EROSION PATTERN OF TWISTED BLADES BY PARTICLE LADEN FLOWS

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ABSTRACT

This paper presents the results of a study to predict turbomachine blade erosion by particle laden flows. Using statistical methods, this work combines particle trajectory calculations with experimental erosion data to determine the erosion of blades. The results of the calculations are presented to show the different patterns of blade material removal distribution over the surface of twisted stator blades for different particle sizes.

NOMENCLATURE

\( C_D \) particle drag coefficient

\( d \) particle diameter (m)

\( E \) blade mass erosion parameter (mg/m²/gm)

\( F \) force interaction parameter between the gas and particles (1/s)

\( m \) coordinate along meridional streamline (m)

\( r \) radial distance from the axis (m)

\( r_c \) radius of curvature of meridional streamline (m)

\( s \) distance along orthogonal mesh lines in through flow direction (m)

\( t \) distance along orthogonal mesh lines in direction across flow, (m)

\( u \) normalized stream function

\( \bar{V} \) flow velocity (m/s)

\( V_p \) particle velocity (m/s)

\( z \) axial coordinate (m)

\( \alpha \) angle between meridional streamline and axial direction (radian)

\( \beta \) angle between flow velocity vector and meridional plane (radian)

\( \phi \) angular coordinate (radian)

\( \rho \) gas density (kg/m²)

\( \rho_p \) particle density (kg/m²)

\( \gamma \) angle between s-line and axial direction (radian)

Subscripts

\( m \) component in direction of meridional streamlines

\( p \) particle

\( r \) component in radial direction

\( s \) component in s-direction

\( t \) component in t-direction

\( z \) component in axial direction

\( \nu \) component in tangential direction

INTRODUCTION

The performance of the gas turbine engines is known to deteriorate rapidly when the operating gas is laden with particles. The solid particles can be the product of combustion or can be present in the surrounding atmosphere in the form of dust, salt or sand. The performance loss can be permanent and/or temporary depending on the nature of the

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particles. The temporary loss of performance was measured experimentally (1) for an axial flow turbine and was shown to be dependent on the rate of the particle to gas mass flow rates. The experimentally measured pressure distribution over compressor and turbine blades (2) showed a reduction in the blade loading when they were tested in a tunnel with gas particle flows. If the particles are erosive they also cause a permanent loss of performance due to the change in the aerodynamic characteristics of the blades, which is caused by erosion.

The erosion of metals by solid particles have been the subject of many experimental investigations. The results of these investigations demonstrate that for a given particle target material combination, the erosion rate is affected by the impacting velocity, impingement angle, and by the metal and gas temperatures (3, 4). It is very important to correctly simulate these effects in the erosion experiments. Carefully designed erosion tunnels where the gas particle stream conditions can be controlled (5). Erosion cascade tunnels have also been used to determine experimentally the change in compressor cascade performance due to erosion (6). The pressure distribution over the blade surface and the inlet and exit total pressure surveys were measured before and after the blades were subjected to erosion by particle laden flows in the tunnel. The change in the airfoil configuration and in its surface-roughness were found to change both blade loading and cascade loss coefficients (6).

The erosion of turbomachine blades can differ significantly from the cascade erosion due to several factors that affect the particle blade impact locations as well as their impacting velocities and impingement angle relative to the blade surfaces. It was shown that the shape of the hub contour and also the radial variation in the blade shape not only affect the particle trajectories but also their radial and circumferential distributions after the blade row (7, 8). Furthermore, since the velocities of the particles as they leave any blade row are generally different in magnitude and direction than the gas flow field (9), the erosion of the blades in multi-stage turomachines is dependent on their stage location.

Particle size has the greatest effect on the particle trajectories, on the frequency of the blade impacts, as well as on the impact conditions. The larger particle trajectories are dominated by their impacts with the blade, and with the hub and tip surfaces, but the smaller particle trajectories are more influenced by the flow field than by their boundary impacts. The rebounding velocities after the surface impacts are different in magnitude and direction from the impacting particle velocities. Rotor impacts in particular can drastically modify the particle trajectories, since circumferential velocities of the rebounding particles can even be higher than the rotor speed itself (9). All these factors combine to produce different blade erosion patterns for the different particle sizes.

**ANALYSIS**

The particle dynamics in a gas solid suspension are determined by the gas-particle interaction and particle-boundary impacts. In turbomachinery applications, the particle concentrations are usually small enough that inter-particle interactions are not considered, in the trajectory calculations. The particles move in the gas flow under the influence of the drag forces until they impact the blades or annular surfaces. Their velocities after these impacts are dependent upon the magnitude and direction of their impacting velocity, relative to the surface. The accurate representation of the flow field, and of the geometry of the various boundaries, is therefore very important in any method of particle trajectory calculations. Hussein and Tabakoff (9) developed the first method for calculating solid particle trajectories in axial flow compressor and turbine stages (9, 2), that models the particle impacts with the blades and their subsequent rebounds. In this method (9) the representation of the blade airfoil shape and the blade to blade flow field at the mean radius are used in the three dimensional particle trajectory calculations. A second method was developed by Hamed (11) which is based on the mid channel hub-to-tip solution coupled with a blade-to-blade velocity gradient equation for a three-dimensional flow field representation. The method presented by Beacher, Tabakoff and Hamed (8) involves a more complex representation of the three dimensional flow field.

**Particle Dynamics**

The equations governing the three dimensional particle motion in the flow field are written in cylindrical polar coordinates as follows:

\[ \dot{r}_p = F(V - r_p) + r_p \omega_p \]

\[ \dot{\theta}_p = F(V - \theta_p) - 2r_p \omega_p \Omega_p \]

\[ \dot{z}_p = F(V - z_p) \]

where \( r_p, \theta_p, \) and \( z_p \) define the particle location in cylindrical polar coordinates, and \( V, \omega_p, \Omega_p \) represent gas velocities in the radial, circumferential and axial directions, respectively, and the particle coordinate derivatives are with respect to an inertial frame of reference. The force of interaction between the two phases, per unit mass of particles is represented by the first term on the right hand side of the equations. It is dependent on the relative velocity between the particles and the gas flow, as well as the particle size and shape. The other terms in the equations represent the centrifugal force and Coriolis acceleration.
Particle-Gas Interactions

The interaction force parameter, $F$, is dependent on the relative velocity between the particles and the gas, on the particle size, and on the gas and particle material densities:

$$ F = \frac{3}{4} \frac{p_0}{p} \frac{C_D}{d} \left[ \left( V_x - r \right)^2 + \left( V_y - r \right)^2 \right]^{1/2} $$

where $p$, $p_0$ are the gas and solid particle densities, $d$ the particle diameter, and $C_D$ the drag coefficient. The drag coefficient is a function of the Reynolds number, which is also based on the relative velocity between the particle and the gas. In the trajectory calculations, empirical relations (10) are used for the drag coefficient of spherical particles.

The Flow Field Representation

Traditionally the complex three dimensional turbomachinery flow fields are synthesized from two-dimensional flow solutions, on blade-to-blade, and hub-to-tip stream surfaces. The blade-to-blade solutions are used in axial machines with large hub-to-tip ratios, while the meridional solutions are used when the radial variations in the blade shape, or when the axial variation in the inner or outer annulus are significant. The second approach is more appropriate for the case of twisted blades and/or in regions of contoured hub or tip annuli. In this work, the solution of the flow field was obtained using the code of reference (12), which combines the matrix and the velocity gradient methods in the numerical solution over the mid channel, hub-to-tip stream surface. The velocity gradient equations along the orthogonal grid lines, $t$, in the hub-to-tip direction is given by:

$$ \frac{dV_t}{dt} = V_c \cos^2 \phi + \cos(\lambda - \phi) \sin^2 \phi \cos \theta \sin \phi \cos \phi + \sin \phi \sin \phi \cos \phi \sin \phi \cos \phi + \cos \phi \frac{dV_m}{dt} \sin(\phi - \theta) + r \cos \phi \frac{dV_\theta}{dt} \sin \phi$$

where $\phi$ is the angle between the gas velocity vector and the meridional plane, $\lambda$ is the angle between the meridional streamline and the axial direction, $\theta$ is the angle between the $t$ grid lines and the radial direction, $\phi$ is the angle between the $s$-coordinate and the axial direction, $r$ is the radius of curvature on the meridional streamlines, $V_m$ and $V_\theta$ are the meridional and circumferential gas velocity components, and $V$ is the total gas velocity.

The solution to equation (5) provides the circumferentially averaged flow velocity component and gas density at the mid-channel hub-to-tip stream surface. This solution is combined with a blade-to-blade velocity gradient equation to account for the circumferential variation of the flow conditions:

$$ \frac{dV_t}{dt} = \cos \phi \frac{dm}{dV_\theta} $$

The flow field computations are performed separately, and the computed flow properties are determined at the grid points of the orthogonal mesh in the mid-channel stream surface (13). The required gas properties at the various locations during particle trajectory calculations are obtained using linear interpolation.

Particle Boundary Interactions

The numerical integration of equations (1)-(3) from the particle's initial conditions provides the particle trajectories until they impact a solid boundary. After impacting a solid boundary, the magnitude and direction of the particle rebounding velocity is dependent on the particle and target materials, and on the impact conditions. Empirical relations were derived from the results of experimental measurements of the particle rebound characteristics which were obtained using high speed photography (3) and laser velocimetry (14). These experimental studies were carried out in special erosion tunnels, which were designed to include the aerodynamic effects in the rebound characteristics. Empirical correlations were derived for the statistical distribution parameters of the experimentally measured restitution ratios as functions of the particle impingement angle (3). These correlations were used in the present study to determine the particle rebounding conditions after blade, hub or tip impacts.

In the three dimensional trajectory calculations the impingement angles are determined from the direction of the impinging velocity and the local normal to the impact surface. The same orthogonal grid which is used in the flow computations is also used in the geometric description of the blade surfaces. The vane shapes are described by the $r$ coordinates of the mid channel stream surface and by the blade-to-blade passage width, while the hub and tip contours are defined by the $(r,z)$ coordinates of the grid points at the inner and outer radii.

Blade Mass Erosion Parameter

The experimental measurements in the erosion tunnel provide erosion data in the form of the erosion mass parameter which is equal to the ratio of the eroded mass of target material to the mass of impinging particles (4). This erosion mass parameter was found to be dependent upon the particle impingement velocity, impingement angle, and on the flow and target temperatures for a given particle target material combination. The computation of blade erosion combines the empirical equation of the mass erosion parameter with the results of the particle...
trajectory calculations. The distribution of the particle impingement velocities and impingement angles and of the frequency of particle impacts over the blade surface affect the resulting blade erosion pattern. A different parameter, $E$, is used to present the computed blade erosion results; it is defined as ratio of the mass of the eroded blade material per unit blade surface area to the total mass of particles ingested by the engine. Using this parameter, $E$, the computed results representation demonstrates the effects of all parameters influencing the blade erosion pattern including the number of blades as well as blade, hub and tip configurations.

RESULTS AND DISCUSSIONS

The erosion pattern in a row of twisted blades were determined by combining the particle trajectory analysis and erosion empirical data using statistical methods. The twisted blades are located in a highly contoured hub region with a tip diameter of 0.335 meter and hub-tip ratio of 0.56 and 0.72 at the blade leading and trailing edges, respectively. The radial variation in the blade stagger angle was between 30° at the hub to 23° at the tip with a constant blade chord of 0.062 meter. Because of the hub shape, the flow field calculations were performed in a (40 x 10) grid that extends about one blade chord upstream and downstream of the blade row. The blades themselves were located within a (13 x 10) grid as shown in Fig. 1. The results of the computation are presented for the erosion of aluminum blades by quartz particle laden flows.

Statistical methods were used in the trajectory calculations with respect to particle distribution at the inlet, where the particle velocities were equal to the local gas velocity. Figures 2 through 5 show the erosion pattern resulting from particles ranging in size between 10 and 100 microns in diameter. The contours of blade mass erosion parameter, $E$, over the blade pressure surface, show the ratio of the mass of blade material erosion per unit blade surface area per unit mass of ingested particles in (mg/m²/gm).

The location of maximum blade erosion is seen to be dependent on the particle size. The maximum erosion for larger particles is seen at the blade hub near the trailing edge. This is the region of both maximum impingement angle ($25^\circ - 30^\circ$) and maximum number of particle impacts. The impingement angle of $20^\circ$ coincides with the angle of maximum erosion for this particle target material combination. The magnitude of the impact velocity of these large particles was nearly constant along the blade surface, since these large particles continue to move nearly with their initial velocity condition up to the point of impact. On the other hand, the smaller particles acquire rapidly the local flow conditions and have much higher impact velocities but much smaller impact angles than the larger particles. The variation in the erosion pattern with particle size can be seen in Figs. 2 through 5. As the size of the particle decreases, the blade location of maximum erosion is seen to move both radially and axially away from the hub trailing edge corner. The blade erosion by the small 10 micron particles is shown in Fig. 5 where the maximum blade material removal is found near the blade mid-chord.

FIG. 1. MERIDIONAL PROJECTION OF THE BLADES AND COMPUTATIONAL GRID.
FIG. 2. BLADE EROSION MASS PARAMETER DISTRIBUTION FOR 100 MICRON PARTICLES.

FIG. 4. BLADE EROSION MASS PARAMETER DISTRIBUTION FOR 20 MICRON PARTICLES.

FIG. 3. BLADE EROSION MASS PARAMETER DISTRIBUTION FOR 50 MICRON PARTICLES.

FIG. 5. BLADE EROSION MASS PARAMETER DISTRIBUTION FOR 10 MICRON PARTICLES.
Comparing Figs. 2 and 5, one can see that, not only is the erosion pattern dependent on the particle size, but that the amount of material removal changes with particle sizes. The higher values of local blade erosion by the smaller particles is due to multiple particle impacts with the blade surface. Unlike the large particles whose velocities are reduced with each impact, these small particles rapidly acquire the local gas velocity after each impact, with subsequent impacts causing greater erosion damage.

The frequency of particle blade impacts are shown in Figs. 6 and 7 for 100 micron and 10 micron particles. The labels on the contours in these figures represent the ratio of the mass of particles impacting blade unit surface area to the average mass of particles ingested per unit frontal area at the blade leading edge. One can observe a large difference between the pattern of the impact frequency of smaller and larger particles. In comparing Fig. 6 with Fig. 2, and Fig. 7 with Fig. 5, one must remember that the material removal by erosion is also dependent on the local impact velocity and impingement angles of the particles. The large particle impact angles were dependent on the location of impact (Fig. 8), while the small particles impact velocities varied considerably with the blade impact location (Fig. 9). All these factors combine to produce the erosion patterns of Figs. 2 through 5.

FIG. 6. FREQUENCY OF BLADE SURFACE IMPACT BY 100 MICRON PARTICLES.

FIG. 7. FREQUENCY OF BLADE SURFACE IMPACT BY 10 MICRON PARTICLES.

FIG. 8. LOCAL IMPACT ANGLE OF 100 MICRON PARTICLES (DEGREES).
TIP

FIG. 9. LOCAL IMPACT VELOCITY OF 10 MICRON PARTICLES (m/s)

CONCLUSION

This work presents the results of a method for calculating turbomachine blade erosion by particle laden flows. Statistical methods are combined with particle trajectory computations and with the experimental data of metal erosion and particle rebound characteristics in the prediction model. The results show that the distribution of material removal by erosion over the blade surface is strongly influenced by the particle size.

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REFERENCES


