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Erosion and Deposition in Turbomachinery

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This paper presents a review of erosion and deposition research in turbomachines and the associated degradation in engine performance caused by particulate matter ingestion. Parameters affecting surface material losses as a result of erosion and development of experimental and analytical approaches to predict flowpath erosion and deposition are discussed. Tests results that quantify the effects of temperature, impact particle composition, impact velocity and angle, and surface material composition are reviewed along with particle restitution data (ratios of rebound to impact velocities and angles). Development and application of models using these data to calculate surface erosion in turbomachinery are described. These models predict particle trajectories in turbomachinery passages to determine impact rates, impact velocities, impact angles and uses the experimentally-obtained erosion data to calculate material losses. Literature on the effects of erosion on turbomachine performance and life is surveyed. Mechanisms of particle delivery and attachment upon arrival at turbomachine flowpath surfaces are also discussed along with experiential models that have been developed to predict surface deposit buildup. Delivery to turbine surfaces can occur as a result of inertial flight, as for erosion, but also through transport mechanisms involving turbulence, Brownian diffusion, and thermophoresis. The particle size range, where each of these mechanisms is dominant for delivery to surfaces, is described. The history and experience of developing models that use these mechanisms to quantify particle delivery rates to turbine flow path surfaces is discussed, along with the use of sticking fraction data to determine the amount of material retained on the surfaces after delivery and the resulting deposit buildup rates. Finally, factors that control whether extreme rates of deposition can occur in turbomachinery are described.

Introduction

SUSPENDED solid particles are often encountered in turbomachinery operating environment because of several mechanisms that contribute to particle ingestion in gas turbine engines. Solid and molten particles can be produced during the combustion process from burning heavy oils or synthetic fuels, and aircraft engines can encounter particles transported by sand storms to several thousand feet altitude.[1] Thrust reverser efflux at low airplane speeds

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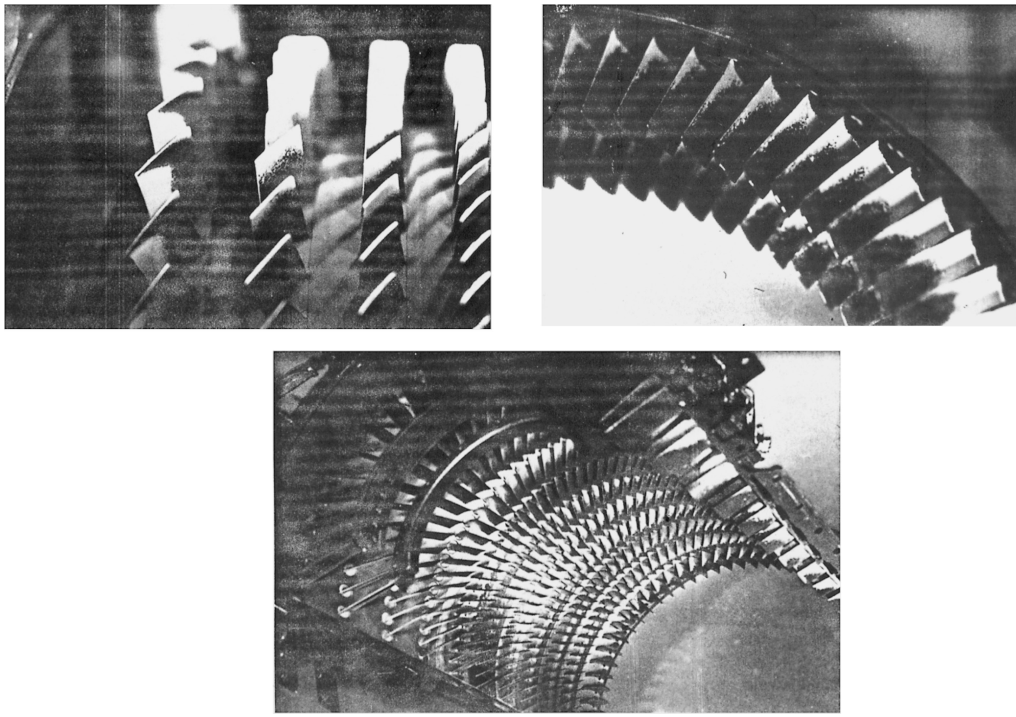

Fig. 1 Multistage compressor erosion.

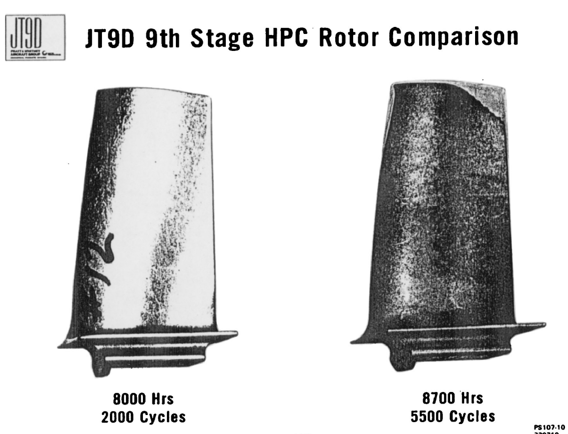

Fig. 2 Effect of flight cycles on compressor blade erosion.

Fig. 3 Volcanic ash deposition on turbine vanes.

as well as engine inlet to ground vortex during high power setting with the aircraft standing or moving on the runway can blow sand, dust, ice, and other particles into the engine. Helicopter engines are especially susceptible to large amounts of dust and sand ingestion during hover, takeoff, and landing. Dust erosion proved so severe during the Vietnam field operations that some engines had to be removed from service after fewer than 100 h of operation.[2] After two decades of technological advances, the loss in power and surge margins as a result of compressor blade erosion caused some helicopter units to be removed after fewer than 20 h during the Gulf War field operations.[3] A picture of T-53 G compressor after erosion tests conducted with runway sand at the University of Cincinnati is shown in Fig. 1.

The light colors indicate the eroded rotor and stator blade surfaces. One can see the leading edge and pressure surface erosion along the first rotor and towards the rotor blade tips and stator blade roots in subsequent stages. In commercial applications, flight cycles determine turbomachinery blade erosion rather than total flight hours (Fig. 2).

Particulate clouds from the eruption of volcanoes present one of the most dangerous environments for aircraft engines. Several incidents have been related to engine operation in volcanic ash cloud environments. Examples of these incidents are a British Airways Boeing 747 powered by four Rolls Royce RB11 engines on 23 June 1982 and a Singapore Airlines Boeing 747-400 aircraft powered by Pratt and Whitney engines approaching Anchorage, Alaska, on 15 December 1989 that entered the volcanic ash cloud from the Mt. Redoubt volcano. Tests performed at the University of Cincinnati showed that volcanic ash is four times more erosive than quartz sand.[4] Commercial aircraft engines encountering volcanic ash clouds indicated more severe problems than those identified in routine Arizona road dust tests, according to military specification MIL E 5007D. Compressor blades and rotor-path erosion, deposition of material on hot section components, and blockage of cooling passages are some of the phenomena experienced in volcanic ash cloud encounters.[5−7] Dunn et al.[8] observed that it is possible to consume the surge margin very quickly when the engine operates in a dust cloud. They attributed this phenomenon to the dust and volcanic ash deposition on the high-pressure turbine vanes (Fig. 3) and the associated rapid increase in burner and compressor discharge static pressure.

In land-based engines, experience with the early coal-burning gas-turbine projects of the Locomotive Development Committee[9] between 1944 and 1963 and subsequently with the Australian coal-burning gas turbine project[10] produced a great deal of information on deposition and erosion. The type of coal used and engine flowpath affected both deposition and erosion, but rotor tip speed had the greatest impact on erosion. Dussourd[11] proposed a simple one-dimensional model for predicting material loss of turbine blades as a result of erosion based on adaptation of bluff-body relations for particle impact velocity and capture. Using existing databases to calibrate the one constant and the velocity exponent in the derived equation, Dussourd projected one times blade life improvement with a 50–60% reduction in flow velocity. Debond or spallation of thermal barrier coatings is an additional degradation mechanism in air- and ground-based turbines. In a recent surface characterization study of nearly 100 land-based turbine components, Bons et al.[12] found surface roughness levels four to eight times greater than the level for production line hardware and observed that film cooling sites are particularly prone to surface degradation. Even small particles of 1 to 30 μ in size have been known to cause severe damage to the exposed components of gas turbines.[13] The associated degradation of blades and flowpath through erosion and deposition causes increased losses and heat transfer to surfaces protected by cooling, reduced stability and life, and can even lead to a complete loss of power.

This paper presents a review of the experimental and numerical investigations of the various aspects associated with particle ingestion, erosion and deposition in turbomachines, and their effects on performance. It includes a summary of results, descriptions of test facilities, and discussion of the methodologies developed for erosion and deposition predictions.

Erosion

Turbomachinery erosion is affected by many factors such as the ingested particle characteristics, gas flowpath, blade geometry, operating conditions, and blade material. Both experimental and numerical studies were conducted to determine the pattern and intensity of compressor and turbine-blade erosion. Grant and Tabakoff[14] and Balan and Tabakoff[15] conducted experimental studies of single-stage axial-flow compressor erosion. Examination of disassembled rotor blades after sand ingestion revealed blunted leading edges, sharpened trailing edges, reduced blade chords, and increased pressure surface roughness. Sugano et al.[16] reported similar observations regarding the changes produced by erosion in axial-induced draft fans of coal-fired boilers. They also determined that blade chord reduction and material removal from the pressure surface increased with particle size.

Richardson et al.[17] presented results of JT9D high-pressure compressor diagnostic study in which they documented the changes in airfoil roughness, blade airfoil, and tip clearance with service. The study indicated that in general the changes correlated well with engine cycles not with hours of engine service. Rotor-blade erosion was observed mainly in the outer 50% of the span, where significant reductions in the blade chord and thickness and changes in the leading- and trailing-edge geometries were observed. Surface roughness measurements indicated quick buildup with no trends observed beyond 2000 cycles. Tip clearances increased as a result of both blade shortening and rubstrip erosion. Dunn et al.[18] measured tip clearance that exceeded specifications by a factor of three with operation in dust-laden environments and reported surge occurrences when the engine was run in this deteriorated state.

Coating and Blade Material Erosion Studies and Facilities

Theoretical studies of material loss by solid particle erosion are predominantly empirical, involving basic assumptions as to the process governing material removal. Different combinations of cutting, fatigue, brittle fracture, and melting mechanisms have been proposed and supported by experimental data from erosion tests. Experimental studies of particle surface impacts are necessary to provide blade material erosion and particle rebound characteristics over the range of impinging conditions encountered in turbomachines. New blade coating materials are often tested for erosion at specified temperatures and particle impact velocities and impingement angles. These tests are carried out in facilities that control particle-laden flow around the target to achieve the desired impact conditions over the tested coupons.

A testing method using a small jet of particle-laden air impacting a stationary specimen was used by Finnie[19] and later by other investigators[20–23] for measuring the erosion characteristics of materials. Photos of samples tested using this type of blast facility at different inclination angles are shown in Fig. 4 (Ref. 23). Large variations in the depth and roughness of the tested surface can be seen in the figure. Dosanjh and Humphry[24] performed a computational study of a particle-laden jet impinging normally on a flat wall. The results indicated significant radial variations in particle concentration, impact velocities, and impingement angle at the target surface. The computed variations were strongly dependent on particle size and on the temperature and level of turbulence in the jet. Erosion wind tunnels control the particles' distribution and velocities in the test section and provide uniform particle impact conditions over the tested surface.[25] In addition, the hot erosion tunnel developed by Tabakoff and Wakeman,[26] and shown schematically in Fig. 5, provides uniform high test-section temperatures for testing turbine-blade materials and coating. Erosion tunnels also enable testing of actual vanes.[27–29]

The results of erosion studies often express the ratio of surface mass or volume removal to impinging particle mass. In general the erosion rate of a given material is affected by the particles' impact velocity and impingement angle. The variation of erosion rate with impingement angle is characteristically different for ductile and brittle material as shown schematically in Fig. 6. This is attributed to the predominantly different mechanisms of cutting and brittle fracture. Typical variations of erosion rates with velocity and temperature are shown in Fig. 7 (Ref. 30). Erosion rate is also affected by particle composition[31] and shape. Figure 8 shows magnified scanning electron micrographs of fly ash, silica sand, and

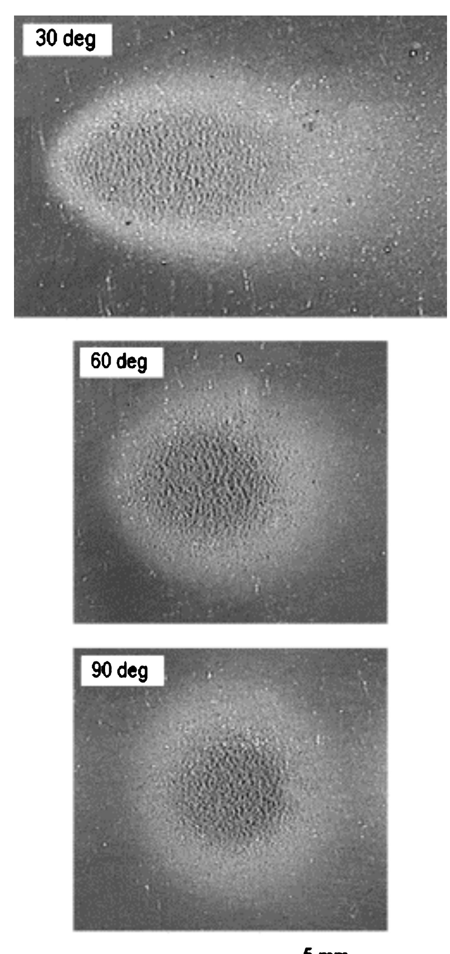

Fig. 4 Samples tested in jet-blasted facility.[22]

Table 1 Wind-tunnel tests of blade materials and coating erosion

Substrate material	Coating	Impact (α), deg	Temperature, °C	Velocity, m/s	Particles	Reference
Cemented	Al_2O_3	0–90	260	140	Aluminum	2
Tungsten	T_iC	0–90	260	140	oxide	31
Carbide	T_iN	0–90	260	140	——	——
MAR 246	——	0–90	815	366	Fly ash	5
X-40	——	0–90	538	305	Fly ash	32
Inco 738	——	0–90	538	305	Fly ash	——
Cobalt	——	0–90	538	145–259	Fly ash	7
Rene 41	——	0–90	649	182–305	Fly ash	33
AM 355	——	0–90	316	122–305	Fly ash	——
Al 2024	——	0–90	Ambient	65–137	Fly ash	8
St St 304	——	0–90	Ambient	65–137	Fly ash	34
St St 304	——	0–90	Ambient	128	Quartz	——
St St 304	——	0–90	Ambient	122	Alumina	——
Ti 6A1-4V	——	0–90	Ambient	65–137	Ash	——
Al 2024	——	0–90	Ambient	92–152	Quartz	9, 35
MAR 246	T_iC	0–90	815	366	Fly ash	10
MAR 246	RT22	0–90	815	366	Fly ash	36
MAR 246	T_iC	0–90	815	305	Chromite	——
Ti-6-4	——	0–90	16–704	152	Aluminum oxide	13
Inco 718	——	0–90	16–704	152	Aluminum oxide	37
Steel 304	——	0–90	30–650	18–305	Aluminum oxide	——
Inco 600	——	0–90	371–493	100–300	Runway sand	14, 38
Waspaloy	Uncoated	0–90	538	305	Chromite	15
	T_iC	0–90	538	305	Chromite	39
Inco 738	——	0–90	482	183–305	——	16
FSX-414	——	0–90	482	183–305	Fly ash	40
X-40	——	0–90	482	183–305	——	——
St Steel 304	——	0–90	30–650	200–330	——	17
Rene 41	——	0–90	30–650	200–330	Fly ash	41
A286	——	0–90	30–650	200–330	——	——
St St 410	TiC	0–90	540	305	Chromite	18
INCO 718	Iron nitride	0–90	540	305	Chromite	42
St St 304	——	0–90	316, 650	120–300	Fly ash	19, 43
Ti-6A1-4V	Various multilayer coatings	0–90	Ambient	185	Aluminum oxide	20, 44
Inco 718	——	0–90	16–704	65–244	Quartz	21
Ti-6-4	——	0–90	16–704	65–244	Quartz	45
St St 355	——	0–90	Ambient—538	99–152	Silica	23
				122–305	Fly ash	46
St St 304	——	0–90	315–650	183–305	——	24
Rene 41	——	0–90	315–650	183–305	Ash	47
Ti-6-4	——	0–90	16–704	152	——	——
Inco 600	——	0–90	370–577	120–240	Quartz	25 48
St St 410	SDG-2207	0–90	565	305	Chromite	26
Inco 718	T_iC	0–90	538	305	Chromite	49
Waspaloy	T_iC	0–90	538	305	Chromite	——
WC	T_iC	0–90	Ambient—650	140	Chromite	——
WC	Al_2O_3	0–90	Ambient—650	140	Chromite	——
WC	T_iN	0–90	Ambient—650	140	Chromite	——
WC	Uncoated	0–90	Ambient—650	140	Chromite	——

aluminum-oxide particles. The latter are most erosive because of their angular shapes and very sharp corners. Erosion test results obtained by Grant and Tabakoff[14] using aluminum-oxide particles and by Kotwal and Tabakoff[31] using alumina and silica particles of different sizes indicate that larger particles produced higher erosion rates, but that the effect of particle size on erosion rate diminished as impact velocity decreased. Table 1 gives a list of some erosion tests with the blade/coating materials and particles used in the tests, the test conditions, and the reference where the results were reported.

Surface roughness characteristics were measured after erosion tests in some investigations.[27,29] Surface roughness was found to correlate closely with the erosion rate in terms of variation with the impact angle, velocity, and particle size. The eroded surface roughness did not change beyond a certain limit even with additional mass removal by erosion.[29] Richardson et al.[17] also reported that compression system airfoil surface roughness did not change beyond 2000 cycles. Figure 9 (Ref. 29) clearly shows the difference between the roughness of the exposed and protected vane surfaces after being tested in the erosion tunnel.

In general, particles encounter repeated impacts with the turbine and compressor surface, and their trajectories are affected by the rebound conditions after each impact. Experimental studies have been conducted to measure the magnitude and direction of particle rebound velocity. Finnie[32] developed a system to measure particle velocities by tracking double-exposed pictures using a stroboscopic light source. Hussein and Tabakoff[33] used high-speed photography to investigate the rebound characteristics of particles from flat targets and to track actual particle trajectories in turbine cascades. Subsequently Grant and Tabakoff,[14] Tabakoff et al.,[25] and Wakeman and Tabakoff[30] used high-speed cameras for particle restitution measurements in the erosion wind tunnel, which was equipped with optical access through the test section.

Because photographic methods were limited to particle sizes greater than 30 μ, Tabakoff and Sugiyama[34] developed a method to use laser Doppler velocimetry (LDV) to measure fly-ash restitution characteristics. LDV was subsequently used in other investigations[35–39] to measure the restitution characteristics for different particle material combinations. Figure 10 (Ref. 36) shows typical LDV results for the velocity and directional restitution ratios. One can see that the restitution ratios exhibit variance around a mean value, which depends on the impact angle. The variance is likely associated with the orientation of nonrounded, particles at the

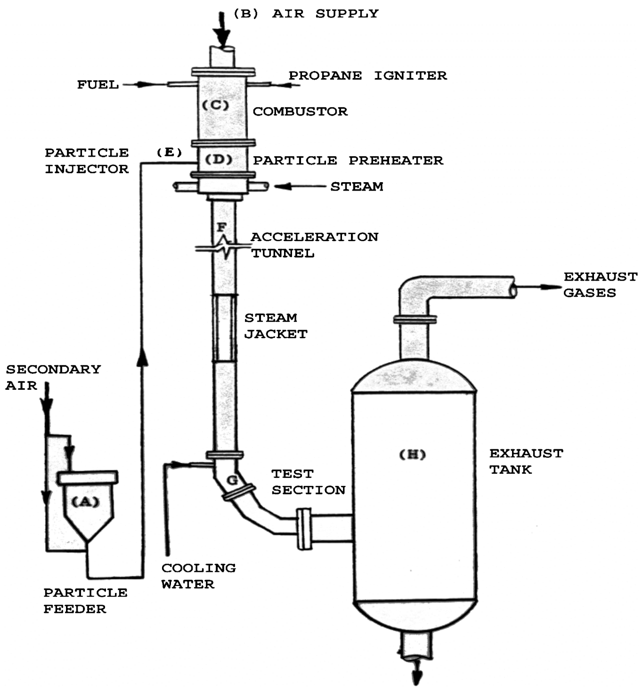

Fig. 5 High-temperature erosion tunnel.

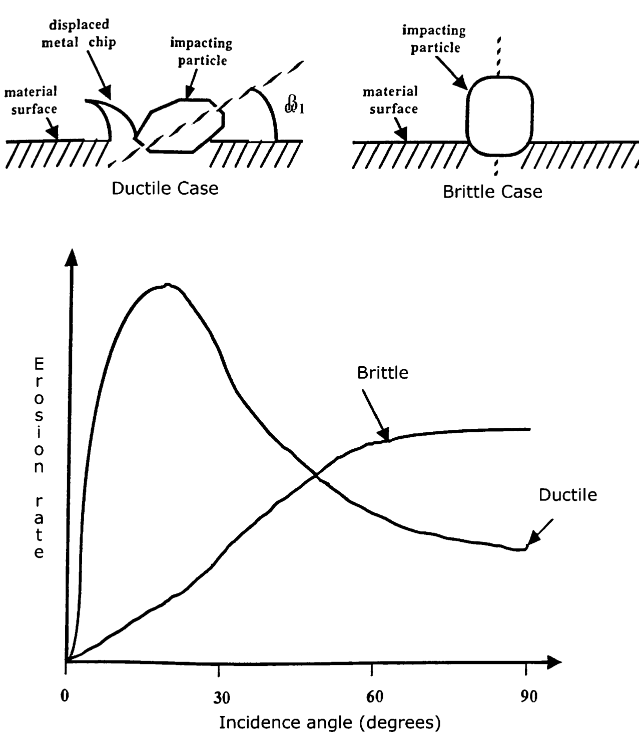

Fig. 6 Erosion rate variation with impact angle.

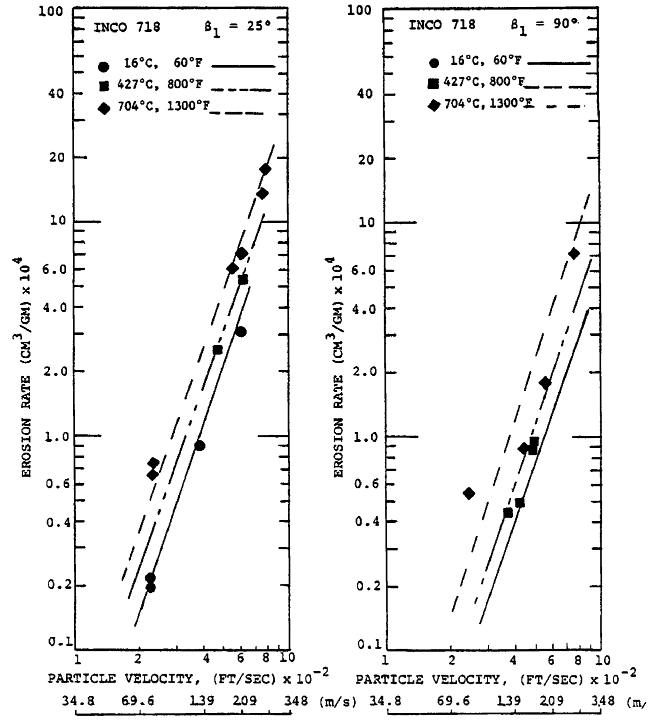

Fig. 7 Erosion test results showing effects of temperature and impact velocity.[30]

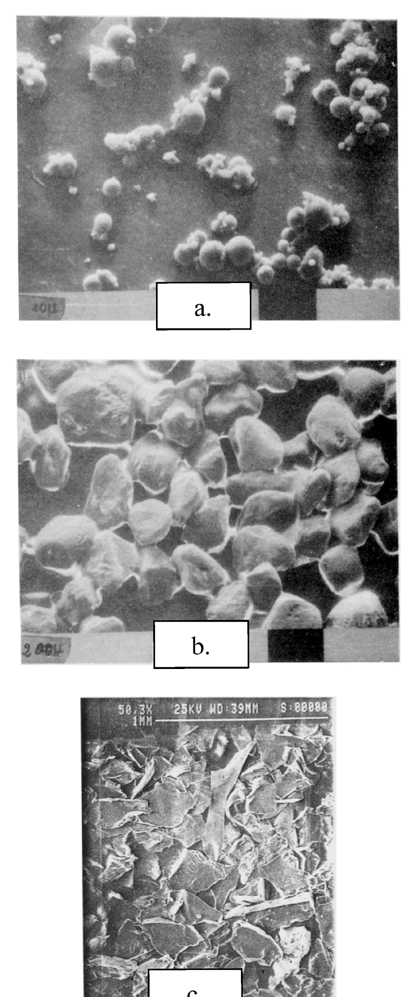

Fig. 8 Electron micrographs of a) fly ash, b) silica sand, and c) aluminum-oxide particles.

time of impact and with the erosion produced target surface irregularities. Particle rebound characteristics were found to be unaffected by the gas or target temperature.[26]

Numerical Simulations of Particle Trajectories and Blade Erosion in Turbomachines

Trajectory simulations are based on the numerical integration of the particles' equations of motion through the turbomachinery blade passages. Because of their higher inertia, the particles lag the gas in turning and acceleration or deceleration, and this causes them to impact the surfaces constituting the various blade passage boundaries. Trajectory simulations therefore require the flowfield and blade passage as input and a model for particle restitution conditions following each surface impact. Hussein and Tabakoff[40] pioneered the methodology for particle trajectory simulations through axial turbine and compressor stages and the use of experimentally based particle restitution models. They presented sample particle trajectories based on the velocity field at the mean diameter and the mean value of the experimental restitution ratios. Their simulations indicated that the number of blade pressure surface impacts increase with increased particle size and with their initial velocity at the stage inlet. They demonstrated that particles gain large circumferential velocities from rotor-blade impacts, which causes them to centrifuge towards the outer casing. In the case of axial-flow turbines, many particles bounce back and forth between the blunt leading edges of the rotor blade and the nozzle vane trailing edge before finally going through the rotor. The computed trajectories through the turbine nozzle were consistent with their earlier experimental visualization in a turbine cascade tunnel using high-speed photography.[41]

Particle trajectory simulations have progressed to include viscous and three-dimensional flow effects following the general advances in the turbomachinery flowfield solutions. The basis for trajectory simulations in turbomachines continues to be Eulerian–Lagrangian with one-way coupling between particles and flow. Flowfield representations in axial-flow machine trajectory simulations progressed from mean streamline combined with spanwise and cross-passage velocities from secondary-flow theory for turbines[42] to inviscid flow on a number of the blade-to-blade stream surfaces for multistage compressors.[43] This was combined with secondary flow and experimentally based streamwise and crossflow velocity gradients near the end walls[44] for multistage turbines. On the other hand, early trajectory simulations in radial-flow machines[45,46] were based on flow solutions on the meridinal planes and panel methods. Currently, three-dimensional flowfield solutions of the Reynolds-averaged Navier–Stokes equations for turbulent flow through blade passages are frequently used in turbomachinery trajectory simulations.[29,47] The sample trajectories through in a turbine-stage cross section shown in Fig. 11 demonstrate the location of particle impacts with the turbine nozzle and rotor-blade surface.

Hamed and Tabakoff[48] developed a methodology to predict turbomachinery blade surface erosion patterns using the computed blade surface statistical impact data from particle trajectory simulations in combination with correlations of erosion test results for blade and coating materials. Tabakoff[43] presented computational results for blade erosion through a T700 five-stage axial compressor. The computed blade leading edge and pressure-surface erosion along the first rotor were followed by rotor-tip and stator root erosion in subsequent stages because of particle radial migration following initial rotor impact. This is consistent with Mann and Warnes[1] observations of multistage compressor blade erosion pattern and with Richardson et al.'s[17] documentation of the changes in compressor blade airfoils and surface roughness with service. Diagnostic measurements of the particles' size variation through helicopter engine[1] compression systems using isokinetic sampling indicated that it became nearly independent of the original size after the low-pressure compression system.

Hamed and Tabakoff[48] and Elfeki and Tabakoff[45] presented computational results for particle trajectories and erosion in a supercharger centrifugal compressor impeller with one and two splitter

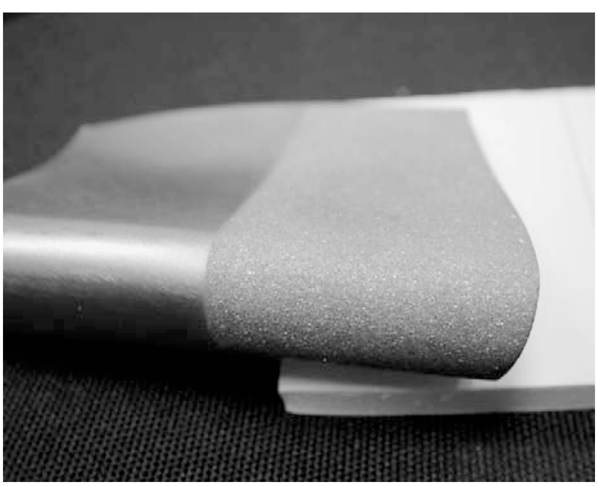

Fig. 9 Vane surface roughness caused by erosion.[29]

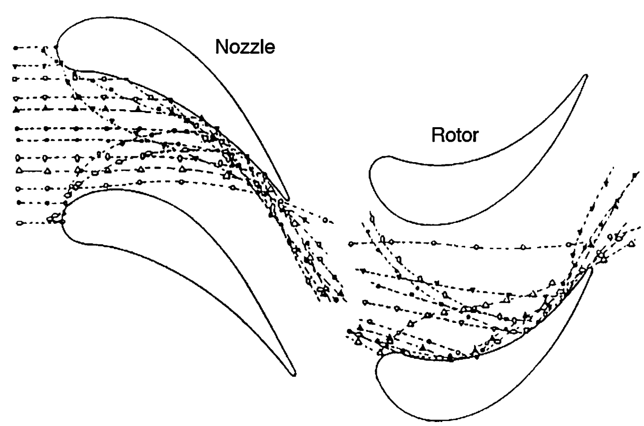

Fig. 11 Trajectories in a turbine stage.

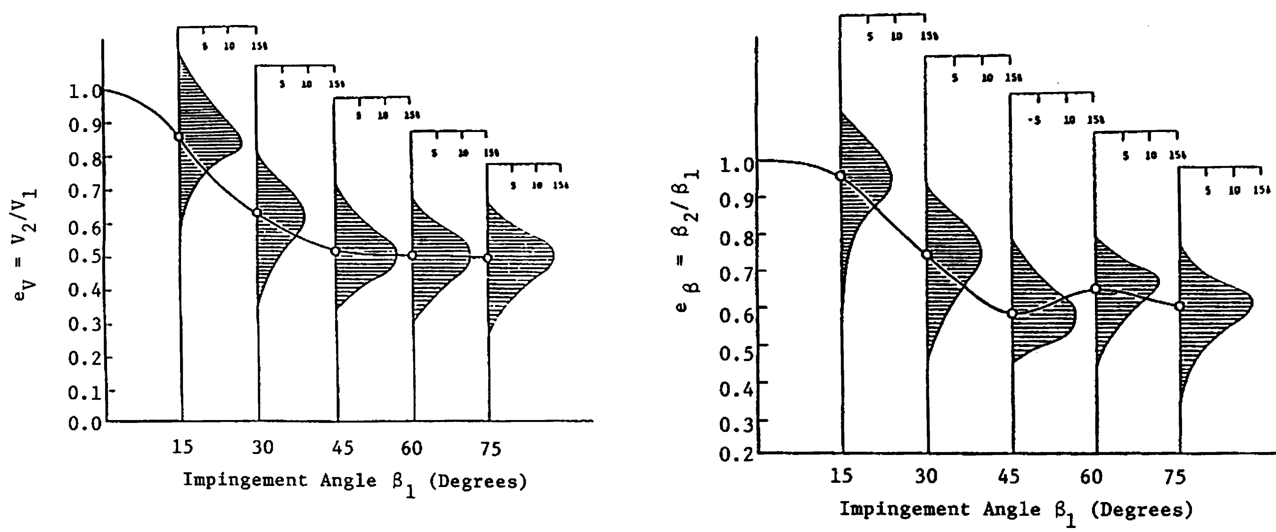

Fig. 10 Typical LDV result for velocity and restitution ratios.[36]

blades, which indicated that particle size strongly influences both blade erosion pattern and intensity. Blade pressure surfaces' erosion were predicted near the casing and increased towards the tip, especially for larger particles. The predictions that were verified in the lab tests of centrifugal compressor erosion[64] are consistent with the mechanical damage pattern of a number of impeller blades following helicopter engine dust ingestion reported by Mann and Warnes.[1]

Beacher and Tabakoff[44] performed particle trajectory analyses through a multistage coal-fired gas turbine. Although no erosion predictions were available, the high concentration of particles near the casing, past the first rotor, correlated well with the observed leading edge and pressure surface wear pattern reported by Smith et al.[9] Metwally et al.[49] conducted a computational study to investigate the effect of blade coating on the erosion of an automotive gas turbine. Their blade surface erosion predictions indicated substantial reduction associated with rhodium platinum aluminide (CRT22B) coating compared to the base MAR-M246 alloy blade.

Tabakoff and Hamed's study[50] of simulated particle trajectories in radial inflow turbines indicated that the highest erosion rate was at the rotor pressure surface near the outer corner of the exit. Experimental and analytical studies of the performance of aircraft auxiliary power turbines with silicon-dioxide particle ingestion[51] indicated a unique phenomenon in which particles became trapped in the vortex region below the nozzles and rotor. This phenomenon, which is caused by the balance between the radial components of the aerodynamic drag and the centrifugal forces acting on the particles, was recorded on film and showed accumulation and eventual blocking of the flow passage. A large reduction in the wheel speed was measured within a few seconds and continued even after discontinuation of particle ingestion.

The motion of suspended particles through turbomachines is essentially a stochastic process because individual particle's point of entry into the machine, its initial velocity vector, and its size and shape are all subject to statistical variation. A number of studies were conducted to investigate the influence of modeling various aspects of these variances on the computed particle trajectories and blade erosion predictions. Tabakoff et al.[52] compared the computed particle trajectories through a two-stage turbine and the associated blade erosion for Cincinnati Gas and Electric fly-ash particle size distribution to those based on the mean particle diameter. The results indicated that nonuniform particle impacts were spread over more of the blade surface, resulting in lower peak erosion values.

Various methodologies were considered to model the effects of the experimentally observed variance in particle rebound characteristics on the erosion of the same two-stage turbine. Initially, Hamed[53] used the Fast Probability Integration Method (FPIM) to characterize the influence of the measured variance in particle rebounds on the particle trajectories through an axial-flow turbine and the associated blade erosion. The FPI-based model resulted in lower estimates of both peak and mean blade surface erosion compared to those computed based on the mean value of the experimentally measured restitution ratios. Subsequently, Hamed and Kuhn[54] developed stochastic particle trajectory simulations based on direct sampling of the actual experimentally measured variance in particle rebound characteristics.[30] These results confirmed that the deterministic bounce model overestimates the blade pressure surface erosion. Another important difference was in the stator blade suction surface erosion near the trailing edge, which was predicted with the direct sampling of the experimental rebound statistics, but not with FPI. This phenomenon was found to be associated with particles reentering the nozzle passage after rebounding from the following rotor.

Effects of Turbomachinery Erosion on Engine Performance and Life

In addition to safety considerations, the damage resulting from turbomachinery erosion has serious consequences from both engineering and economic standpoints. According to Kleinert,[55] erosion is the primary cause for fuel consumption increase in modern turbofan engines. Measurements of isolated compressor and cascade performance following erosion cycles[14] indicated reduction in compressor adiabatic efficiency and stage loading and an increase in cascade total pressure losses. Blade loading reduction, which was noticeable in the outer 50% of the rotor span, increased with erosion cycles as more erosive silica particles passed through the compressor. Sugano et al.[16] presented the measured change in axial-induced draft fan performance with the laps of running time in a coal ash environment. The most significant effect was the drop in stall point by 5% when the eroded blade chord reduction reached 10%. Similar lowering of the surge limit in eroded fans was reported by Ghenaiet et al.,[47] who also characterized the increased tip clearance and measured the drop in efficiency caused by sand erosion of a single-stage ventilation fan with C4 rotor blades made from cast aluminum.

Tabakoff and Simpson[56] recently conducted an exhaustive experimental study of the erosion characteristics of various compressors and turbine-blade materials and coatings. In addition to erosion weight loss, they characterized the corresponding change in chord and thickness of compressor cascades with and without coatings. Subsequently Kline and Simpson[28] conducted a full engine sand ingestion test demonstration of a T64 RB01 "rainbow" compressor with alternate bare and coated blades. After ingestion of 35 kg of sand, they reported 25% loss in horsepower and had to stop the engine caused by surging. They confirmed the cascade erosion results[56] and determined that virtually 100% of the engine performance loss was attributable to erosion of the bare blades. Edwards and Rouse[57] explained how the gas generator power and surge margins are affected by the eroded compressor performance both through the drop in surge line caused by erosion and through the rise in operating line caused by the increased turbine inlet temperature required to maintain the power level with the loss in compressor efficiency. They also discussed how turbine efficiency loss as a result of erosion reduces gas generator efficiency and requires operation at yet increased temperatures, which also causes the operating line to rise above normal and contributes to the reduction in surge margin.

Schmucker and Schaffer[58] conducted an experimental study to determine the effects of reworked blades for the most common defects associated with erosion on axial compressor performance, namely, damaged leading and trailing edges, rounded tips, and rubbed coatings. The tests of a high-pressure five-stage research compressor were done with reworked leading- and trailing-edge blades mixed with new blades, with 1.5-mm tip rounded rotor blades at the leading and trailing edges and with 1–3% equivalent radial tip clearance. The largest losses in surge margin and in efficiency (7.5 and 2%, respectively) were associated with a 1% increase in tip clearance. The rounded tip rotor blades resulted in 4% loss in surge margin and 0.4% loss in efficiency. The losses in performance for reworked blades were 2% in surge margin and less than 0.5% in efficiency and mass flow rate.

Several investigators developed models to simulate the effects of various aspects of the increased tip clearance and changes in compressor blade airfoils shapes and surface roughness on performance. Richardson et al.[17] developed a model for the associated high-pressure compressor performance deterioration based on measurements of in-service engine parts. They reported data on each stage tip clearance change caused by blade and flowpath erosion and on rotor airfoil changes at six radial locations for each stage. They used the data in a performance model to estimate the loss in efficiency and flow capacity associated with changes tip clearance and in airfoil leading- and trailing-edge angles, chord, and thickness. Their estimates of compressor efficiency loss and engine thrust-specific fuel consumption (TSFC) rise agreed with fleet prerepair engine performance average above 1500 cycles. The authors also reported that cold-section refurbishment through restoration of tip clearances, cleaning of airfoils, and replacement of those with chord lengths out of a recommended limit were credited with 1.3% restoration in TSFC. Batcho et al.[59] developed a model for compressor stage performance deterioration that incorporated tip clearance and secondary flow loss models and thin airfoil theory lift and drag changes associated with airfoil mean camberline. They used the model to examine the response of an eroded compressor and estimated 51% reduction in surge margins and 45% in surge pressure ratio with compressor erosion. Tabakoff et al.[60] and Hamed et al.[61] developed a stage-stacking model for the loss in performance caused by compressor erosion, which was validated using the single-stage data of Balan and Tabakoff.[15] Subsequently Tabakoff et al.[62] used the same analysis combined with a thermodynamic model to study the restoration of performance through water injection.

Nagy et al.[63] developed erosion-resistant coating life model and applied it to coated compressor blade erosion by quartz particles. The life model, which is based on 1.8% reduction in the chord length, was used to calculate the mass of erodent for coated airfoils' life for various coating thicknesses. Naik et al.[64] presented the results of a detailed investigation on the erosion resistance and durability of polymer matrix composite coating on Rolls-Royce AE 3007 bypass vanes. The rainbow (coated/uncoated) vane erosion tests in the erosion tunnel demonstrated two to eight times improvement relative to the bare metal under conditions simulating 5000 flight hours. In addition both structural laboratory vibratory tests and engine durability tests demonstrated the capabilities of the coatings for propulsion applications.

Deposition

Simulation of Particle Delivery to Turbine Surfaces

Mechanisms of Deposition

There are two types of mechanisms involved in turbine deposition and effects on performance: delivery of impurities to turbine surfaces and attachment (sticking) of impurities delivered to surfaces.

Mechanisms of Delivery

Impurities from inlet air or fuel can enter the turbine flow passages as particles (in solid or liquid form) and, often for the hot section, as gaseous species that had been vaporized in upstream combustion or gasification processes. Vaporized impurities that enter the hot section can condense as liquids on cooled turbine surfaces or in the gas stream as the temperature and pressure drop through the turbine stages. Dominant mechanisms of delivery of particles to turbine flowpath surfaces are inertial impaction, turbulent diffusion/eddy impaction, Brownian diffusion, and thermophoresis.

For inertial impaction, the particles have sufficient mass to deviate from turning gas flow streamlines, penetrate airfoil boundary layers, and essentially crash onto airfoil surfaces. Smaller particles can be entrained in turbulent eddies in the surface boundary layers to be swept toward airfoils and end walls (turbulent diffusion). Even though eddies dissipate near surfaces, the particles have sufficient inertia to coast to the surfaces (eddy impaction). Yet smaller particles with insufficient mass to be delivered by inertial effects can be transported to surfaces by impacts with the thermally agitated gas molecules in surface boundary layers. For extremely small particles, the random impacts can produce "random walk" Brownian diffusion delivery to the surfaces. If the surface is cooled (as for airfoils of upstream hot section stages), the energy of the random impacts on particles from thermally agitated gas molecules in the thermal boundary layer is higher at the hot side of the particle farther from the cooled surface than the cooler side of the particle. This produces a net average impact force from gas molecules in the direction toward the surface that transports these particles to cooled components (thermophoresis).

Models for Particle Delivery to Turbine Surfaces

Perhaps the earliest work[65] that applied existing theories of particle transport to turbines conducted analyses to predict deposition on airfoils as a result of inertial impaction, vapor diffusion, and Brownian diffusion. The inertial impaction relations used by Smith resulted from prior work by Taylor,[66] who had studied the impingement of water droplets on aircraft wings. In these and subsequent analyses of inertial impaction deposition in turbines, Newtonian equations of motion for particles subject to drag forces from the fluid were integrated, and their trajectories and impact rates on airfoil surfaces were calculated. McCreath[67] integrated equations of motion for 15-micron particles in Tyne turbine stator vane and rotor-blade passages and found reasonable agreement with deposition buildup measured over their pressure surfaces in experiments. Dring et al.[68] showed excellent agreement between calculated trajectories and photographs of trajectories over a range of particle diameters (Stokes numbers from ~0.1 to 1.9) for experiments using a symmetric airfoil. At turbine flowpath conditions, integration of particle equations of motion considering only fluid drag forces typically applies to particles larger than a few microns in diameter (Stokes number on the order of 1 or larger), for which particles have sufficient inertia so that the other mechanisms already described have a relatively small effect on transport to airfoil nose and pressure (concave) surfaces. Convex (suction) airfoil surfaces are shielded from direct inertial impaction of larger particles so that the other mechanisms just described cause deposition on those surfaces from particles smaller than a few microns in diameter.

Developments in theory of particle transport and deposition for small particles (Stokes number $\ll 1$) that provided the basis for later applications to turbines include the work of Lin et al.,[69] Friedlander and Johnstone,[70] Davies,[71] and Cleaver and Yates.[72] The developments of Lin et al. were used by Parker and Lee[73] in studies of deposition of submicron particles on turbine blades. Friedlander and Johnstone indicated that, for particles on the order of a micron in diameter, existing Brownian and turbulent theories under predicted deposition measured on surfaces in experiments, and they proposed that particle transport in that size range near to surfaces is associated with inertial flight to surfaces (eddy impaction) resulting from velocity imparted to particles by turbulent eddies. Davies developed a relation for stopping distance from the surface for which transport is dominated by inertial flight. Moore and Crane[74] incorporated Davies' stopping distance relations in their diffusion analyses of particle transport to turbine blades related to corrosion. They also calculated inertial impaction delivery to turbine airfoils for particles in the diameter range from 1 to 10 μ. Hidy and Heisler[75] published a survey of the state of the art of small particle transport and deposition in the late 1970s.

Application of Particle Delivery Models to Turbine Deposition

In the late 1970s to mid-1980s, Rosner and associates[76,77] published extensively on the theories of condensation, turbulent diffusion, and thermophoretic transport of particles in boundary layers. Much of this research was directed to delivery of corrosive compounds from turbine flowpaths to bounding surfaces (e.g., airfoils). Menguturk and Sverdrup[78] incorporated previous particle delivery theory advancements for the mechanisms of turbulent and Brownian diffusion into a turbine deposition model and showed the model predicted deposition rates that agreed reasonably well with experimental deposition data for pipes and a turbine cascade. Wenglarz[79] used this model to calculate deposition rates in a 50-MW coal-fired pressurized fluidized bed combustion turbine for alternate particulate cleanup systems. An approach was also developed to estimate turbine power drops as a result of blockage of the stator passage throats (minimum flow area in the expander) and maintenance intervals for deposit removal to restore power. Other later examples of applying particle delivery models to predict turbine deposition are given by Ahluwalia et al.[80] and Frackrell et al.[81] Ahluwalia et al. combined several mechanistic models for particle and vapor transport to include the simultaneous contributions of Brownian and turbulent diffusion, thermophoresis, eddy impaction, and inertial impaction. Predicted deposition using the models agreed well with deposition measured in pipe flow and reasonably well with measured deposition in a turbine cascade. Particle delivery rates were then calculated on the surfaces of the first-stage stator vane of a large turbine. Frackrell et al. reviewed particle delivery modeling approaches for application to turbines and compared model predictions against experimental deposition data for pipe flow and flow around cylinders, including a probe exposed to deposition in a rig representing combustion products from a coal gasification system.

Calculated deposition profiles using an inertial impaction model for particle sizes of about 5 and 15 μ were shown to agree well with deposition measured on the first-stage vanes and blades in a low-speed, two-stage model turbine. Deposition rates over the concave and convex surfaces of the first-stage stator vane of a large utility turbine were then calculated for two ranges of particle sizes.

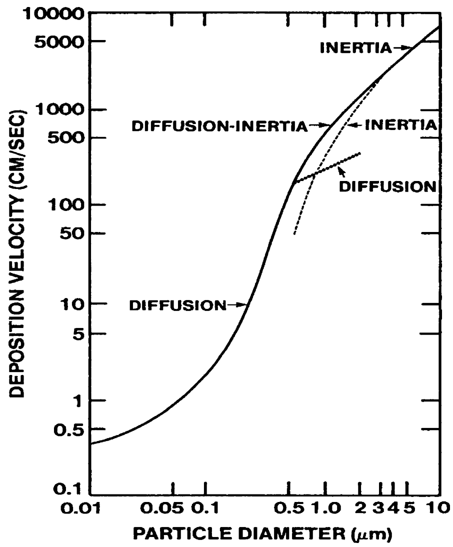

Fig. 12 Turbine vane deposition vs particle diameter.

In the 1990s, natural gas became the fuel of choice for land-based turbines, and most of the attention shifted away from alternate turbine fuels along with concerns about resulting turbine flow path degradation. By the turn of the century, little research and development was directed to turbine deposition. An exception has been work in Europe by El-Batsh and Haselbacher described in a number of publications. For example, these authors published evaluations and verification of particle delivery models for applications to turbines in 2000 (Ref. 82) and calculation of turbine cascade deposition effects in 2002 (Ref. 83).

Relative Rates of Delivery for Mechanisms

Figure 12 illustrates the effect of particle diameter on deposition velocities (deposition rates normalized to gas stream particle concentration) as calculated by a particle delivery model for the concave (pressure) surface trailing edge of the first stator vanes in a large utility turbine. Turbulent diffusion dominates at the smaller diameters shown on the plot. For increasing diameters, eddy impaction enhances turbulent diffusion for surface delivery, and then inertial impaction dominates for particles larger than a few microns in diameter. The deposition velocity curve starts to flatten at diameters in the vicinity of 0.1 micron as a result of the effects of Brownian diffusion at smaller sizes. Because Brownian diffusion rates increase with decreasing particle diameter, this results in a minimum in the deposition velocity curve at a small diameter below 0.01 μ that is not shown on the plot. Although the model used did not include thermophoresis, the depth of the minimum would depend on the degree of airfoil surface cooling and corresponding magnitude of thermophoric effects.

Buildup of Impurities Delivered to Turbine Surfaces

Because of the high mass flow rates for gas turbines, the preceding mechanisms are sufficient to cause significant mass delivery of impurities to turbine surfaces, even for minute concentrations (e.g., <1 ppmw) of impurities in the flow stream. For example, a large turbine with mass flow of 1000 lb/s experiences more than 28,000 lb of impurities in an 8000-h operating year for a flowpath particulate concentration of 1 ppmw.

Although significant quantities of impurities can be delivered by the preceding mechanisms to turbine passage airfoils and end walls, whether or not excessive deposition occurs depends on whether or not there is attachment or sticking of the impurities upon arrival at those surfaces. Competing mechanisms of attachment and removal are described by Tabakoff et al.[84] and are not discussed in detail here. However, one of the main conclusions was that molten phases need to be delivered to the turbine surfaces to sufficiently attach particles so they are not removed and re-entrained in the flow stream. A small molten mass fraction (a few percent and sometimes less) of total material delivered to the surfaces can result in excessive rates of deposition and strong deposits. A review of past test results for a number of alternate fuels by Wenglarz and Wright[85] showed a fuel-ash-dependent transition temperature above which deposition (and corrosion) increase drastically along with the characteristics of these degradations (e.g., an increase in gas temperature of 200°F can increase deposition rates by two orders of magnitude[86]). Below the transition temperature, the main contributor to molten phases is vaporized ash species that condense in a small diameter range ($\sim$0.01 μ). Above the transition temperature, larger particles in the 1-μ and larger diameter range are molten. As illustrated in Fig. 12, delivery rates to turbine surfaces for the micron diameter range are much higher that rates for the 0.01-μ range so that much greater levels of molten phases can be delivered to turbine surfaces for gas stream temperatures above the transition temperature. Accordingly, Wenglarz and Wright concluded that the most important factor determining the level of molten phases delivered to turbine hot-section surfaces and whether there are extreme rates of deposition is probably the gas stream temperature relative to the melting point of the flowpath impurities in the larger particle diameter range.

Summary

A review is given of the experimental and analytical studies of erosion and deposition in turbomachines by ingested particles and the associated performance loss. Experimental investigations of particle-surface interactions in special tunnels that control particle impact conditions provide blade and coating material erosion and particle restitution characteristics. Numerical simulations of partial dynamics through the blade passage provide the particle delivery conditions on passage surfaces. Turbomachinery erosion and deposition predictions combine the computed surface-interaction statistics with experimentally and theoretically based erosion/deposition models. In compressors, erosion increases tip clearance, shortens blade chords, increases pressure surface roughness, blunts the leading edge, and sharpens the trailing edge. Particles centrifuge after their first rotor impact, which limits erosion damage to the outer regions in subsequent stages. The increased tip clearances and changes in airfoil shapes cause by erosion to turbomachinery causes performance deterioration. In turbines, inertial impact at high velocities of particles larger than a few microns in diameter on airfoil leading edges and pressure surfaces can cause erosion or deposition depending on the balance of hard versus molten particles. Deposition of smaller particles on airfoil suction surfaces is associated with turbulent diffusion/eddy impact. Deposition is expected to become more important in the first stage of turbine hot sections as turbine inlet temperatures increase due to the higher fractions of molten particles. Increased fuel consumption, decreased efficiency, flow capacity, and reduced power and surge margins have been attributed to fan and compressor erosion.

References

[1]Mann, D. L., and Wares, G. D., "Future Direction in Helicopter Engine Protection System Configuration," AGARD-CP-588, Paper No. 4, March 1994.

[2]Mund, M. G., and Guhna, H., "Gas Turbine Dust Air Cleaners," American Society of Mechanical Engineers, Paper 70-GT-104, Aug. 1970.

[3]Sirs, R. C., "The Operation of Gas Turbine Engines in Hot & Sandy Conditions-Royal Air Force Experiences in the Gulf War," AGARD-CP-558, Paper No. 2, May 1994.

[4]Tabakoff, W., "Review of Material Erosion Exposed to Aerodynamic Conditions," U.S. Dept. of Engineering, Rept. on Program Review, Oak Ridge, TN, April 1986.

[5]Mitchell, H. J., and Gilmore, F. R., "Dust-Cloud Effects on Aircraft Engines: Emerging Issues and New Damage Mechanisms," RDA-TR-120012-001, Research/Development Associates, Palo Alto, CA, March 1982.

[6]Chambers, J. C., "The 1982 Encounter of British Airways 747 with the Mt. Galuggung Eruption Cloud," AIAA Paper 85-0097, 1985.

[7]Smith, W. S., "International Efforts to Avoid Volcanic Ash Clouds," AIAA Paper 85-0101, 1985.

[8]Dunn, M. G., Baran, A. J., and Miatah, J., "Operation of Gas Turbine Engines in Volcanic Ash Clouds," American Society of Mechanical Engineers, 94-GT-170, June 1994.

[9]Smith, J., Cargill, R. W., Strimbeck, D. C., Nabors, W. M., and McGee, J. P., "Bureau of Mines Coal-Fired Gas Turbine Research Project: Test of New Turbine Blade Design," RI 6920, U.S. Dept. of the Interior, Bureau of Mines, Washington, DC, 1967.

[10]Atkin, M. L., and Duke, G. A., "The Operation of a Modified Ruston Hornsby Gas Turbine on N.S.W. Bituminous Coal," Aeronautical Research Lab. Dept. of Supply, Australian Defense Scientific Service, Rept. 133, Aug. 1971.

[11]Dussourd, J. L., "A Simple One-Dimensional Model for Primary Turbine Blade Erosion Prediction," American Society of Mechanical Engineers, Paper 83-GT-164, June 1983.

[12]Bons, J. P., Taylor, R. P., McClain, S. T., and Rivir, R. B., "The Many Facets of Turbine Surface Roughness," American Society of Mechanical Engineers, 2001-GT-0163, June 2001.

[13]MacCay, R., "The Gas Turbine as a Source of Continuous Precise Power," American Society of Mechanical Engineers, Paper 69-GT-20, May 1969.

[14]Grant, G., and Tabakoff, W., "Erosion Prediction in Turbomachinery Resulting from Environmental Particles," *Journal of Aircraft*, Vol. 12, No. 5, 1975, pp. 471–478.

[15]Balan, C., and Tabakoff, W., "Axial Compressor Performance Deterioration," AIAA Paper 84-1208, June 1984.

[16]Sugano, H., Yamaguchi, N., and Taguchi, S., "A Study on the Ash Erosion of Axial Induced Draft Fans of Coal-Fired Boilers," TR, Vol. 19, Mitsubishi Heavy Industries, Tokyo, Japan, Feb. 1982.

[17]Richardson, J. H., Sallee, G. P., and Smakula, F. K., "Causes of High Pressure Compressor Deterioration in Service," AIAA Paper 79-1234, June 1979.

[18]Dunn, M. G., Padova, C., Moller, J. G., and Adams, R. M., "Performance Deterioration of a Turbofan and a Turbojet Engine upon Exposure to Dust Environment," *Journal of Engineering for Gas Turbine and Power*, Vol. 109, No. 2, 1987, pp. 336–343.

[19]Finnie, I., "Erosion of Surfaces by Solid Particles," *Wear*, Vol. 3, No. 1, 1960, pp. 87–103.

[20]Sheldon, G. L., "Similarities and Differences in the Erosion Behavior of Materials," *Journal of Basic Engineering*, Vol. 89, No. 3, 1970, pp. 619–625.

[21]Tilly, G. P., "A Two Stage Mechanism of Ductile Erosion," *Wear*, Vol. 23, No. 2, 1973, pp. 87–93.

[22]Hutchings, W. H., "A Model for the Erosion of Metals by Spherical Particles at Normal Incidence," *Wear*, Vol. 34, No. 2, 1983, pp. 269–281.

[23]Oka, Y. I., Nishimura, M., Nagahashi, K., and Matsumura, M., "Control and Evaluation of Particle Impact Conditions in a Sand Erosion Test Facility," *Wear*, Vol. 250, No. 2, 2001, pp. 736–743.

[24]Dosanjh, S., and Humphry, J. A., "The Influence of Turbulence on Erosion by a Particle-Laden Fluid Jet," *Wear*, Vol. 102, Nos. 1–12, 1985, pp. 309–329.

[25]Tabakoff, W., Grant, G., and Ball, R., "An Experimental Investigation of Certain Aerodynamic Effects on Erosion," AIAA Paper 74-639, July 1974.

[26]Tabakoff, W., and Wakeman, T., "Test Facility for Material Erosion at High Temperature," American Society for Testing and Materials Special Publication 664, West Conshohocken, PA, 1979, pp. 123–135.

[27]Balan, C., and Tabakoff, W., "A Method for Predicting the Performance Deterioration of a Compressor Cascade Due to Sand Erosion," AIAA Paper 84-1208, June 1984.

[28]Kline, M., and Simpson, G., "The Development of Innovative Methods for Erosion Testing a Russian Coating on GE T64 Gas Turbine Engine Compressor Blades," American Society of Mechanical Engineers, Paper GT2004-54336, June 2004.

[29]Hamed, A., Tabakoff, W., Rivir, R. B., Das, K., and Arora, P., "Turbine Blade Surface Deterioration by Erosion," Paper No. ASME-IGTI 2004-54328, June 2004.

[30]Wakeman, T., and Tabakoff, W., "Measured Particle Rebound Characteristics Useful for Erosion Prediction," American Society of Mechanical Engineers, Paper 82-GT-170, June 1982.

[31]Kotwal, R., and Tabakoff, W., "A New Approach for Erosion Prediction due to Fly Ash," *Journal of Engineering for Power*, Vol. 103, 1981, pp. 265–270.

[32]Finnie, I., "An Experimental Study on Erosion," *Proceedings of the Society for Experimental Stress Analysis*, Vol. 17, No. 2, 1960, pp. 65–70.

[33]Hussein, M. F., and Tabakoff, W., "Dynamic Behavior of Solid Particles Suspended by Polluted Flow in Turbine Stage," *Journal of Aircraft*, Vol. 10, No. 7, 1973, pp. 334–340.

[34]Tabakoff, W., and Sugiyama, Y., "Experimental Methods of Determining Particle Restitution Coefficients," *Proceedings of the ASME Symposium on Polyphase Flow and Transient Technology*, American Society of Mechanical Engineers, New York, Aug. 1980, pp. 203–210.

[35]Tabakoff, W., Malak, M., and Hamed, A., "Laser Measurements of Solid-Particle Rebound Parameters Impacting on 2024 Aluminum and 6AI-4V Titanium Alloys," *AIAA Journal*, Vol. 25, No. 5, 1987, pp. 721–726.

[36]Tabakoff, W., and Malak, M., "Laser Measurements of Fly Ash Rebound Characteristics for Use in Trajectory Calculations," *Journal of Turbomachinery*, Vol. 109, No. 3, 1987, pp. 535–540.

[37]Tabakoff, W., "Measurements of Particles Rebound Characteristics on Materials Used in Gas Turbines," *Journal of Propulsion and Power*, Vol. 7, No. 5, 1991, pp. 805–813.

[38]Tabakoff, W., and Hamed, A., "Experimental Investigation of Particle Surface Interactions for Turomachinery Applications," *Laser Anemometry Advances and Applications*, edited by A. Dybbs and B. Ghorashi, American Society of Mechanical Engineers, New York, 1991, pp. 775–780.

[39]Tabakoff, W., Hamed, A., and Murugan, X., "Effect of Target Materials on Particle Restitution Characteristics for Turbomachinery Applications," *Journal of Propulsion and Power*, Vol. 12, No. 2, 1996, pp. 260–266.

[40]Hussein, M. F., and Tabakoff, W., "Computation and Plotting of Solid Particle Flow in Rotating Cascades," *Computers and Fluids*, Vol. 2, No. 1, 1974, pp. 1–15.

[41]Tabakoff, W., and Hussein, M. F., "Trajectories of Particles Suspended in Flows Through Cascades," *Journal of Aircraft*, Vol. 8, No. 1, 1971, pp. 60–64.

[42]Ulke, A., and Roulean, W. T., "The Effects of Secondary Flows on Turbine Blade Erosion," American Society of Mechanical Engineers, Paper 76-GT-74, March 1976.

[43]Tabakoff, W., "Compressor Erosion and Performance Deterioration," *Journal of Fluids Engineering*, Vol. 109, No. 2, 1987, pp. 297–306.

[44]Beacher, B., and Tabakoff, W., "Trajectories of Ash Particles Through a Coal-Burning Gas Turbine," American Society of Mechanical Engineers, Paper 84-GT-122, 1984.

[45]Elfeki, S., and Tabakoff, W., "Erosion Study of Radial Flow Compressor with Splitters," American Society of Mechanical Engineers, Paper 86-GT-240, June 1986.

[46]Tabakoff, W., and Hamed, A., "Effect of Environmental Particles on a Radial Compressor," AIAA Paper 88-0366, Jan. 1988.

[47]Ghenaiet, A., Elder, R. L., and Tan, S. C., "Particle Trajectories Through an Axial Fan and Performance Degradation due to Sand Ingestion," American Society of Mechanical Engineers, Paper 2001-GT-0497, June 2001.

[48]Hamed, A., and Tabakoff, W., "Experimental and Numerical Simulations of the Effects of Ingested Particles in Gas Turbine Engines," *Erosion, Corrosion and Foreign Object Effects in Gas Turbines*, Von Karman Inst., Brussels, 1994.

[49]Metwally, M., Tabakoff, W., and Hamed, A., "Blade Erosion in Automotive Gas Turbine Engine," *Journal of Engineering for Gas Turbines and Power*, Vol. 117, Jan. 1995, pp. 213–219.

[50]Tabakoff, W., and Hamed, A., "Temperature Effect on Particle Dynamics and Erosion in Radial Inflow Turbines," *Journal of Turbomachinery*, Vol. 110, April 1988, pp. 258–246.

[51]Clevenger, W., and Tabakoff, W., "Dust Particle Trajectories in Aircraft Radial Turbine," *Journal of Aircraft*, Vol. 13, No. 10, 1976, pp. 786–791.

[52]Tabakoff, W., Hamed, A., and Metwally, M., "Effect of Particle Size Distribution on Particle Dynamics and Blade Erosion in Axial Flow Turbines," *Journal of Gas Turbine and Power*, Vol. 113, Oct. 1991, pp. 607–615.

[53]Hamed, A., "An Investigation in the Variance in Particle Surface Interactions and Their Effects in Gas Turbines," *Journal of Engineering for Gas Turbine and Power*, Vol. 114, April 1992, pp. 235–241.

[54]Hamed, A., and Kuhn, T. P., "Effects of Variational Particle Restitution Characteristics on Turbomachinery Erosion," *Journal of Engineering for Gas Turbine and Power*, Vol. 117, July 1995, pp. 432–440.

[55]Kleinert, G., "Turbofan Engine Maintenance for Fuel and Hardware Conservation," *Sermatech Review*, Vol. 33, 1990, pp. 2, 3.

[56]Tabakoff, W., and Simpson, G., "Experimental Study of Deterioration and Retention on Coated and Uncoated Compressor and Turbine Blades," AIAA Paper 2002-2373, Jan. 2002.

[57]Edwards, V. R., and Rouse, P. L., "U.S. Army Rotorcraft Turboshaft Engines—Dust Erosion Considerations," AGARD-CP-558, Paper No. 3, April 1994.

[58]Schmucker, J., and Schaffer, A., "Performance Deterioration of Axial Compressors due to Blade Defects," AGARD-CP-558, Paper No. 16, April 1994.

[59]Batcho, P. F., Moller, J. C., Padova, C., and Dunn, M. G., "Interpretation of Gas Turbine Response due to Dust Ingestion," Vol. 109, July 1978, pp. 344–352.

[60]Tabakoff, W., Lakshiminarasimha, A. N., and Pasin, M., "Simulation of Compressor Performance Deterioration due to Erosion," *Journal of Turbomachinery*, Vol. 112, No. 1, 1990, pp. 78–112.

[61]Hamed, A., Tabakoff, W., and Singh, D., "Modeling of Compressor Performance Deterioration due to Erosion," *International Journal of Rotating Machinery*, Vol. 4, No. 4, 1998, pp. 243–248.

[62]Tabakoff, W., Kaushik, S., and Lakshiminarasimha, A. N., "Performance Improvement of an Eroded Axial Flow Compressor Using Water Injection," AIAA Paper 90-2016, July 1990.

[63]Nagy, D. R., Parameswaran, V. R., MacLeod, J. D., and Immarigeon, J. P., "Protective Coatings for Compressor Gas Path Components," AGARD-CP-558, Paper No. 7, April 1994.

[64]Naik, S. K., Sutter, J. K., Tabakoff, W., Siefker, R. G., Haller, H. S., Cupp, R. J., and Miyoshi, K. K., "Wear Resistant Polymer Matrix Composites for Aerospace Applications," American Society of Mechanical Engineers, Paper GT2004-54330, June 2004.

[65]Smith, H. C. G., "A Theoretical Note upon the Mechanism of Deposition in Turbine Airfoil Fouling," Memo. M.145, National Gas Turbine Establishment, Pyestock-in-Farnborough, Hants, England, UK, Feb. 1952.

[66]Taylor, G. I., "Notes on Possible Equipment and Technique for Experiments on Icing on Aircraft," R.M. 2024, British Aeronautical Research Council, London, England, UK, Jan. 1940.

[67]McCreath, C. G., "The Role of Salt Particulate Matter in the Hot Corrosion Phenomenon Exhibited by Gas Turbine Power Plants Operated in a Marine Environment," *Power Industry Research*, Vol. 2, 1982, pp. 1–15.

[68]Dring, R. P., Casper, J. R., and Suo, M., "Particle Trajectories in Turbine Cascades," *Journal of Energy*, Vol. 3, No. 3, 1979, pp. 161–166.

[69]Lin, C. S., Moulton, R. W., and Putnam, G. L., "Mass Transfer Between Solid Walls and Fluid Streams," *Industrial and Engineering Chemistry*, Vol. 45, No. 1, 1953, pp. 636–640.

[70]Friedlander, S. K., and Johnstone, H. F., "Deposition of Suspended Particles from Turbulent Gas Streams," *Industrial and Engineering Chemistry*, Vol. 49, No. 7, 1957, pp. 1151–1156.

[71]Davies, C. N., "Deposition from Moving Aerosols," *Aerosol Science*, Academic Press, New York, 1966.

[72]Cleaver, J. W., and Yates, B., "A Sub Layer Model for Deposition of Particles from a Turbulent Flow," *Chemical Engineering Science*, Vol. 30, 1975, pp. 983–992.

[73]Parker, G. J., and Lee, P., "Studies of the Deposition of Submicron Particles on Turbine Blades," *Proceedings of the Institute of Mechanical Engineers*, Vol. 186, No. 38, 1972, pp. 519–526.

[74]Moore, M. J., and Crane, R. I., "Aerodynamic Aspects of Gas Turbine Blade Corrosion," *Deposition and Corrosion in Gas Turbines*, edited by A. Hart and A. Cutler, Wiley, New York, 1973, pp. 35–57.

[75]Hidy, G. M., and Heisler, S. L., "Transport and Deposition of Flowing Aerosols," *Recent Developments in Aerosol Science*, edited by D. T. Shaw, Wiley, New York, 1978, pp. 135–165.

[76]Rosner, D. E., Chen, G. C., Fryburg, G. C., and Kohl, F. J., "Chemically Frozen Multicomponent Boundary Theory of Salt and/or Ash Deposition Rates for Combustion Gases," *Combustion Science and Technology*, Vol. 20, 1979, pp. 87–106.

[77]Rosner, D. E., and Fernandez de la Mora, J., "Particle Transport Across Turbulent Non-Isothermal Boundary Layers," *Journal of Engineering for Power*, Vol. 104, No. 4, 1982, pp. 885–994.

[78]Menguturk, M., and Sverdrup, E. F., "A Theory for Fine Particle Deposition in 2-D Boundary Layer Flows and Application to Gas Turbines," American Society of Mechanical Engineers, Paper 81-GT-54, March 1981.

[79]Wenglarz, R. A., "An Assessment of Deposition in PFBC Power Plant Gas Turbines," *Journal of Engineering for Power*, Vol. 103, No. 3, 1981, pp. 552–560.

[80]Ahluwalia, R. K., Im, K. H., Chuang, C. F., and Hajduk, J. C., "Particle and Vapor Deposition in Coal-Fired Gas Turbines," American Society of Mechanical Engineers, Paper 86-GT-239, June 1986.

[81]Frackrell, J., Brown, K., and Young, J., "Modelling Particle Deposition in Gas Turbines Employed in Advanced Coal-Fired Systems," American Society of Mechanical Engineers, Paper 94-GT-467, June 1994.

[82]El-Batsh, H., and Haselbacher, H., "Effect of Turbulence Modeling on Particle Dispersion and Deposition on Compressor and Turbine Blade Surfaces," American Society of Mechanical Engineers, Paper 2000-GT-519, May 2000.

[83]El-Batsh, H., and Haselbacher, H., "Numerical Investigation of the Effect of Ash Particle Deposition on the Flow Field Through Turbine Cascades," American Society of Mechanical Engineers, Paper GT-2002-30600, June 2002.

[84]Tabakoff, W., Hamed, A., and Wenglarz, R., *Particulate Flows and Blade Erosion*, Lecture Series Publ., von Kármán Inst. for Fluid Dynamics, Rhode-Saint-Genese, Belgium, No. 2, 1988, pp. 34–40.

[85]Wenglarz, R. A., and Wright, I. G., "Alternate Fuels for Land-Based Turbines," *Materials and Practices to Improve Resistance to Fuel Derived Environmental Damage in Land- and Sea-Based Turbines*, Rept. 1009173, EPRI, Palo Alto, CA and Colorado School of Mines, Golden, CO, Oct. 2003, pp. 4-45–4-64.

[86]Wenglarz, R. A., and Fox, R. G., "Physical Aspects of Deposition from Coal-Water Fuels Under Gas Turbine Conditions," *Journal of Engineering for Gas Turbines and Power*, Vol. 112, Jan. 1990, pp. 9–14.