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## A Flow Visualization Study of Axial Turbine Tip Desensitization by Coolant Injection from a Tip Trench

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### ABSTRACT

The effect of coolant injection from a tip trench was investigated in a large-scale rotating turbine rig. Coolant is injected into the tip gap from discrete injection holes, located in a tip trench and directed towards the pressure-side. Surface flow patterns are visualized by a mixture of oil and paint. The mixture is applied on the blade pressure-side and allowed to seep onto the tip platform. Injection rates of 0.4%, 0.5%, 0.6%, and 0.7%, at a gap height of 1.40% blade height were investigated. Flow patterns for a gap height of 0.72% blade height are compared to the larger clearance gap. The flow visualization technique successfully identifies flow features like pressure-side edge separation, and reattachment and recirculation on the tip surface. The location of the reattachment line from the pressure-side edge varies little along the length of the blade and occurs at about two gap heights from the pressure-side edge. At the large gap height the tip gap flow is fully separated over the last 5% of the blade axial chord. Surface oil flow lines are directed almost normal to the camber-line along most of the tip surface. Flow patterns with injection indicate that the ejected coolant effectively blocks the leakage flow. The coolant jets are turned towards the blade suction-side and appear to form a film on the tip surface. Some of the visualization material is carried by the leakage flow into the passage and is deposited on the blade suction surface, thereby giving an indication of the inception and growth of the leakage vortex. Suction surface patterns with injection indicate that leakage flow may be entering the adjacent passage at multiple locations.

### NOMENCLATURE

$C_{ax}$	Rotor tip axial chord length = 0.08514m
$M_{inj}$	Coolant to free stream mass flow rate ratio
$N$	Rotor speed, rpm
PS	Blade pressure-side
SS	Blade suction-side
TE	Blade trailing edge
$h$	Rotor blade height = 0.123 m
$t$	Clearance gap height, m

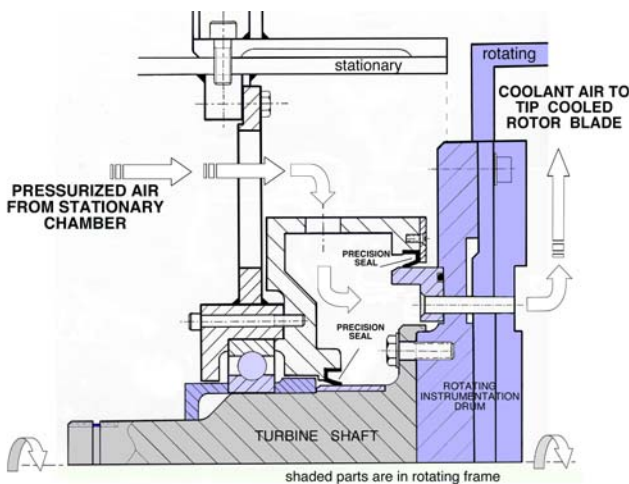
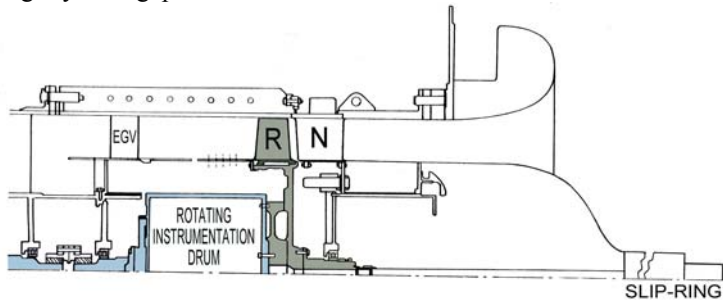
### INTRODUCTION

Coolant injection from a tip trench was shown to reduce leakage vortex size and improve measured total pressure in the region affected by the leakage vortex by Rao and Camci [1, 2]. The motivation for the current study is primarily to understand the effect of the coolant jets on flow in the tip gap, in a rotating frame of reference. More importantly, this form of investigation is likely to yield qualitative information regarding heat transfer to blade tip surface and the area of influence of the coolant injected into the tip gap. Such information would be useful in optimizing tip injection schemes. As noted by Bunker [3], the increase in overall thermal efficiencies due to active blade cooling justifies the use of compressed air, up to a certain point. The potential benefits of the specific coolant injection scheme reported derive from the realities that face the engine designer as reported by Harvey [4]. Turbine mean radius and casing are flared to allow for constant axial velocities through all turbine stages. Thus, it is difficult to maintain design tip clearances, even with careful attention to manufacturing tolerances due to the effect of tolerance stacking. Aerodynamic benefits of coolant injection from the tip surface may be less sensitive to deviations of the actual clearance gap height from that of the design clearance.

Investigating the details of tip gap flows is cumbersome, whether conducted in cascades or in rotating rigs. The intrusive probes that must be used to measure the flow tend to have similar dimensions as the gap height. However, qualitative information may be obtained by using flow visualization techniques. Information regarding the various visualization techniques may be found in Merzkirch [5] and Yang [6]. Aunapu et al [7] used ink dot flow visualization to study the effect of various techniques to modify turbine passage endwall flows in a cascade. Endwall secondary flows were investigated in a linear cascade by Wang et al [8] using smoke wires and laser light sheet. Allen and Kofskey [9] employed smoke to visualize the development of leakage and secondary flows in a low-speed rotating rig. Dring and Joslyn [10] applied Ozalid paper onto airfoil surfaces in a large scale rotating turbine. Ammonia discharged from upstream surface pressure taps

reacted with the paper to leave dark streaks. They found that the pressure surface had strong radial outflow at midspan that was unaffected by the tip gap height. Radial flows were also observed on the suction surface, due to the secondary and tip leakage effects.

Film cooling of turbine blade tips is currently receiving more attention. Experimental investigation of a modeled blade tip is reported in Kim et al [11]. Kwak and Han [12] investigated film cooling of gas turbine blade tips in a linear cascade. Blade tip heat transfer coefficients were found to increase with gap height. Film cooling from radial holes along the camber line was shown to be more effective at larger clearances and at higher blowing ratios. Pressure-side coolant injection was found to increase film effectiveness over the tip surface. Hohlfeld et al [13] numerically simulated the film cooling effect of dirt purge holes on turbine blade tips. Coolant ejected from the purge holes served to block the leakage flow at a tip clearance of 0.54% blade height. However, as gap height was increased to 1.64% span the blocking effect decreased. At the large clearance, shroud cooling effectiveness increased with blowing ratio, while tip surface cooling effectiveness first decreased and then increased. Acharya et al [14] also computationally simulated film cooling of turbine blade tips. Film cooling at three different gap heights was simulated. Coolant injection was found to alter the leakage vortex and also decrease the heat transfer coefficient along the coolant trajectory. Film cooling effectiveness was found to increase slightly with gap size.



**Figure 1** Axial Flow Turbine Research Facility (AFTRF) and coolant air transfer system for blade tip injection

## FACILITY DESCRIPTION

**Turbine Research Facility:** The facility used for the current research is the Axial Flow Turbine Research Facility (AFTRF), at The Pennsylvania State University, Fig. (1). Lakshminarayana et al [15] and Camci et al [16], provide a detailed description of the design of this facility. The AFTRF is a large scale, cold turbine facility that produces about 60 kW. A single stage axial turbine is driven by the air flow generated by two axial fan stages. The generated power is absorbed by an eddy current brake, which also controls the rotor speed to within  $\pm 1$  rpm. The outer casing was fitted with an optical window for the present study. Total pressure and temperature measurements are conducted at stage inlet and exit by total pressure probes and thermocouples. The important turbine design data are listed in Tables (1) and (2) respectively.

**Table 1** AFTRF Facility Performance Data

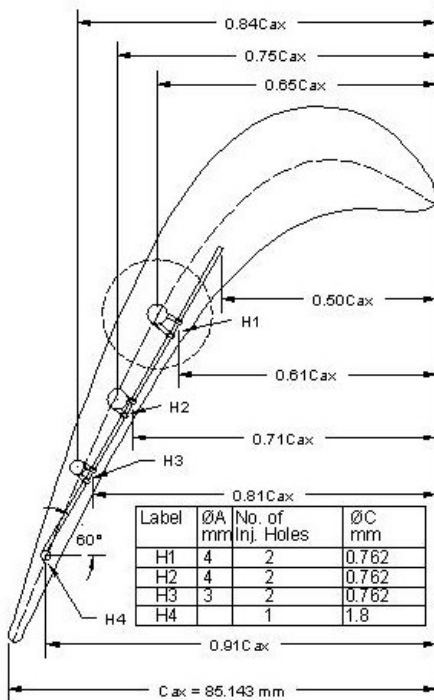
Inlet Total Temperature; $T_{01}$ (K)	289
Inlet Total Pressure; $P_{01}$ (kPa)	101.36
Mass Flow Rate; $\dot{Q}$ (kg/sec)	11.05
Rotational Speed; $N$ (rpm)	1300
Total Pressure Ratio; $P_{01}/P_{03}$	1.0778
Total Temperature Ratio; $T_{03}/T_{01}$	0.981
Pressure Drop; $P_{01}-P_{03}$ (mm Hg)	56.04
Power; $P$ (kW)	60.6

**Air Transfer System:** Coolant air is sent from stationary frame to rotating frame by the air transfer system (ATS), described in Fig. 1. A detailed description of the ATS is provided in Rao and Camci [1]. Although air leakage in the ATS is minimized by special seals, the coolant mass flow rate is accurately measured by a calibrated orifice located in the rotating frame, prior to blade entry. The orifice pressure taps are connected to a pressure transducer mounted in the rotating frame. A coin and brush type slip-ring transfers the data from the rotating frame to the stationary frame.

**Tip Cooled Rotor Blade:** The rotor blade count is 29 and the design tip clearance is  $t/h=0.73\%$ , as noted in Table (2). A designated test blade (Blade #21), with  $t/h=1.40\%$  is used for investigations involving coolant injection. The test blade is shown in Fig. (2a), with a tip surface that has a trench with four sets of injection holes. Injection holes H1, H2, H3, and H4 are located at 61%, 71%, 81%, and 91% blade axial chord respectively. A common blade root plenum supplies coolant to four individual radial plenums simultaneously. At 91% axial chord, the injection hole (H4) is a single radial hole that opens directly into the blade root plenum. Two holes of diameter 0.76 mm, inclined towards the blade pressure-side at  $45^\circ$  to the radial direction are drilled at all other locations, as shown in Fig. (2b). The trailing hole in each set is inclined  $10^\circ$  with respect to the leading hole. Each set opens into a single radial plenum. The blade plenum is connected via high pressure tubing to the ATS.

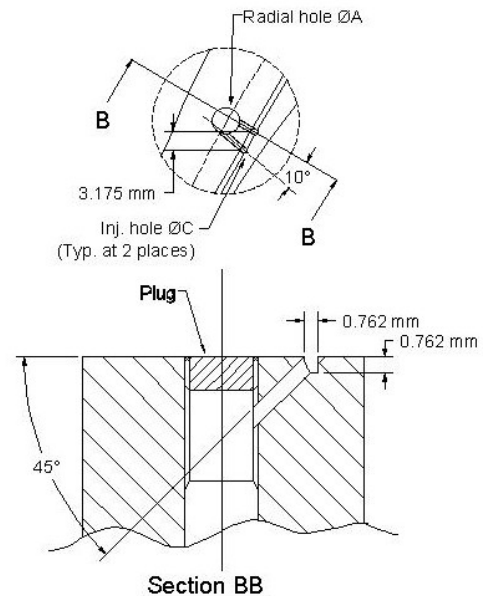
**Table 2** AFTRF Stage Blade & Vane Data

Rotor hub-tip ratio	0.7269
Blade Tip Radius; $R_{tip}$ (m)	0.4582
Blade Height; $h$ (m)	0.1229
Rotor Blade:	
Relative Mach Number	0.24
Number of Blades	29
Chord; (m)	0.1287
Axial Tip Chord; (m)	0.085
Spacing; (m)	0.1028
Turning Angle; Tip / Hub	95.42° / 125.69°
Tip Clearance; (mm)	0.9
Reynolds Number ( $\times 10^5$ ) inlet / exit	(2.5~4.5) / (5~7)
Nozzle Vane:	
Number of Vanes	23
Chord; (m)	0.1768
Spacing; (m)	0.1308
Turning Angle;	70°
Reynolds Number ( $\times 10^5$ ) inlet / exit	(3~4) / (9~10)

**Figure 2a** Test Blade Tip Surface

**Flow Visualization Technique:** The flow visualization technique employed in this study consisted of applying a mixture of oil and paint on the blade pressure surface. The oil used was ashless dispersant, SAE 40 aviation oil (Aeroshell oil W 80). The paint used was titanium white artists' oil color

containing titanium oxide and zinc oxide pigments. Paint on the pressure surface moves under the action of both centrifugal forces due to rotation and aerodynamic shear forces. During startup, the thickness of the visualization material is significantly reduced, due to centrifugal action. Some of the paint thrown off the pressure surface is carried into the tip gap by the leakage flow. The thickness of the visualization material deposited on the tip surface is extremely small. The material so deposited traces a path across the tip surface under the influence of the aerodynamic shear generated by the gap flow.

**Figure 2b** Test Blade Tip Surface Cross-Section Showing Injection Hole Details

**Operation:** The blade surfaces were coated with smooth flat black paint to allow for better contrast with the white paint used and to avoid reflections during image acquisition. Paint was then applied, on the pressure surface, with a soft brush as evenly as possible. Images of the painted surface were acquired to ensure reasonable repeatability in paint application between tests. The optical window was then fastened and the first fan stage was started. This brought the turbine to a stable speed of about 1240 rpm in approximately 30 seconds. The second fan stage was started at this time and in 30 seconds both the turbine rotor speed and flow rate were sufficiently stable. Thereafter, the rotor speed was increased to the corrected operating speed. Thus, the time required for the rotor to reach operating speed was less than 90 seconds in a total run time of about 20 minutes. A strobe light controlled by the AFTRF trigger pulse was used to conduct visual observations of the blades during the tests. It was observed that some of the paint started splattering on the casing when the speed reached about 700 rpm. Thus by the time the rotor reached operating speed some amount of paint is carried on to the tip surface. Paint deposited onto the tip surface then moves in well defined dots, under the action of aerodynamic shear. The test was terminated when no motion was observed for over a minute, which on average was 20 minutes after startup. It must be noted that the mixture never dried hard and could still be smeared.

Coolant mass flow rate injected is stated as a percent of core mass flow rate, assuming coolant is injected from all blades. Most of the tests involving coolant injection were conducted by commencing injection prior to startup of the turbine. For the case of  $M_{inj} = 0.4\%$  however, a test was conducted where injection was commenced after the rotor had reached operating speed. The various test cases presented in this paper are summarized in Table (3).

**Table 3** Description of Tests Conducted

Test Case	Blade #	t/h%	$M_{inj}\%$	Description
T1	21	1.40	0	Flat tip
T2	7	0.72	0	Flat tip
T3	21	1.40	0	Tip with trench
T4	21	1.40	0.4	Injection at $N = 0$
T5	21	1.40	0.4	Injection at operating speed
T6	21	1.40	0.5	Injection at $N = 0$
T7	21	1.40	0.6	Injection at $N = 0$
T8	21	1.40	0.7	Injection at $N = 0$

**Image Acquisition:** Images of the surface patterns were recorded using a Nikon Coolpix 4300 digital camera. The camera has an optical zoom of 3x with 4.0 effective mega pixels. The images captured have a resolution of 300 dpi, with tip surface images saved as 24 bit true color (TIFF) files.

## EXPERIMENTAL RESULTS & DISCUSSION

The images presented show flow patterns on the tip platform and paint deposition on the suction surface by the tip leakage flow. Images of the tip platform are overlaid with a reference grid showing the camber line and a row of lines, with a spacing of  $0.05 C_{ax}$ .

**Pressure Surface Oil Patterns:** Figure (3a) is an image of a typical blade pressure surface after the application of paint. The paint is applied so that it has no preferred direction. Care is taken to ensure uniform paint thickness. The pressure surface patterns after the test are shown in Fig.(3b). In contrast to Fig.(3a) the paint has a definite orientation in the radial direction. The oil layer on the surface of the rotating concave surface is forced radially outwards due to centrifugal forces on the oil film. During startup the aerodynamic shear, imposed by the passage flow in the relative frame, on the oil layer is less significant in comparison to the centrifugal forces due to the initial thickness of the oil film. The patterns on the pressure surface are not indicative of the passage flow. However, the curvature of the patterns is indicative of the relative strengths of aerodynamic and centrifugal forces imposed on the oil film. The blade surface is visible in some areas where all the paint has washed out.

**Leading Edge Oil Patterns:** Near leading edge patterns shown in Fig. (3c), are inclined due to the strong aerodynamic shear expected in this region. It appears that flow stagnation occurs very near to the pressure-side of the leading edge. There is a

distinct black line visible from just above the blade root that extends all the way to the tip and might represent the stagnation region. The lack of fluid friction allows paint from close to the hub to be accelerated all the way up to the tip by purely rotational effects. Dring and Joslyn [10] also report strong radial outflow near the leading edge. They attribute this radial outflow to an inviscid secondary flow effect. It can be seen that the line terminates in an arc about 10% blade height above the hub, as shown in Fig.(3c) by a circle. In this region the centrifugal pumping of the paint is probably comparable to the aerodynamic shear. Flow close to the hub would actually attempt to move paint towards the hub as it stagnates and flows back to the saddle point.

**Near Trailing Edge Patterns:** In about the last third of the blade the paint lines are leaning towards the trailing edge. Lines that begin below mid-span do not reach the tip and are oriented towards the blade wake. This orientation depends roughly on the ratio of centrifugal force to shear force.

**Visualization in A Gap with Nominal Clearance,  $t/h = 1.40\%$  (Case T1):** Figure (4) shows the tip surface patterns on the test blade (Blade #21) with a flat tip and a tip clearance of  $t/h = 1.40\%$ . The trench is blocked by applying tape on the tip platform and cutting it to the tip shape. An extremely thin layer of smooth flat black paint is then sprayed on the tape.

One of the general observations that can be made is the paint accumulation on the tip surface all along the PS edge of the blade. As compared to the rest of the tip surface, only a few paint streaks are seen to start from the accumulated paint in the region  $0-0.30 C_{ax}$  along the PS edge. Additionally, these streaks do not extend to the SS edge of the tip surface. Flow in this region comprises mainly of the inlet boundary layer, thereby generating lower wall shear on the tip surface. Tip surface paint accumulation is due to some of the visualization material being carried by the inlet flow passing through the tip gap. The paint lines that do form indicate turning of gap flow towards the camber-line as it progresses to the suction-side of the tip gap, as seen in Fig. (4b). Linear cascade, shroud surface pressure measurements by Bunker et al [17] indicates minimal pressure difference across the first quarter of the blade. Numerical simulation of flow in the same cascade by Ameri [18] shows gap flow streamlines in this region to originate primarily from the rotor inlet flow. Blade tip and casing surface pressure measurements by Xiao et al [19] in the AFTRF also indicate minimal gap pressure differential, thereby supporting the observations made here.

A definite reattachment and recirculation pattern is seen on the tip surface from about  $0.3 C_{ax}$ . A demarcation line can be seen between two flow directions, one that causes paint to move towards the blade SS edge and another that indicates reverse flow towards the blade PS corner. Paint carried by the leakage flow into the gap is deposited on the tip platform when the flow re-circulates near the PS corner. Subsequently, the paint moves either towards the suction-side, or stays trapped in the separation bubble. Chord-wise orientation of paint lines at reattachment may indicate a three-dimensional reattachment. The direction of paint lines in the recirculation zone indicates the chord-wise flow that is set up by the positive chord-wise

pressure gradient in the tip gap. The recirculation patterns between 0.4 and 0.5  $C_{ax}$  are not as well defined. The smearing could be a result of the separation bubble lifting off the tip platform and being ejected into the passage, as conceptualized by Bindon [20]. Casing surface pressure measurements by Xiao et al [19] in the AFTRF show tightly spaced pressure contours in this region of the tip gap. The rapid acceleration of fluid entering the gap is accompanied by increasing wall shear, causing more of the visualization material to be washed away. Immediately behind this smeared region and in the direction of the leakage flow is an area that contains very little paint. Since visual observations indicated no wetness, due to oil, it is possible that most of the paint carried into the gap does not reach the tip surface.

The features from blade mid-chord to the trailing edge are very similar. There is paint accumulation on the PS corner, a reattachment line, and flow towards the SS corner. The location of the reattachment line normal to the PS edge changes very little along the blade length. Reattachment occurs at about 4%  $C_{ax}$  (2\*gap height) from the PS edge, between 0.3 and 0.65  $C_{ax}$  along PS edge. The width decreases at about 0.75  $C_{ax}$  along PS edge, where the reattachment occurs at about 3%  $C_{ax}$ . The reattachment occupies half of the gap at about 0.8  $C_{ax}$  and the gap flow is fully separated in the last 5%  $C_{ax}$ . The streaks leading towards the SS edge are more or less normal to the camber line up to about 0.8  $C_{ax}$  along camber line, after which the streaks are turned more towards the camber-line. An interesting observation is the path followed by the paint after impinging on the tip platform. It was noted earlier that paint lines are oriented towards blade TE at reattachment and subsequently these lines turn towards either blade PS edge and into the bubble, or blade SS edge. This turning is seen to be more gradual for flow towards SS edge than in the direction of the bubble. Therefore, the recirculating flow experiences severe acceleration towards the PS corner. This behavior is consistent with the significantly low PS edge pressures measured by Xiao et al [19] in the AFTRF and by Bindon [21] in a linear cascade. After about 0.6  $C_{ax}$  the streaks turn more sharply towards SS corner. This change may result from a drop in chord-wise pressure gradient. The surface flow patterns observed are similar to the streamline patterns, on a plane parallel to and very close to the tip surface, obtained from a steady computational simulation by Prasad and Wagner [22].

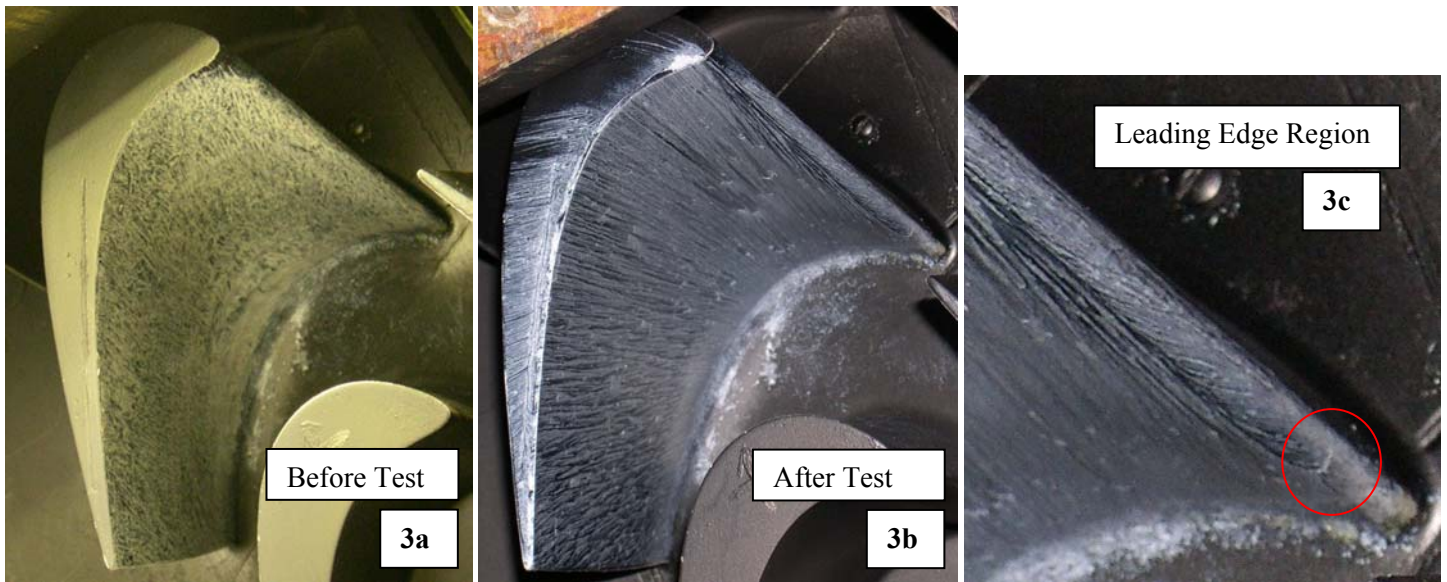
**Heat Transfer Implications:** The tip surface flow patterns observed also have important heat transfer implications. Impingement of over tip leakage flow causes higher heat transfer to the region near the PS corner of the blade. Acceleration of fluid into the recirculation bubble results in higher wall shear, enhancing heat transfer to the tip surface around the reattachment line. Tip heat transfer coefficients measured by Kwak et al [23] in a linear cascade show a region of maximum heat transfer coefficient beginning at the PS corner and extending into the tip surface. This region also covers the entire blade chord. Additionally, chord-wise flow in the recirculation bubble could trap high temperature fluid entering the blade row, thereby exposing the near PS corner of

the tip surface to near inlet total temperatures. Previous hot streak studies, for example Prasad and Hendricks [24], indicate that the maximum temperature in the core of the passage flow entering the blade row usually migrates to the PS corner of the blade tip. Fully separated gap flow, as observed in the last 5% blade chord, would lead to decreased heat transfer due to low momentum activity in this region.

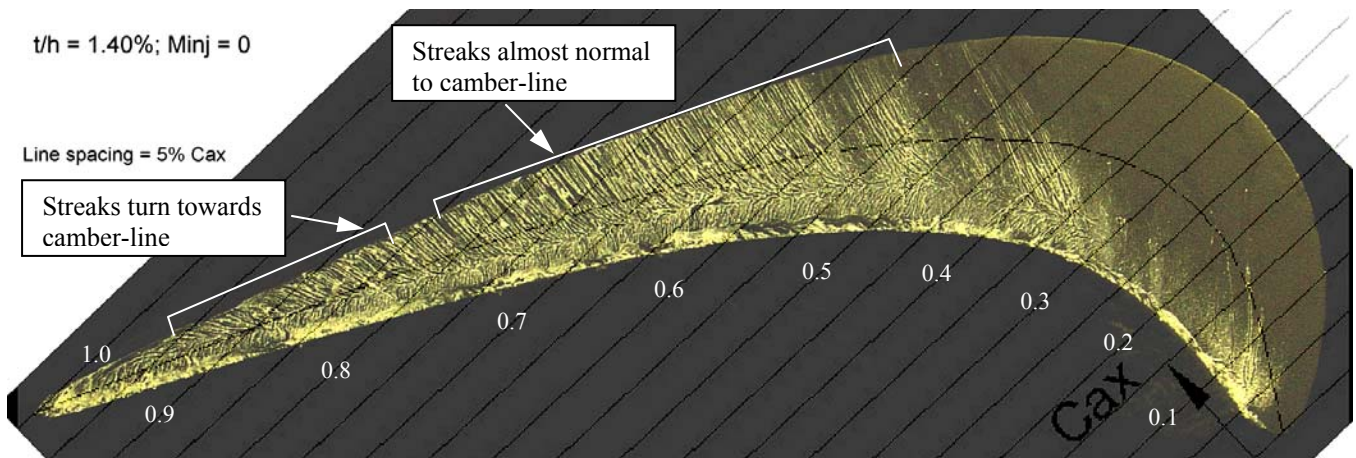
**Visualization in A Gap With Tight Clearance,  $t/h = 0.72\%$  (Case T2):** The tip surface flow patterns on a blade (Blade #7) with half the clearance gap as that of the test blade is shown in Fig. (5). The region near the PS corner indicating reattachment and recirculation is reduced at the smaller clearance gap. Reattachment occurs at about 2%  $C_{ax}$  (2.1\*gap height) from the PS edge. The narrow appearance of the separation zone near the PS corner could be a result of turbulent shear influence of the casing. Minimal paint lines are formed in the region up to about 0.25  $C_{ax}$  along PS edge. Normal to 0.35  $C_{ax}$  along the pressure-side, a circle identifies a region of smeared paint lines, similar to that shown in Fig. (4) and attributed to the possible ejection of the separation bubble. Thus, there seems to be a shift towards the leading edge of some of the consistent flow features when the gap height is reduced. In a direction normal to the PS corner and in the region between 0.65 and 0.7  $C_{ax}$  along the pressure-side there is a region of higher shear, as evidenced from the observation that more of the tip surface is visible. This is not observed in the large tip clearance case and hence would seem to be characteristic of smaller clearance gaps. As will be shown later in the paper, suction surface traces show that significant leakage flow appears to enter the passage just upstream of this region. Hence, the higher velocity and shear, in this region could be due to proximity of leakage vortex to the suction surface. Measured blade pressure coefficient in Xiao, et al [19] shows a significant dip in the suction surface pressure around 0.6  $C_{ax}$ . The return of dense paint patterns to the left of this region would indicate the movement of the leakage vortex away from blade suction surface. In the case of  $t/h = 1.40\%$  the vortex forms much farther away from the suction surface and hence a reduced influence on the gap flow.

There is no sign of a fully separated tip in this case, as even at the trailing edge there is a distinct direction to the paint lines indicating flow post reattachment towards blade SS edge. Lines near the trailing edge are however not oriented almost normal to the camber-line. This is attributed to the increased tangential momentum of the leakage flow as it enters the tip gap. It was shown earlier that pressure surface patterns qualitatively indicate increased wall shear due to passage flow. The flow starts to turn away from normal to camber line at about 0.8  $C_{ax}$  along the camber line. Bindon [20] indicates that in the near TE region of the tip, flow in the separation bubble may be moving away from the trailing edge. The orientation of paint lines in the recirculation zone indicate however that the flow is indeed towards the trailing edge. While it is not clear from the paint patterns, it is expected that the bubble is ejected into the blade wake.

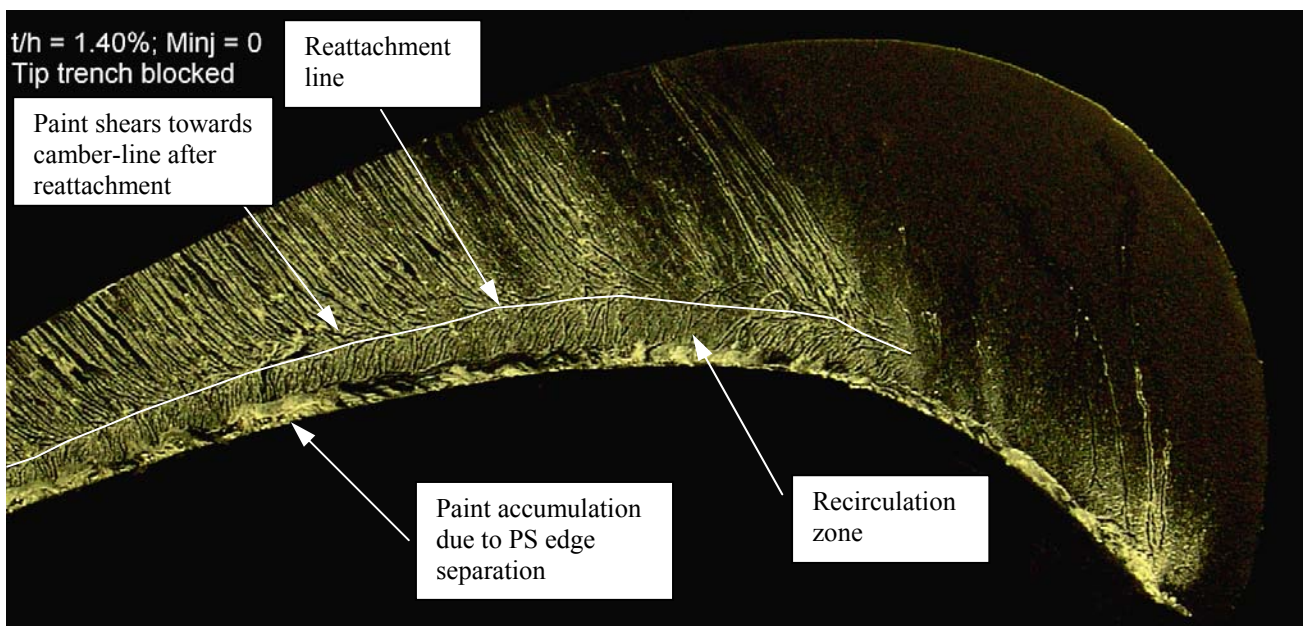




**Figure 3** Blade Pressure Surface, a) before test, b) after test, c) Enlarged view from b.

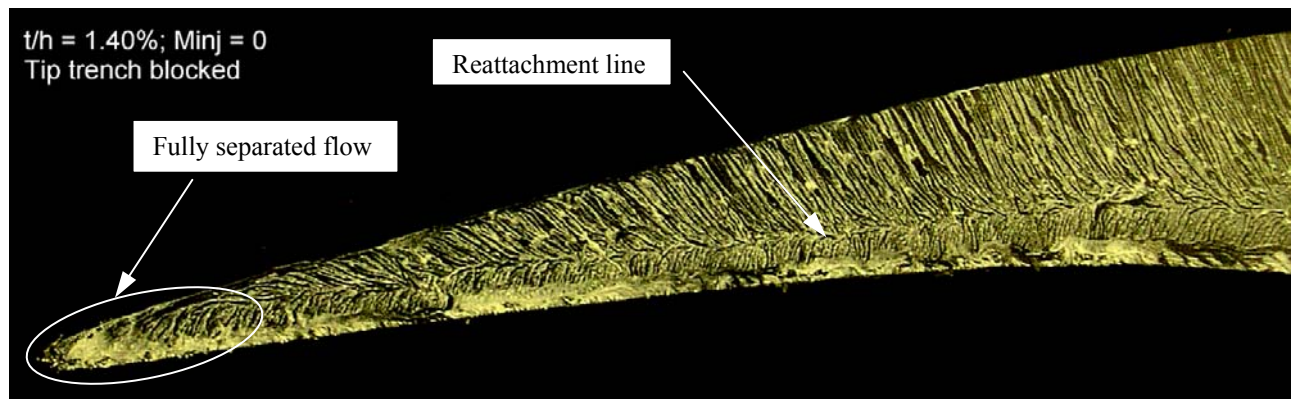


**Figure 4a** Surface Flow Patterns for T1; Blade #21,  $t/h = 1.40\%$ ,  $M_{inj} = 0$

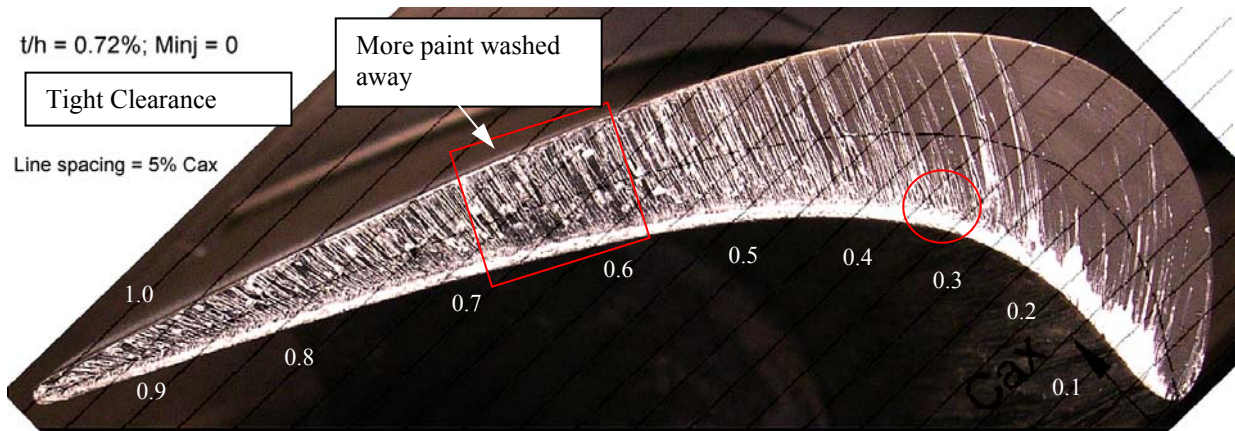


**Figure 4b** Surface Flow Patterns near Leading Edge for T1; Blade #21,  $t/h = 1.40\%$ ,  $M_{inj} = 0$

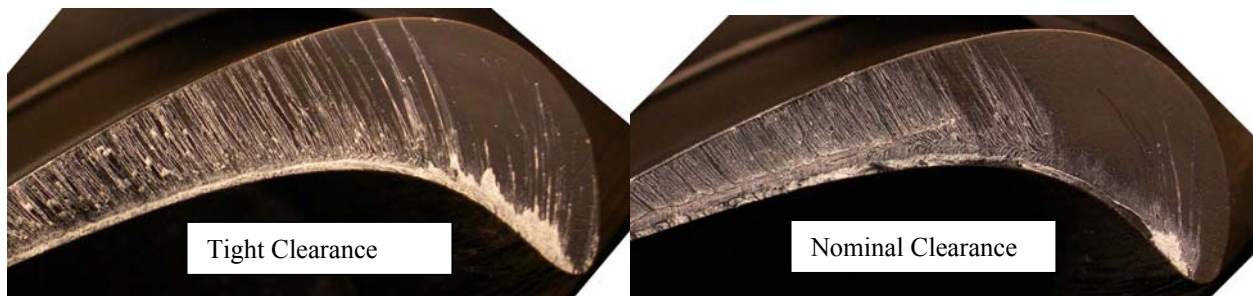




**Figure 4c** Surface Flow Patterns near Trailing Edge for T1; Blade #21,  $t/h = 1.40\%$ ,  $M_{inj} = 0$



**Figure 5** Surface Flow Patterns for T2; Blade #7,  $t/h = 0.72\%$



**Figure 6** Comparison of Surface Flow Patterns for Blade #7 ( $t/h = 0.72\%$ ) and Blade #21 ( $t/h = 1.40\%$ )



**Figure 7** Comparison of Suction Surface Traces for T2 (Blade #7) and T1 (Blade #21)

**Comparison of Visualization From Nominal and Tight Clearance:** To compare the paint accumulation in the near leading edge region images obtained from the same test are shown in Figure (6). The trench in Blade #21 was filled in by silicon sealant. The visualization from tight clearance in Fig. (6) shows thicker and more visible paint accumulation on the tip surface when compared to the large clearance picture. The outer casing shear influence on the near tip flow is much stronger at the smaller clearance. When the clearance is large, more visualization material is swept away from the tip surface because the leakage flow imposed shear dominates in the gap region. Lower momentum in the tight clearance gap and much smaller separation region cause more paint to accumulate on the tip surface of Blade #7. Paint carried by the re-circulating fluid in the bubble would also deposit paint in this region as the shear stress is reduced at the edges of the bubble. The accumulation does not necessarily reflect the flow in this region.

It appears that irrespective of the tip gap height, reattachment occurs at a distance of about 2 gap heights from the PS corner of the blade. Harvey [4] notes that in instances where the blade thickness is less than 2.5 gap heights the clearance flow is unlikely to attach. Additionally, at the large gap height the flow appears to be fully separated beyond the point where blade thickness is 3.56 mm (2.1\*gap height). In investigating the behavior of squealer tips, Dey [25] concluded that squealers performed best at small gap heights. The change in location of the reattachment line between the two gap heights presented might be a cause for benefits due to squealer tips to decrease with increase in the clearance gap.

**Table 4** Measurements from Tip Leakage Vortex Trace on Suction Surface

Test Case	Blade #/ (t/h%)/(M <sub>inj</sub> %)	Approximate beginning of SS Trace as % C <sub>ax</sub>	Trace width at TE as %h	Width of paint free zone at TE as %h
T1	21/1.40/0	0.7	15	6
T2	7/0.72/0	0.65	12	3
T4	21/1.40/0.4	0.6	10	5
T6	21/1.40/0.5	0.8	8	-
T7	21/1.40/0/6	0.75	10	-
T8	21/1.40/0.7	0.8	12	-

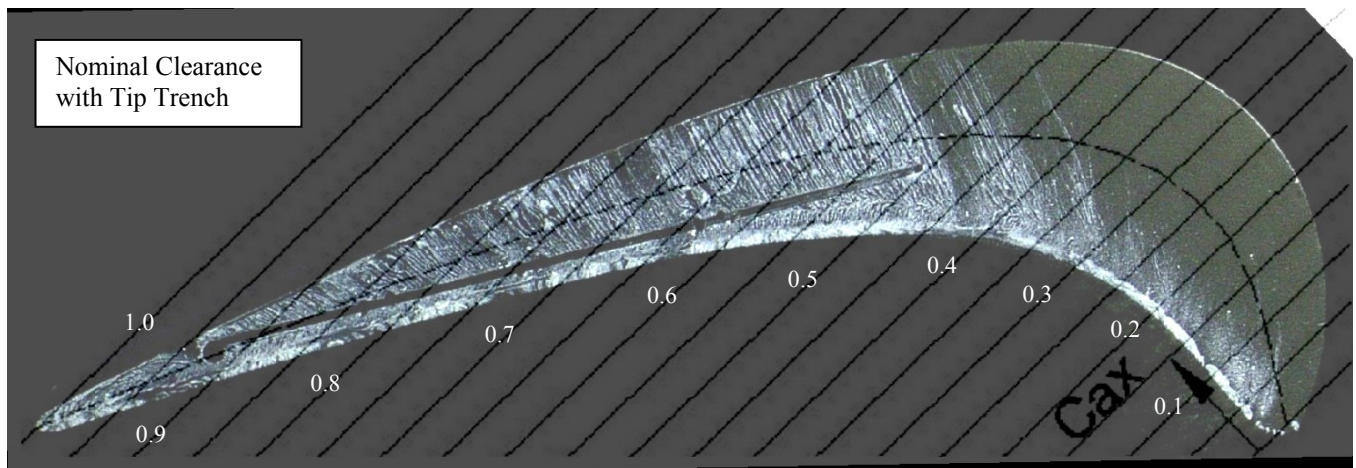
**Heat Transfer Implications of Tight Clearance:** The area affected by flow reattachment on the tip surface is reduced at the smaller clearance gap. This would confine the region of enhanced heat transfer closer to the PS corner. Measurements by Kwak et al [23] show that at the smallest gap, the maximum heat transfer coefficients are confined to a narrow region close to the PS corner. Flow reattachment on the tip surface, in the last 5% chord, would lead to increased tip heat transfer near the blade trailing edge. This behavior is also captured in simulations by Ameri et al [26]. The increase in average tip heat transfer in about the last quarter chord, with

decreasing gap height, is attributed to the size and extent of the separation bubble.

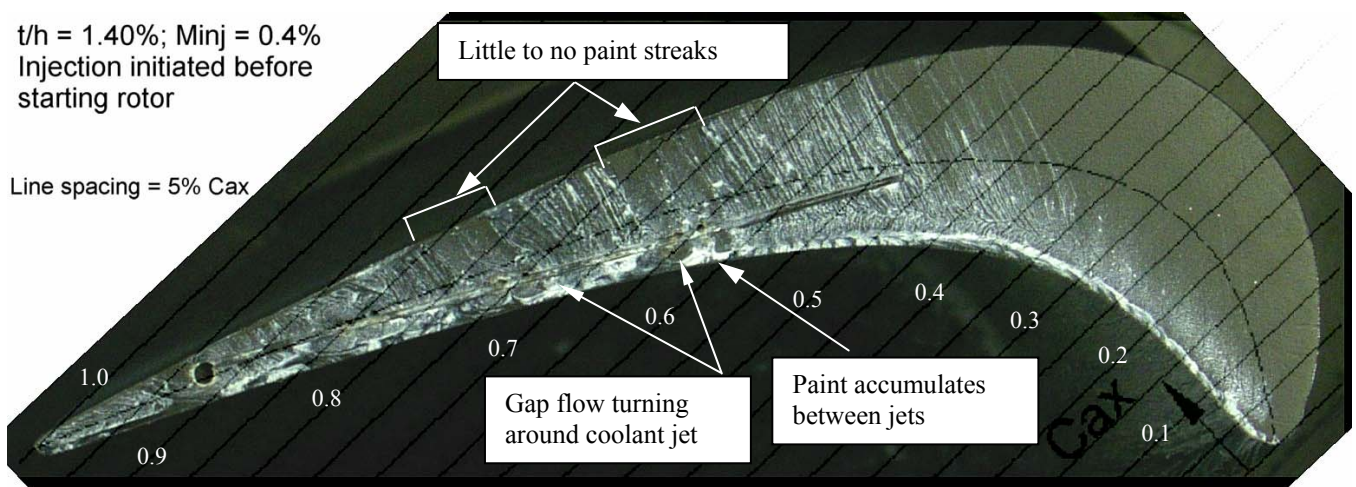
**Paint Deposition on Blade Suction Surface:** Leakage flow carries some of the visualization material onto the blade suction surface near the blade tip. Suction surface patterns for tight clearance (Blade #7) and nominal clearance (Blade #21) are compared in Fig. (7). It may be observed that the streaks start out bright and fade along the chord. Based on measurements, the paint trace begins close to 0.65 C<sub>ax</sub> along the SS edge for Blade #7 and close to 0.7 C<sub>ax</sub> for Blade #21. This data is tabulated in Table (4). This movement of flow features towards leading edge with decrease in gap height was also pointed out in the discussion of tip surface patterns. The paint streak was observed to be brighter on Blade #7, probably indicating more paint deposition. At the trailing edge the width of the paint patch is about 12% blade height and it begins 3% blade height below the tip platform. For Blade #21 the patch width is about 14% blade height and there is a paint free region of 6% blade height from the tip. It appears that the paint streak grows much faster for Blade #21 than for Blade #7. This is consistent with the fact that increased vorticity entrains more fluid. Total pressure measurements downstream of the rotor by Rao and Camci [1] show that the leakage vortex occupies 15% blade height for a blade with t/h = 1.40%, and about 10% blade height for a blade with t/h = 0.72%. Additionally, the leakage vortex for blade with t/h = 0.72% was seen to have moved substantially towards the blade suction surface. Thus, it is submitted that the variation seen in paint deposition is supported by the total pressure measurements. Near tip suction surface heat transfer coefficient measurements by Kwak, et al [22] indicate a general trend of reduction in maximum heat transfer coefficient with increase in gap height. This is accompanied by a spreading of the maximum heat transfer zone. The results shown here appear to follow the same trend.

**Influence of Tip Trench (Case T3):** The effect of the tip trench on the gap flow is presented in Fig. (8). As compared to the flat tip surface flow patterns, there appears to be little change in surface flow in the front half of the blade. The reattachment line is seen to meet with the tip trench near 0.55 C<sub>ax</sub> along the camber line. There is no distinct reattachment line along the rest of the tip surface. However, the patterns between trench and PS edge show recirculatory pattern up to H1. The pattern then appears again, not quite as distinctly, after H2. Between H1 and H2 the region between trench and PS edge shows more paint accumulation than the flat tip. It is possible that the reattachment line terminates on the SS edge of the trench and the trench weakens the recirculation. There is no paint accumulation in the trench, except close to 0.5 C<sub>ax</sub>, indicating that reattachment does not occur in the trench. It is expected that a chord-wise flow is set up in the trench. One of the interesting changes from the flat tip is the region of low paint concentration to the left of H1. The reason for this is unknown and it is not observed at the other injection locations. The suction surface trace of the leakage vortex was very similar to that presented for the flat tip (Case T1).

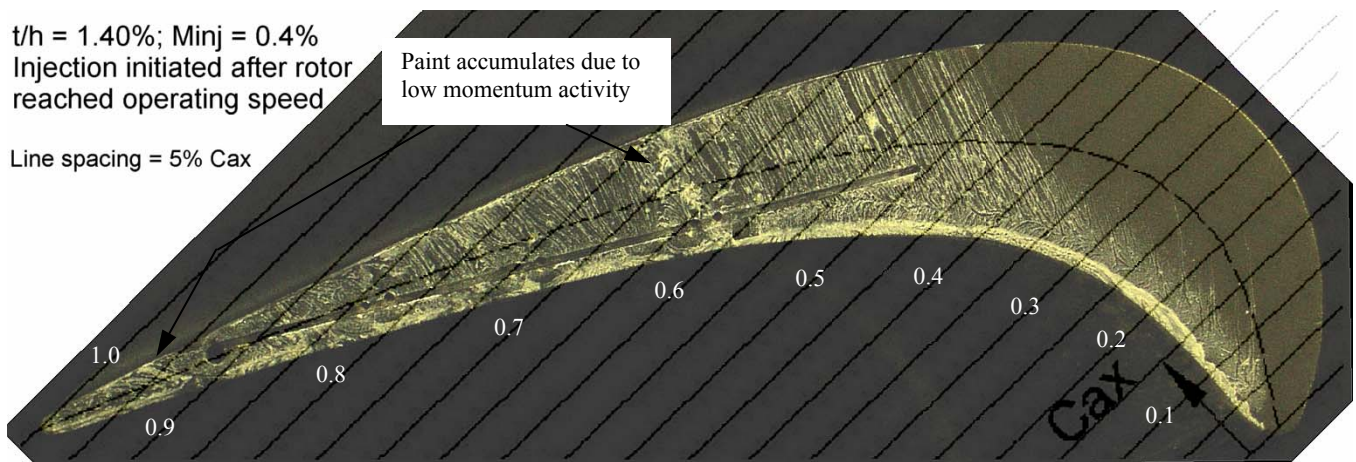




**Figure 8** Surface Flow Patterns for T3; Blade #21 with Trench,  $t/h = 1.40\%$ ,  $M_{inj} = 0$



**Figure 9** Surface Flow Patterns for T4; Blade #21,  $t/h = 1.40\%$ ,  $M_{inj} = 0.4\%$



**Figure 10** Surface Flow Patterns for T5; Blade #21,  $t/h = 1.40\%$ ,  $M_{inj} = 0.4\%$

**Visualization with Tip Injection ( $t/h=1.40\%$ ,  $M_{inj} = 0.4\%$ ):**

This particular injection case was tested in two different ways, as described in Table (3). Figure (9) shows the surface flow patterns when injection was commenced before startup, while Fig. (10) was obtained for injection after rotor reached the operating speed.

**Injection commenced before start-up (Case T4):** With injection fully stabilized before start-up it is expected that areas of the tip surface influenced by coolant injection will show decreased concentration of paint streaks. This could be a result of either the coolant jets blocking the leakage flow, or due to the coolant jets forming a film over the tip surface.

Surface flow patterns up to about  $0.55 C_{ax}$  along the PS edge observed in Fig. (9) are similar to those observed for no injection and large gap. The reattachment line, apparent separation bubble ejection, and paint streaks towards the SS corner are similar to that for flat tip (Case T1) and tip with trench (Case T2). The reattachment disappears after  $0.6 C_{ax}$  along PS edge, close to H1. Jet penetration into the leakage flow, due to coolant injection from H1, leaves an arc-like pattern between the trench and the PS edge. Separation is not completely eliminated and the divergence of the jets from each other allows paint to accumulate, from the PS corner up to the trench. Behind H1 there is a large area with little to no paint streaks on the tip surface. Thus the coolant jets spread out as they turn and flow towards the SS edge of the blade. The leading jet does not lean towards the trailing edge and is turned back sharply. The trailing jet on the other hand does have a  $10^\circ$  angle towards the trailing edge and is turned more gradually. The lack of paint accumulation at  $0.65 C_{ax}$  along PS corner indicates that the trailing jet is successful in changing the leakage path. Once the jet is turned back it covers a larger area on the tip platform than the leading jet. Immediately behind the injection holes there are very few paint streaks, when compared to the no injection cases. The streaks that do exist are located in between the injection holes. Thus, the influence of the jets is to prevent some of the separation, eliminate recirculation, and form a film over the platform. Between H1 and H2 paint accumulates at the PS edge and paint streaks are formed downstream of the trench. These patterns are however lighter and spaced farther apart than those on the front part of the blade.

The path of leakage flow around the leading jet from H2 is somewhat discernible by the curvature of the paint streaks. It appears that separation is mostly eliminated by the trailing jet at H2. The jets are again turned back, leaving a large clear region behind the jets. Injection from H3 is not much different in the effect it has on the gap flow. The coolant jets start out towards the pressure-side and are turned to flow towards the suction-side. Tip separation is reduced along the PS edge from about  $0.72 C_{ax}$  to  $0.85 C_{ax}$ , the region of influence of H2 and H3. Downstream of H3 the paint is considerably smeared suggesting mixing of coolant and leakage fluid. The last injection hole (H4) is radial and hence allows for separation to occur between  $0.85 C_{ax}$  and  $0.9 C_{ax}$ . It appears however to block the leakage flow beyond  $0.9 C_{ax}$ , forcing the leakage to pass more tangentially through the gap. More importantly there are no signs of a fully separated tip. A general

observation that can be made is the accumulation of paint in the trench, especially in the vicinity of H1 and between H2 and H3. It was shown in Case T3 that these regions were free of paint, suggesting that, with injection, leakage flow reattaches in the trench.

**Injection commenced at operating speed (Case T5):** Figure (10) shows tip surface flow patterns for the case when the injection is initiated after the rotor reached operating speed. The patterns are qualitatively different. In this case, by the time the injection is initiated, there is some deposition and shearing of paint on the tip platform. Injection is fully stabilized 30 seconds after rotor speed is set to operating speed. Subsequently, with injection it is expected that areas of low flow momentum activity will display greater concentration of paint, while a lower concentration of paint will indicate flow with greater momentum. Interrogating the image with this perspective it is clear that both Fig. (9) and Fig. (10) essentially represent the same flow patterns. The reattachment line terminates at about  $0.6 C_{ax}$ . The first set of injection jets start out towards the pressure-side and are turned away towards the suction-side. Paint accumulation behind H1 is dense, indicating low flow velocities in this region. The accumulation is particularly high behind the trailing jet of H1 and this could be due to the orientation of the hole. The higher jet velocities lead to lighter patterns on either side of the injection holes, as more paint is washed out. This is a clear indication of formation of a film over the tip surface. Downstream of H2 the patterns are also similar to that in Case T4. The accumulation of paint due to lower momentum flow actually occurs to the left of the trailing jet, instead of behind it. Streak patterns along blade PS edge are comparable to Case T4. As a sign of repeatability, the bright paint streak that occurs downstream of H4 in Case T5 is almost identical to the dark streak in Case T4. Interestingly, one of the changes that may be observed is the lack of paint accumulation in the tip trench when injection is commenced after the rotor reached operating speed. This is similar to Case T3. This suggests that most of the paint is carried onto the tip platform in the first 90 seconds of run time, the rest of the time is needed to develop the patterns observed.

**Other Injection Rates:** The other injection rates tested were,  $M_{inj} = 0.5\%$ ,  $0.6\%$ , and  $0.7\%$ . These results are shown in Fig.(11), Fig.(12), and Fig.(13), respectively. In each case, leakage flow up to about  $0.6 C_{ax}$  is unaffected by the injection. At H1 the patterns are comparable to those observed in Fig. (9). Higher jet momentum has almost eliminated paint accumulation due to PS edge separation, upstream of H1. Coolant film on the surface produces clear regions, while paint streaks are formed immediately downstream of the jets. More paint streaks are formed downstream of the trench as injection rate increases. This is not unexpected since an increase in jet exit velocity decreases jet spreading. The patterns however are not as sharp and distinct as those upstream of  $0.5 C_{ax}$ , indicating mixing of coolant with the bulk leakage flow. The most striking difference for these injection rates is that the leading jet covers more surface than the trailing jet. This is opposite to that observed for  $M_{inj} = 0.4\%$ . Additionally, it

appears that the influence of the trailing jet begins farther downstream along the blade chord than for  $M_{inj} = 0.4\%$ . This is again consistent in that greater jet momentum will better resist turning due to leakage flow. There is also significant paint accumulation in the trench. At H2 the patterns are similar to those shown for Case T4, while the variations may be explained as caused by increasing injection rates. PS edge separation is again almost eliminated in all cases. The most interesting change is exhibited by injection from H3. The jet trajectories are defined better at the higher injection rates of  $M_{inj} = 0.6\%$  and  $M_{inj} = 0.7\%$ . The leading jet appears to be more effective in covering the tip surface than the trailing jet. The influence of the trailing jet is farther to the left of the trailing jet. Injection from H4 appears to stagnate around the hole and flow over the SS edge into the passage. There is again no sign of a fully separated tip at all three injection rates.

#### **Tip Surface Heat Transfer Benefits of Coolant Injection:**

Coolant injection reduces the effects of flow separation and reattachment on the tip surface. This would lead to a decrease in heat transfer to the tip surface. The surface flow patterns also indicate that in the region between the tip trench and SS corner of the tip surface a reduction in tip heat transfer is possible. Blockage of the leakage flow leads to low momentum activity between the injection holes and the SS corner. Additionally, the coolant jets turn towards the SS corner and form a film over the tip surface. Both these effects would also reduce heat transfer to the tip surface.

#### **Paint Deposition on Blade Suction Surface with Injection:**

The suction surface traces of the tip leakage vortex are shown in Fig. (14) for  $M_{inj} = 0.4\%$ ,  $0.5\%$ , and Fig. (15) for  $M_{inj} = 0.6\%$ ,  $0.7\%$ . For  $M_{inj} = 0.4\%$  the streak pattern is similar to that obtained without tip injection and is seen from approximately  $0.6 C_{ax}$ . This is actually closer to the leading edge than in the case of  $t/h = 0.72\%$ . It appears that blockage due to coolant injection from H1 is causing the leakage flow to turn away from the engine axis. Visual observations showed that there was more paint deposition. This could result from the leakage vortex moving closer to the suction surface, a result supported by the total pressure measurements in Rao and Camci [1]. The width of the patch, at the trailing edge, is about 10% blade height and the clear region measures 5% blade height from the tip. In comparison to the flat tip case there is some movement of the vortex closer to the blade tip. The trace appears to start closer to the trailing edge for Case T6. Indeed, the trace is not continuous, rather shows multiple leakage entry paths, at  $0.8 C_{ax}$  and  $0.88 C_{ax}$  along the SS edge, into the passage. There is a paint free region between the two entry points and the patch extends 8% blade height from the tip. The greatest paint deposition occurs after  $0.95 C_{ax}$ . Injection at  $M_{inj} = 0.6\%$  also displays multiple entry points along the suction surface, the first one located at  $0.75 C_{ax}$  along SS edge. Maximum paint deposition occurs beyond  $0.95 C_{ax}$  along SS edge. The trace measures 10% blade height from the tip. At  $M_{inj} = 0.7\%$  the first clear entry point is at

$0.8 C_{ax}$ . There is a very light trace that appears to start at  $0.73 C_{ax}$ . It was noticed that even when using the same mixture, the sharpness of the patterns varied, probably due to initial room temperature. This might be a reason for the traces to show up much later along the suction surface for cases T6 and T7. The patch extends 12% blade height from the tip for T7. The maximum paint deposition occurs after  $0.95 C_{ax}$  along SS edge. It is clear that other than at the lowest injection rate, the injection jet near the trailing edge does cause leakage flow near the trailing edge to be channeled into the passage. From a heat transfer perspective these results show that the heat transfer coefficient on the suction surface may be greater than that for  $t/h=0.72\%$ . It also identifies a potential problem area, close to the trailing edge region where the heat transfer may actually be increased beyond that experienced by a blade with  $t/h=0.72\%$ .

#### **CONCLUSIONS**

Oil paint was used to visualize tip leakage flow in a large scale rotating turbine facility. It is believed to be the first such study presented in literature available in the public domain. Results were presented for flat tip at gap heights of  $0.72\%$  and  $1.40\%$  blade height. Desensitization due to coolant injection from a tip trench was also studied at injection mass flow rates of  $0.4\%$ ,  $0.5\%$ ,  $0.6\%$ , and  $0.7\%$  of the turbine mass flow.

The visualization technique employed was able to distinguish many important features of turbine tip leakage flow. Pressure-side edge separation causes paint accumulation on the PS corner of the tip surface. Reattachment of leakage flow on the tip surface was also clearly defined. A distinct line is formed separating flow towards blade SS edge and that trapped in the recirculation. The orientation of paint lines at reattachment suggests a three-dimensional reattachment.

The near PS corner region of maximum heat transfer, typical of axial turbine blades, may be attributable to the following flow phenomena; impingement of leakage flow on to the tip surface, acceleration of flow in the separation bubble towards the PS corner, and chord-wise flow within the separation bubble that can transport high temperature fluid from near the leading edge.

For the large clearance gap, the reattachment line lies, on an average, 3.5 mm from the PS edge. The reattachment line is located about 2 mm from the PS edge at the small clearance gap. However, when measured in terms of gap height the distance, PS edge to reattachment line is more or less constant at  $2 \times \text{gap height}$ , at both gap heights.

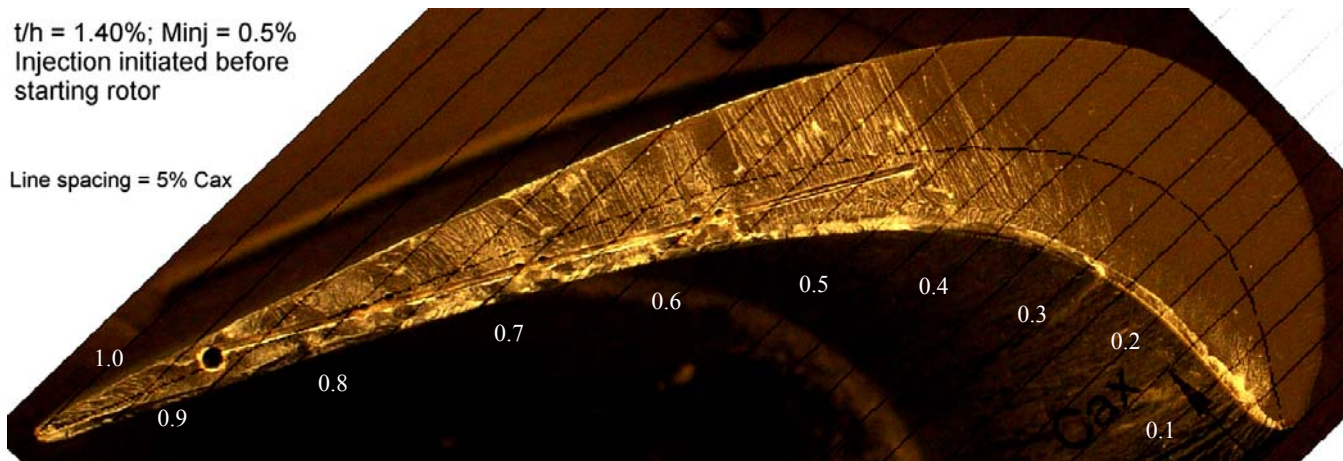
Leakage flow in the last 5% of the blade fails to reattach on the tip surface at the large clearance. When clearance is reduced by half, there are no indications of fully separated flow over the tip surface in this region. This leads to increased tip surface heat transfer near the trailing edge.

A high shear zone is observed at about  $0.75 C_{ax}$  along the camber-line, at the small clearance gap. This is attributed to increased gap velocity due to leakage vortex proximity to the suction surface.



$t/h = 1.40\%$ ;  $M_{inj} = 0.5\%$   
Injection initiated before  
starting rotor

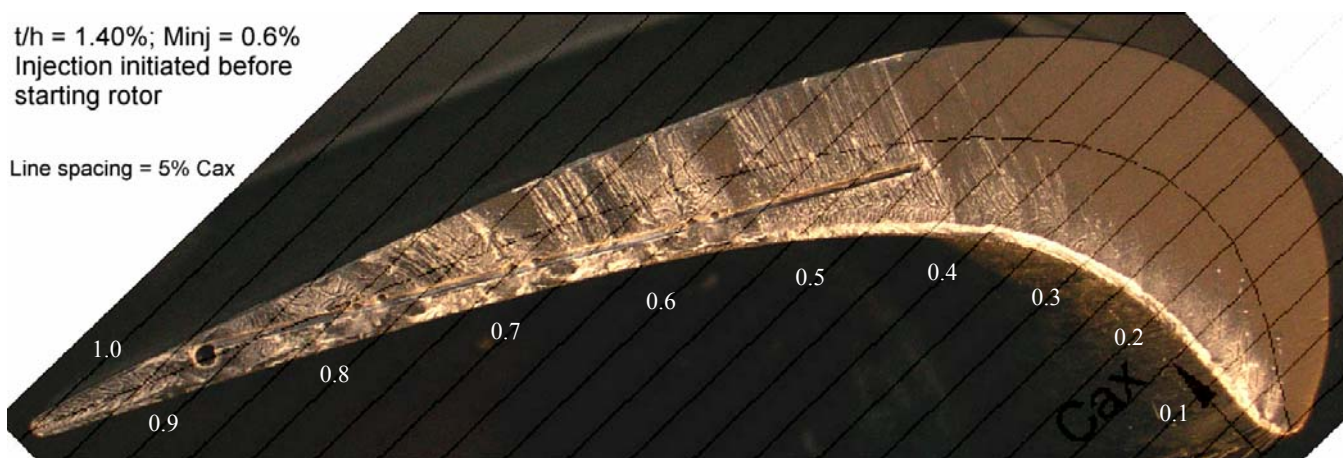
Line spacing = 5% Cax



**Figure 11** Surface Flow Patterns for T6; Blade #21,  $t/h = 1.40\%$ ,  $M_{inj} = 0.5\%$

$t/h = 1.40\%$ ;  $M_{inj} = 0.6\%$   
Injection initiated before  
starting rotor

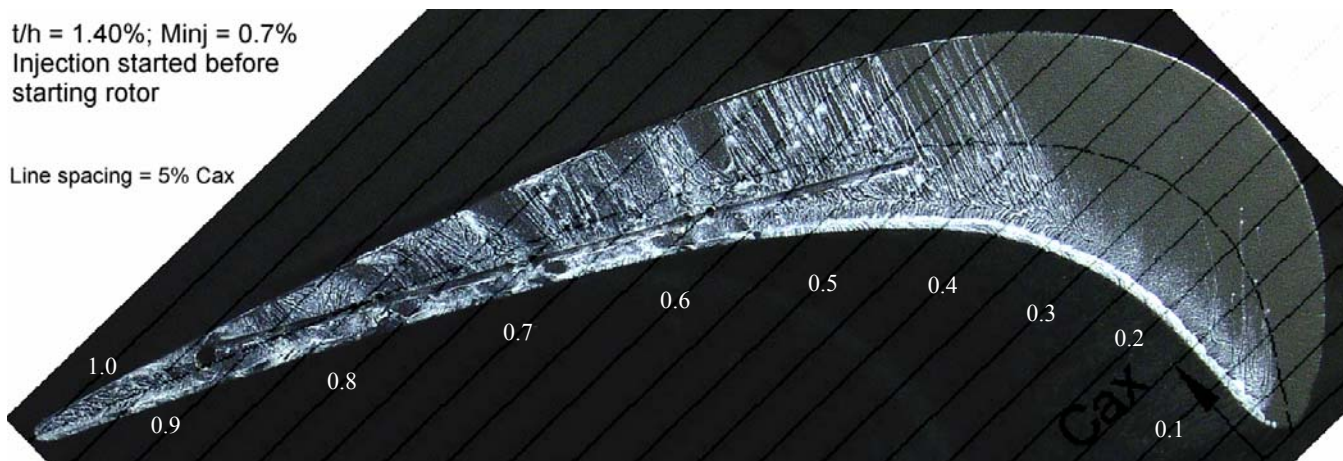
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**Figure 12** Surface Flow Patterns for T7; Blade #21,  $t/h = 1.40\%$ ,  $M_{inj} = 0.6\%$

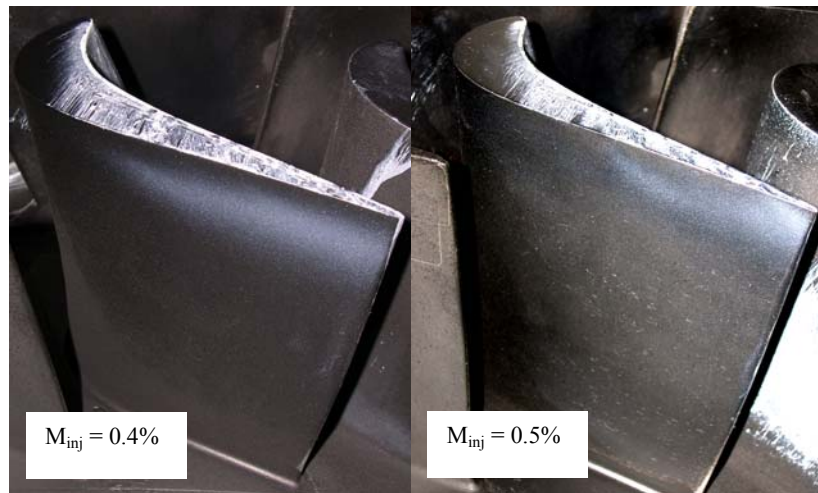
$t/h = 1.40\%$ ;  $M_{inj} = 0.7\%$   
Injection started before  
starting rotor

Line spacing = 5% Cax

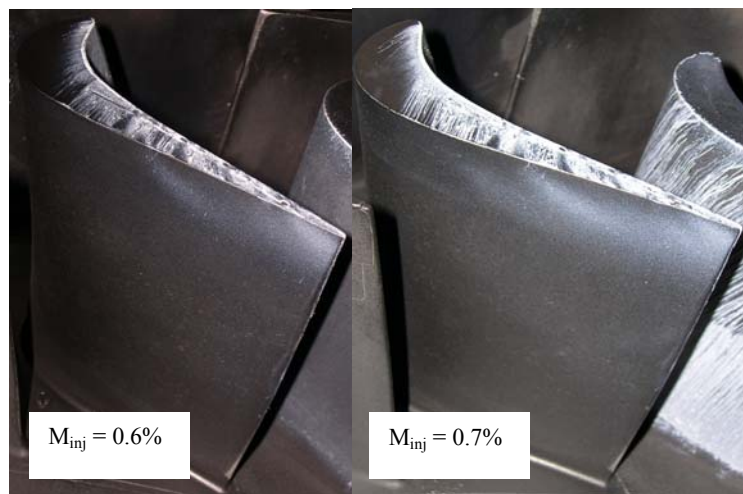


**Figure 13** Surface Flow Patterns for T8; Blade #21,  $t/h = 1.40\%$ ,  $M_{inj} = 0.7\%$





**Figure 14** Comparison of Suction Surface Traces T5 and T6



**Figure 15** Comparison of Suction Surface Traces T7 and T8

## CONCLUSIONS (...continued)

Pressure-side corner separation is substantially reduced at all injection rates tested. Recirculation is completely eliminated in the last 40% of blade axial chord. This should reduce not only the gap mixing losses, but also heat transfer to the tip surface in this region. Flow in the last 1/3<sup>rd</sup> of the blade is substantially changed, including the elimination of fully separated tip region.

Coolant jets form localized films on the tip platform, at all injection rates. The leading jet of each injection set forms a film to the right of the hole, while the trailing jet forms a film to the left, due to inclination towards the trailing edge.

At 0.4% injection rate the trailing jets cover the largest area on the tip surface. At the other three injection rates the best surface area coverage is obtained from the leading jets. Thus, orientation of cooling jets appears to depend upon the amount of coolant injected. Increasing the injection rate also appears to cause more mixing between the coolant and the leakage fluid.

Leakage flow is blocked by the coolant jets, leading to low momentum activity between the injection holes and the SS corner.

Blade tip heat transfer between the tip trench and SS corner is expected to decrease due to both film formation and blockage effects.

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