Mechanism, Characterization, Pattern and Effect of Roughness over Turbine Blade: A Review

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Abstract: The roughness over the blade surface is generally created by solid and water particles impact and also due to corrosion. The roughness patterns are also depends on fluid dynamics of flows i.e. growth of boundary layer, Reynolds number, pressure distribution, and flow angles variation etc. In the present paper mechanism of roughness creation, its quantification, pattern and effect have been reviewed.

Keywords: Mechanism of Roughness, Cascade, Boundary Layer, Roughness.

I. MECHANISMS OF ROUGHNESS

In turbines, roughening of blade surface is caused by erosion, corrosion, and deposition, individually or in tandem due to a variety of physical and chemical phenomena. It results in change in blade profile and roughness over the surface that varies along the blade span as well as from initial stage to final stage. Brief description on each of these three mechanisms is given below.

A. Erosion

Erosion is removal of material by cutting and ploughing by particles or local melting of material due to localized high temperature caused by particle impact. In a particular particle-target material combination, particle size, impacting velocity, impingement angle, and metal and fluid/gas temperature affect the erosion rate and its location, [Hamed and Fowler 1983]. Tabakoff [1984] observed that erosion increases by 2.5 times when temperature increases from 26°C to 649°C and by 6.5 times when velocity increases from 197 m/s to 328 m/s. Water drops (50-450 µm diameter) present in wet steam impinge on blades and cause erosion mainly at leading edge [Ansari, 1986]. In a two stage turbine, particles that initially impact the leading edge on either pressure or suction sides, again impact the pressure surface closer to the trailing edge [Tabakoff and Metwally, 1992]. Erosion increases radially towards the blade tip and increases axially from trailing to leading edge. The resulting removal of blade material (original or deposited) generates peaks and valleys on surfaces that deepen and widen with operation. For an automotive gas turbine engine, Metwally et. al [1995] observed that the stator blade suffers maximum erosion at leading edge and at trailing edge near the hub, whereas for the rotor blade maximum erosion occurs mostly at the outermost radial locations. The mechanism of erosion also depends on the growth of the boundary layer over the blade surface and angle of incidence, [Mann, 1999].

1. Particle dynamics

Adverse effect of particle-laden gas flow on turbine torque, power and efficiency increases with increase in particle concentration and particle mean diameter, Tabakoff et al. [1976]. As operating power plants age, the particle concentration in the steam/water increases and consequently, the performance deteriorates continuously. In general, the dynamics of particles through turbo machines is determined by gas-particle interaction and particle surface impacts. Using high speed photography, Hamed [1984] concluded that the hub impacts reflect the particles in the radial direction while the blade impacts reflect the particles in the circumferential direction. He also saw that trajectories of large particles are dominated by their surface impacts, whereas small particles are strongly influenced by the flow field. It was also observed that for very large particles (~1000 μm), the impacts are distributed over the entire pressure surface and erosion increases towards the hub trailing edge. However, the blade erosion due to impacts by smaller particles increases with increase in impact velocity on the pressure surface from mid-chord towards the tip. In another study Stephenson et al. [1986] observed that erosion of turbo machinery material by pyrolytic carbon particles is a function of the temperature and oxide thickness also. Lower temperature and thicker oxide scales favour brittle erosion behaviors.

To minimize erosion a coating over the blade surface is applied. Tungsten carbide and chromium carbide super D-Gun coatings not only have better erosion resistance than their D-Gun analogs, but cause little or no degradation of the fatigue properties of the blade alloys, [Walsh et al.,1995]. Shanov and Tabakoff [1996] observed that with hot wall chemical vapor deposition (CVD) of TiC, erosion rate increases with the impingement angle to a maximum at 90°. The TiC coating showed better protection on stainless steel 410 than on INCO 718.

B. Corrosion

The presence of oxygen, carbon dioxide and wetness in steam are responsible for chemical reactions with blade surfaces. This phenomenon produces roughness either due to random thickening of blade profile if the oxidized material adheres to the blade surface or by random thinning
if the oxidized material tears off from the blade surface. In the latter scenario, it could also contribute to erosion of downstream stages. Corrosion depends on the electrochemical processes taking place at the boundaries of contact, usually between wet steam and the metal. Povarov and Tomarov [1985] attributed corrosion as a formation of micro cells at the surface of metal consisting of anodic section where metal loses its ions and electrons and cathodic section where electrons are absorbed and, hence, the rate of corrosion is governed by overall current through the circuit. Magnetite thus formed has matching crystalline lattice parameters and adheres strongly to the blade acting as a protective layer, a process called passivation. The protective layer is disrupted due to solid particulate erosion and, thereafter, it is difficult to arrest corrosion which results in increased metal loss. The depth of erosion-corrosion is greatest in the temperature range of 150-190 °C due to instability of magnetite. It is less at higher temperatures due to the strong protective layer of magnetite and also at lower temperatures due to retardation of the chemical reactions. Wet steam forms a liquid film on the blade which reduces supply of oxygen to the metal and prevents formation of a passivating layer and, hence, metal loss due to erosion-corrosion caused by other factors increases with wetness. Komarov and Yurkov [1991] reported that corrosion damage occurs only on the parts operating in the phase transition zone, i.e., dry saturated to 6% wet, and no corrosion occurred on blades operating in the superheated region. Vasilenko [1991] has reported that there is no corrosion in the pH range of 7-11, but it occurs in the range of pH<6 and also at pH >12, where fatigue strength of the blade material falls considerably.

C. Deposition

Cotton and Schofield [1971] observed copper salts deposits of 1.0 mm on the nozzles of the 1st stage and 2.4 mm deposits on the 7th stage of a power plant steam turbine. On the rotor blades, deposits varied from 0.3 mm on the 1st stage to 0.5 mm on the 4th stage and 0.7 mm on the 7th stage. Water flowing in the steam path, though well treated, contains salts that are deposited on various surfaces including turbine blades. These salt deposits (David, [1999]) produce rough nesses and alter the blade profile causing performance deterioration and also affect the natural frequency of blading due to added mass on the blades [Stamatis, et al.1999]. The sticking tendency of salts can be controlled by mixing some additives in the working fluids which loosen up the deposits.

II. ROUGHNESS CHARACTERIZATION

To analyze the effect of different level of roughness over the performance parameters, quantification of roughness is required. The roughness has been characterized on the basis of the height of peaks, the structure of roughness and the waviness of surface. The various terms employed for surface roughness are shown in Figure 1.

Sand roughness height \((k_s)\) is the roughness formed by sand grain of size \(k\), when they are closely packed. Centerline average (c.l.a) or Arithmetic average (a.a) or Roughness height \((R_s)\) is the arithmetic average of the departure of the profile above and below its centerline, throughout the prescribed sampling length and in a plane normal to the surface. It is therefore the ratio of sum of the area above and below the centerline to total sampling length. Peak to valley height \((R_p)\) is the difference between the mean heights of the peaks and valley. Root mean square value \((R_q)\) is the square root of ratio of integration of square of distance \((y)\), above and below its centerline with distance over the sample length to the sample length.

Equivalent rough nesses for typical emery paper grades in terms of grit size, c.l.a., \(R_p\), and \(k_s\) have been suggested by different authors and are also given in Table 1.

Different physical measuring instruments are used to measure the roughness. Optical instruments are also used to measure the roughness without physically touching the surface. In-situ roughness is also measured with the help of replica of the surface on polymer sheets or on dental cements and the same can be measured in laboratory. Comparators are also used in absence of accurate measurement to get a fair idea about level of roughness.

III. ROUGHNESS PATTERN

As discussed above erosion, corrosion and deposition depends on various factors and hence the roughness varies from hub to tip, leading edge to trailing edge and initial stage to last stage. The pattern of roughness observed by different authors is summarized here. Cotton and Schofield [1971] observed copper salts deposits of different levels of roughness in rotor and nozzle blades. Similarly, Bolcs and Sari [1988] observed the deposits mainly on the pressure surface, and only a small number of particles stick to the suction surface. Taylor [1990] observed that the first stage blades of TF-100 aircraft turbine were the roughest (10.7 \(\mu\)m) on suction surface at leading edge region, whereas the same stage blades of TF-39 were roughest on the pressure surface near mid-chord (6.86 \(\mu\)m) and trailing edge region (5.5 \(\mu\)m). Bons et al.[2001] observed that some regions on both the suction and pressure surface are prone to specific roughness mechanism, and transition between rough and smooth regions are gradual but could be very abrupt.

In a 210 MW steam turbine, Samsher et al.[2006] observed that the rotor blades of initial stages of IP turbine are subjected to solid particle erosion at suction surface, and deposition over the pressure surface. The inlet steam in these turbines is superheated and the roughness can be attributed primarily to solid particle impact and deposits. The similar roughness was also observed in the rotor and stator blades of the initial stages of the LP turbine. The steam at exit of 8th stage LPT stator was wet and impact of liquid drops could be the cause of erosion on 8th stage rotor blades. The observations on the last four (5th - 8th) stages of...
LPT stator, i.e. roughening due to deposition only. The roughnesses are predominantly in the form of bands (at mid-chord, leading edge, or trailing edge) spread all over the span.

The magnitude and the statistical character of the roughness varied substantially from point to point around the blade; the blade thus does not have a single roughness value.

IV. FLUID DYNAMICS OF FLOW OVER BLADES

A. Boundary layer growth over blade surface

As the flow moves over the surfaces, the boundary layer thickness grows with distance (x) in direction of flow (equation 1), the rate of growth also depends on pressure gradient, [Schlichting, 1968].

\[ \frac{\delta_{99}}{l} = 5 \left( \frac{x}{R_e} \right) \]  

(1)

Where \( \delta_{99} \) is boundary layer thickness, l, characteristic length, \( R_e \), Reynolds number.

The boundary layer is laminar for a small characteristic length (l), but for longer characteristic length, it becomes thicker, and after some length the flow inside it becomes unstable (transition) followed by increase in growth rate of the boundary layer thickness leading to turbulent Boundary layer. In presence of adverse pressure gradient, the boundary layer separates from the surface. Separation of boundary layer results in high loss of energy in the form of eddies. Constant pressure at a location over the profile is the sign of separated flow at that location. The inviscid outer flow imposes a pressure at every point on the outer edge of the boundary layer and remains constant in the boundary layer perpendicular to wall. The pressure distribution imposed by the outer flow is of considerable importance in the boundary layer growth and if pressure increases in the flow direction it is possible that the boundary layer could separate.

Bammert and Sandstede [1980] observed that boundary layer thickness on the suction side for a smooth surface increases gradually up to 33% of contour length and then the rate of increase is more towards trailing edge with possibility of flow separation. On the pressure side, the boundary layer thickness first increases, reaches a maximum at approximately mid of the contour length and become thinner just before the trailing edge. Near the trailing edge, boundary layer thickness again starts increasing. Typically the boundary layer is laminar up to approximately 28% of contour length on the pressure side. On the suction side, boundary layer for smooth surface is laminar up to approximately 82% of the contour length. With roughness of 120 grade and 40 grade emery paper, the momentum thickness increases respectively, by 1.5 and 2 times the thickness with smooth blades, Bammert and Sandstede [1980].

B. Hydraulic Smooth Surface and Effect of Reynolds number

Surfaces produced by a variety of processes, such as machining, honing, grinding, polishing, etc. are not absolutely smooth. Increasing the surface finish, i.e. reducing roughness, increases the production cost substantially. The finished blade has some roughness and tolerances associated with this manufacturing trade-off. This value of surface roughness is considered as starting base value and is not treated as roughness until it influences the performance. If the roughness peaks are within the laminar sub-layer, there is no effect on the skin friction and the surface is treated as a hydraulically smooth surface. However, if the peaks are comparable or greater than the laminar sub-layer, the losses increase because of increase in the shear stress and the surface is said to be rough. The admissible value of surface peaks which can be treated as hydraulically smooth (K_{adm}) depends on the Reynolds number (R_e) and a characteristic length (L) as per the following criteria, Schlichting [1968]:

\[ \frac{K_{adm}}{L} \leq \frac{100}{R_e} \]  

(2)

The roughness of hydraulically smooth level in low pressure turbine (low Reynolds number) is not hydraulically smooth for high pressure turbine blades (high Reynolds number) and results in increased in loss. At high Reynolds number, the flow undergoes a change from laminar to turbulent motion characterized by strong mixing of fluid in a direction normal to the flow. This motion results in increased momentum transfer in a transverse direction. If pressure gradient is positive, the value of critical Reynolds number at which flow become turbulent, decreases, and if pressure gradient is negative it increases [Schlichting, 1968]. In turbine blades pressure gradient is positive at leading edge of the pressure surface and trailing edge part of the suction surface.

If Reynolds number is increased, the friction factor and, hence, energy loss decreases as boundary layer is suppressed. and after a particular value there is no further decrease in loss, this value of Reynolds number is called self-similarity Reynolds number. Self-similarity Reynolds number varies with turbulence level, convergent level, inlet angle and profile shape etc. Thinner the trailing edge, higher the self-similarity Reynolds number. In case the boundary layer is turbulent and roughness peaks are within the laminar sub-layer, the behavior is same as above but when roughness peaks starts penetrating the turbulent region, the loss curve peals off, and the rate of decrease in friction coefficient reduces with increase in Reynolds number. Further increase in Reynolds number results in penetration of more roughness peaks into turbulent region causing increase in friction coefficient. The loss becomes independent of Reynolds number when all the roughness peaks have penetrated into turbulent region.
An increase in Reynolds number and roughness at separation point delays the laminar separation. This will result in less loss. But if flow does not show any symptoms of separation then increase in Reynolds number or roughness moves transition points ahead and boundary layer becomes turbulent early causing increase in loss. Coton et al [2001] showed that loss increases by a factor of 10 when pitch chord ratio is increased from 1 to 1.74 at constant Reynolds number of 1.9x10^5. He also observed that increase in Reynolds number from 1.9x10^5 to 6.8x10^5 reduces losses by a factor of 2 compared to pitch-chord ratio of 1.

C. Effect of aspect ration, pitch-chord ratio, Mach number and inlet flow angle

Deich, et al., [1965] has presented the performance characteristics of different profiles used in steam turbines. For the same inlet angle, pitch chord ratio and stagger angle, the loss coefficient increases with aspect ratio, also the loss is less for higher Mach number, Figure 2 (a). Similarly, the loss coefficient decreases with increase in inlet flow angle and for higher aspect ratio the loss is less for the same Mach number, pitch chord ratio and stagger angle, Figure 2(b). The loss coefficient also decreases with increase in Mach number, Figure 2(c). The energy loss coefficient for a typical profile is 4.3 % at Mach number of 0.6 which decreases to 3.5 % when Mach number is increased to 0.9, keeping other parameters constant. The boundary layer thickness decreases with Mach number (Mee at al. [1992a, b1]) in the range of 0.65-0.85. With further increase in the Mach number there is enormous increase in boundary layer thickness due to increase in pressure gradient over the accelerating region near the throat. The wake is asymmetric at the trailing edge, but it becomes near symmetric at a distance away from the trailing edge and center of the wake curves away from the pressure surface due to static pressure gradient. The loss coefficient decreases with pitch chord ratio unto certain value, further increase in pitch-chord ratio the loss coefficient increases, Figure 2(d).

D. Formation of wake

The behavior of flow through a rectilinear cascade of turbine is studied by Samsher [2002]. Flow in a turbine blade cascade is an example of confined flow. The boundary layer growth on the suction and pressure surfaces, trailing edge thickness and possibly separated flow leads to the formation of low energy region in the exit flow fields, Figure 3. There are distinct separate lanes with considerably low velocities and presence of turbulence and vortices. These are called blade wakes (Shlyakhin [1974]). The fluid velocity decreases from free stream velocity to minimum in the wake. The shape of the wake depends on the trailing edge thickness, boundary layer thickness on the blade surfaces, shape and roughness of the profile, amongst others. Thicker the trailing edge or boundary layer leads to a thicker wake. The shape of the wake (height and width) is shown in Figure 3. The area of the wake represents the energy loss across the blade channel. The wake width is smallest just after the blade trailing edge and increases down stream. The lack of symmetry in the wakes is due to difference in developments of the boundary layer on both sides. The wake sucks the fluid from the core and, hence, intensive mass transfer takes place between the wake and the core flow that results in an increase in wake width with distance from exit of the blade [Gostelow, 1984]. This intensive mixing, results in losses that are known as mixing losses.

The shape of the wakes at cascade exit is just like the pulse of human body. Any problem or deviation inside the inter-blade channel in reflected in either of the wake parameters, i.e., width, height, and shifting towards suction or pressure surface. If the boundary layer is thicker in the suction surface the wake peak shifts towards the suction surface, the same behaviour is observed on the pressure surface. Thicker wake is an indication of increase in surface roughness. If mixing of fluid in the core region and wake region is more the height of the wake is low and less mixing results in longer height. The wake width and velocity defect increase with a decrease in either turbulence level or Reynolds number.

1. Effect of pressure distribution on wake

The rate of growth of boundary layer also depends on pressure gradient as shown in following equation. If pressure gradient (dp/dx) is positive the gradient of velocity in y direction (du/dy) will be higher causing thicker boundary layer, [Schlichting, 1968].

\[
\frac{dp}{dx} = \mu\left(\frac{d^2u}{dy^2}\right)_w
\]  

(Where \(\mu\) is viscosity, \(p\) pressure, \(u\) velocity, \(x, y\) represent x and y distance in respective direction, \(w\) represents wall)

Roughness increases the boundary layer thickness, which in-turn reduces the core flow region. Due to displacement of streamlines from both surfaces towards the core flow, the velocity in the in viscid region increases. Increase in velocity along the surface results in reduction in the pressure over the respective surface.

Assuming that the rear stagnation point is at the extreme point over the trailing edge for the smooth blade, the wakes shaded have a definite direction with a definite pressure distribution of the pressure over the pressure and suction surfaces. If the pressure distribution over suction/pressure surface changes due to any influence, the rear stagnation point and, hence, wakes shift either towards suction or pressure surface [Gostelow, 1984], Figure 4(a). Now, application of the roughness over different locations of the blade changes the pressure distribution, which is different from the smooth case. Decrease in pressure towards trailing edge of pressure surface or increase in pressure over suction surface compared to smooth blades, shifts stagnation point towards suction surface (Figure 4(a&b), stagnation point 2). Increase in pressure over pressure surface and drop in pressure over suction surface shifts stagnation point towards pressure surface (Figure 4 (a&b) and stagnation point 3) and...
shift the wake in the respective direction. Due to adverse pressure gradient over longer contour length, boundary layer over the suction surface is thicker than the pressure surface, Kind, et al. [1996].

2. Effect of exit angle on wake

The flow near the blade surface is guided by curvature of the blade, suction surface being having more angle with axial direction, the flow along the suction surface has highest exit angle and lowest along the pressure side. The flow stream away from the blade surface has less effect of pressure and suction surfaces and has approximately constant exit angle. In the wake region the streamlines coming along pressure and suction surface bend towards the stagnation point, causing overturning in the suction surface side and under turning at pressure surface side. In case of thicker wake (caused by rough blade or thicker trailing edge) the suction side exit angle will be further higher and pressure surface angle will be further lower. Hence, the difference between maximum and minimum angle will be more and also pitch-wise distance over which the variation in exit angle take place will be more. Shifting of wake due to change in location of rear stagnation point results in considerable variation in exit flow angle [Gostelow, 1984], Figure 5 (a). A very small effect on static pressure and less than 1° change in averaged deviation angle were observed due to roughness created by pasting sand grains of size 338, 722, and 1020 µm diameter over the blades of rectilinear cascade, Kind et al. [1996]. In case of separation of boundary layer from the suction surface the flow will not follow the blade surface from separation point and angle will be more axial. If the separation is delayed then the angle will increase from axial direction (Coton, et al. [2001]). As reported by Deich, et al., [1965], exit angle also increases (from tangential direction) with increase in stagger angle and pitch-chord ratio, Figure 5(b).

V. EFFECT OF ROUGHNESS ON ENERGY LOSS COEFFICIENT

In a rectilinear cascade of rotor/nozzle blade Forster [1967] observed that the efficiency decreases by 0.1 - 7.2 % and 0.5-6.8 % when roughness of 400-800 grades emery paper is applied over entire rotor and nozzle blade, respectively. Zwebek and Pilidis [2003] in a computational study observed that the steam turbine power output reduces by 3.3 % when turbine blade surfaces deteriorated (erosion) by 5 %. In a low speed, single stage axial flow turbine with roughness of 400 µm over entire blade surface, the efficiency decreased by 11 % and 8 % by applying roughness over stator and rotor blades respectively, Yun, et. al. [2005].

In a study by Samsher [2002] it was observed that pasting of 50 grade roughness over the entire blade, the loss coefficient increases by 265 % and 205 % for reaction profile and impulse profile, respectively. Similarly, when the same roughness was applied only over entire suction and pressure surface separately on both the profiles, loss coefficient increase by 145 and 83 % with suction surface and by 87 % and 33 %, with pressure surface for reaction profile and impulse profile, respectively.

In another study by Samsher [2007a], it was observed that deterioration in the performance is more for impulse profile (77 %) than reaction profile (62 %) when 50 grade roughness is applied over suction surface leading edge. The same roughness over mid-chord and trailing edge region increases loss coefficient by 190 % &175 % and 138% & 127 %, respectively for impulse and reaction profiles. Similarly over pressure surface, increase in loss coefficient, with roughness over leading edge is by 83% & 23%, over mid-chord by 17 % & -2 %, over trailing edge 75% & 23%, respectively, for impulse and reaction profiles.

Comparing the loss coefficient with smooth thickened and rough thickened blade, Samsher [2007b] observed that mass-averaged value of loss coefficient increases by 131 %, and 44% for rough-thickened and smooth-thickened blade over entire blade surface. With the same roughness and thickness over entire suction and pressure surface, mass averaged values of loss coefficient increase by 107% & 26 % and 52 % & 7 %, respectively, for rough-thickened and smooth-thickened cases. These results can be interpreted as the effect of roughness caused by deposition also subtracting the thickness effect; the same can be taken as effect of roughness caused by erosion.

VI. CONCLUSION

The roughness over he blade surface is generated by erosion, corrosion and deposition. The roughness thus generated is quantified in terms of $K_c$, C.l.a., $R_s$, $R_p$, $R_t$, and $R_e$ etc. The roughness pattern observed over the in-service turbine blade depicts that the roughness varies along the span from leading edge to trailing edge and also from stage to stage. Depending on boundary layer thickness and trailing edge thickness, the wake is formed at exit of cascade. The shape of wake, i.e., the height, width and position of wake peak, changes with the change in geometrical / flow condition of inter-blade channel. Any variation inside the channel is reflected in the wake shape. The roughness over entire blade surface, entire suction and entire pressure surface separately, is more detrimental when it is applied over reaction profiles. Over suction surface of reaction profile, roughness at trailing edge region is more detrimental than at leading edge region, but roughness at mid chord region is the most detrimental. The effect of localized roughness over pressure surface is much less detrimental at all the three regions. Similarly, for suction surface of impulse profile, trailing edge region is more detrimental than leading edge region but here also roughness at mid chord is the most detrimental. Roughness at one-third of pressure surface at leading edge is more detrimental than that at trailing edge region, while at mid chord region it is the least sensitive. Roughness over
impulse profile is more detrimental than reaction profile for all the localized locations. The roughness caused by deposition is more detrimental than the roughness caused by erosion.

REFERENCES


[34] Vasilenko, G. V., Water-chemistry factors in corrosion damage to the moving blades and discs of turbines, Thermal Engg., 1991, 38, 609-611.


APPENDIX

Table 1 Conversion of emery paper roughness into different roughness terms

<table>
<thead>
<tr>
<th>Emery grade</th>
<th>Grit Size k, (in x 10^{-3})</th>
<th>c.l.a, (in x 10^{-3})</th>
<th>Peak to valley, (in x 10^{-3})</th>
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(Ref. Forster [1966-67])

<table>
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<th>Equivalent k, (in x 10^{-1})</th>
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(Ref. Speidel's Comparison (cited in Forster [1966-67]))

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(Ref. Bammert and Sandstede [1972])

Figure 1 Roughness characterization

\[ R_p : \text{Mean peak to valley height, } R_a : \text{Centerline average value} \]
\[ R_a = \frac{1}{L} \int_0^L y \, dx, \text{ where } L: \text{ sampling length,} \]
\[ y: \text{deviation from centerline, } dx: \text{sampling elemental distance} \]
\[ (R_s)^2 = \frac{1}{L} \int_0^L y^2 \, dx, \quad R_s: \text{Root mean square value} \]
\[ \lambda: \text{Spacing parameter or wavelength} \]
Figure 2: Variation of loss coefficient with aspect ratio, inlet angle, Mach number, and pitch-chord ratio of typical profiles.
Figure 3  Boundary layer growth over blade surface and nomenclature of wake.
(a) Shifting of wake due to shifting of rear stagnation point

(b) Pressure distribution at trailing edge region of blade.

Figure 4: Illustration of shifting of rear stagnation point and wake caused by change in pressure distribution over the blade surface.
Point 1, 2, and 3 as shown in Figure 2.3

a) Exit angle as a function of stagnation point location

b) Exit angle as a function of pitch-chord ratio and stagger angle

Figure 5 Variation of exit angle with location of rear stagnation point and pitch-chord ratio.