. Once again the actual temperature reduction achieved at the blade is less than the amount of supply temperature reduction. However, it is improved with the proposed design because 155 °F in blade supply temperature reduction is achieved (was 140 °F)for our example of 200 °F reduction in supply temperature.

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Summary

- 'Cooled' Cooling Air Reduces Pre-Swirler Exit Velocity Because of the Lower Sonic Velocity and System Pressure Losses Reducing the Pre-Swirler Pressure Ratio
- Radial Location of the Pre-Swirler Must Be Adjusted to Account for These Effects and Still Meet the Blade Supply Pressure Requirement
- Pre-Swirler Supply Temperature Must Be Overcooled to Achieve A Given Reduction in Blade Supply Temperature

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