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Article

Impact of Dust Particle Flow on the Geometrical Integrity of Gas Turbine Compressor Blades

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Abstract: The compressor in a gas turbine is a central component, directly influencing its geometry, aerodynamics, weight, efficiency, and operational reliability. Technological properties in compressor blades play a determining role in terms of determining engine aerodynamics as well as its behavior mechanically. The blade's strength and rotor integrity directly imply their reliability, where failure in blades may result in localized damage in engines and harsh consequences. Operational conditions of compressor blades subject them to varied forms of degradation in terms of geometry, mass, material properties, and surface conditions. The leading edge is exposed to erosion, blade tips may experience deformation, and roughness of surfaces may increase dramatically through contact by external particles such as dust. The work examines motion and behavior of particles of dust in flow's path in an axial compressor as well as their consequences in terms of erosion in blades, geometric variations, as well as engine's general performance. A computational simulation is developed to mimic airflow as well as behavior of particles in the compressor, and ANSYS Fluent simulation is used. Comparative analysis from simulation results to experimental values provide insight into dust-driven influences in terms of degradation. The results provide a basis point in terms of assessing operational risk, developing protection against blade erosion, as well as superior diagnostic methods in terms of gas turbine engines.

Keywords: dust particles, erosion, airflow, axial compressor, blade geometry

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1. Introduction

Compressor blade breakdown and erosion in gas turbine engines are a result of a variety of engine and environmental factors. Of great concern is erosion from airborne dust, which is a great challenge to engine reliability and performance [1]. The extent and characteristics of dust are a factor of environmental pollution, humidity, and climatic conditions. The dust, entering compressor flow paths at variable velocities and angle of incidence, impinges against blades, causing deformation of blade geometry and radial clearance changes [2]. Empirical information has indicated that, out of engine components, compressor is most eroded, where rotor blades are most eroded in comparison to stator blades. Geometrical compressor blade characteristic is blade S-shaped profile curvature, directly affecting radial clearance and aerodynamics efficiency [3]. Where as blade geometry variations have been studied for a span of decades, quantification of blade variations is not precisely defined. In previous work, erosion and blade shape deformation have been quoted as being dominant failure reasons in gas turbine engines. Since corrosion and wear are most exposed in compressor regions, a core section is described as a basis for designing diagnostic techniques, protecting strategies, and standard repair procedures in order to remedy blade flaws during engine maintenance [4]. Major research topics that are essential to explore are blade geometrical parameter changes in erosive conditions, dust particles within the flow path, and blade surface erosion distribution. The current work introduces a mathematical approach to predict compressor blade stages' geometrical parameters' effect from airborne dust concentration [5]. The model also simulates dust particles' paths in the compressor flow path as a basis for erosion effect analysis as well as protective action [6]. When operating GTE in dusty atmospheres, experience with GTE operation in dusty atmospheres has shown that when the airflow is contaminated with foreign particles smaller than 0.4 mm, compressor blades are damaged, which is defined as erosive wear. This is one of the most common types of operational damage and depends on the concentration of solid foreign particles in the air (it can be 0.2... 1.9 g/m3), the design features of GTE components, and their location on the aircraft. It contributes to [7]: - an increase in the probability of fatigue failure of working compressor blades due to fatigue strength and changes in resonance modes; - a deterioration in engine efficiency due to wear of gas and air path design elements; - a deterioration in engine gasdynamic parameters; - a decrease in gasdynamic stability reserves. The wear rate is directly proportional to the dust concentration up to 1 g/m3. With increasing concentration, wear slows down, apparently due to the collision of abrasive particles. The higher the proportion of quartz in the dust, the more dangerous it is. The quartz content decreases with decreasing particle size [8].In the work [9], it was noted that the negative impact of dust (sand) on the performance and reliability of aircraft gas turbine engines occurs as a result of dust (sand) entering the engine under the influence of wind and its accumulation in the internal cavities of a malfunctioning gas turbine engine when the aircraft is parked in the open air, and as a result of the operation of the gas turbine engine in a dusty atmosphere near the ground surface. Experience in operating gas turbines and the results of platform dust tests (model and full-scale) have shown that the influence of dust (sand) can lead to the following consequences [10]: - corrosive wear of compressor blades; - contamination of transmission lines and heat exchange surfaces of the air-cooling system of the "hot section" parts; - contamination of fuel injectors and fuel manifolds (which leads to burnout of the flame tube and deterioration of the temperature field at the exit of the combustion chamber); - formation of glassy deposits on the turbine nozzle blades; - penetration of dust into the bearing cavities and the oil system. Statistics show that the causes of damage to compressor blades, leading to premature removal of aircraft engines, are approximately distributed as follows [11]:

2. Materials and Methods

The methodology for investigating the impact of dust particle flow on the geometrical integrity of gas turbine compressor blades is structured around an experimental and computational approach. The primary goal is to analyze how various dust particle types, sizes, and flow velocities affect the wear, erosion, and overall shape of compressor blades under operational conditions.The experimental setup involves a dedicated test rig designed to simulate the operational environment of gas turbine engines. This rig includes a controlled dust injection system, a high-speed airflow chamber, and test compressor blades made from typical materials used in gas turbine engines, such as titanium alloys.Dust Particles: Various types of dust particles, including sand and volcanic ash, are selected based on their prevalence in different operating environments. These particles are characterized by size distribution and hardness using a laser diffraction analyzer and scanning electron microscope (SEM). Flow Conditions: The airflow is simulated at varying speeds to replicate the operational range of gas turbines (typically between 200 to 300 m/s). The pressure, temperature, and humidity levels are adjusted to match typical turbine conditions.Blade Material and Configuration: The compressor blades are manufactured with the same material properties and dimensions as those in commercial turbines. The blades are mounted on a rotating disc to simulate actual engine operation, with rotation speeds corresponding to those found in turbines.

3. Results and Discussion

a) abrasive wear of compressor blades: 30% - 35%;
b) ingress of foreign objects from the runway (RWY) and flight paths (TWY): 25% - 30%;

c) ingress of birds and ice during flight: 15% - 20%;

Operating errors made by personnel: 15-30%. Dust leads to premature failure of gas turbine engines, as wear on compressor blades limits their service life, with axial compressors experiencing greater wear than centrifugal compressors. Ring coatings, which reduce the radial clearance over axial compressor blades, and labyrinth seals also wear out . Engine-compressor components experience the greatest wear, especially first-stage blades (along the inlet edge height and concave side), as well as later-stage blades (along the circumferential portion due to dust centrifugation in the first stages of the compressor).[12] Paper presents the results of a study on the causes of the deterioration of JT9D engine parameters and performance during operation.[13] The study was based on documents and data obtained from five airlines, two airframe manufacturers, and Pratt & Whitney Aircraft Company (P&WA) for the period from early 1973 to December 31, 1976. The estimated distribution of causes of engine performance degradation (with a service life of up to 3,500 flight hours) was 40% due to flight loads, 40% due to corrosion, and 20% due to thermal deformation of components. stated that when an engine operates in a very dusty atmosphere, incoming dust has a corrosive effect on the compressor and turbine blades and can also settle as solid deposits on hot engine parts.[14] The nature of the effect of dusty air on engine operation depends on the physical and chemical nature of the dust, its dispersed composition, and the dust concentration in the total volume of air sucked into the engine compressor.[15] Diluted dust can also be deposited on the compressor blades, changing the blade geometry and roughness, resulting in reduced efficiency and, consequently, reduced pressure boost and compressor performance.Various operational methods are employed to minimize dust particle intrusion into gas turbine engines, including occasional washing of the intake case along with intake filters Despite these precautions, erosion of compressor blades persists, typically increasing from the compressor inlet to the outlet, as illustrated in Figure 1. Erosion initially induces slippage in the airflow, leading to abrupt variations in engine operating parameters.[16] Significant deviations or the occurrence of compressor surge may necessitate engine shutdown to prevent damage.

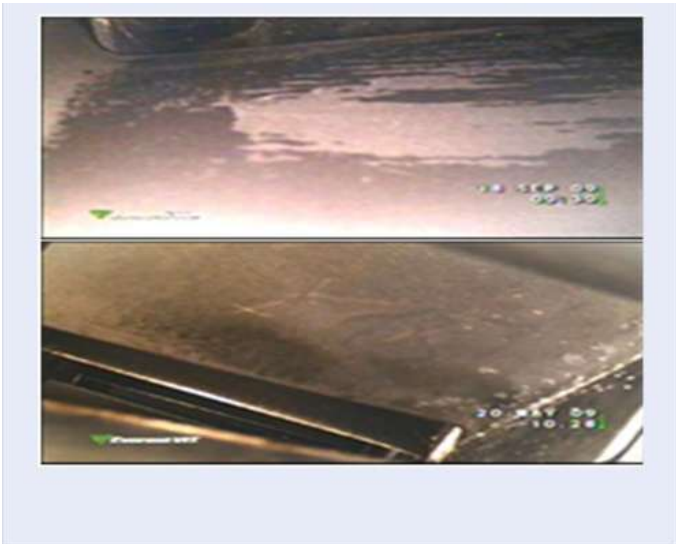

Figure 1: Erosion of compressor blade in gas turbine engine.

Accurate assessment of dust particle trajectories within the airflow is critical for understanding blade erosion mechanisms.[17] Because of their greater density in comparison to air, dust particles have lower-curvature paths than surrounding airflow streamlines. To simulate these interactions, We are to calculate meridional section and blade cascades' flow range. The radial and rotational accelerations have similar static pressure gradients in radial and cross-section planes between blades for dust particles and air. The dust particles' radial and rotational accelerations may be calculated from equivalent accelerations from an air proportion of equivalent dust particle densityThis framework enables calculation of the rotational velocity components of airflow in both relative and absolute terms. By assuming that axial velocities of air and dust particles are equivalent, velocity vectors of dust particles can be determined at any point within the blade flow path.[18] This also allows estimation of the frequency and location of particle impacts on critical blade regions—primarily the leading edge and pressure surface—thereby quantifying the extent of blade erosion. Additionally, the methodology permits prediction of dust particle trajectories in the meridional plane, facilitating analysis of dust redistribution along the blade height and providing a comprehensive understanding of erosion patterns.

Dependence of Blade Erosion on Dust Particle Dynamics

The analysis of theories is carried out for velocity components of a dust particle in composite motion, as is presented in Fig. 2, where absolute velocity is ccc, relative velocity is www, and blade rotational velocity is u. Considering particle motion in a radial direction, its corresponding centripetal acceleration could be presented as follows:

$$\frac{dc_r}{dt} = \frac{c_{ul}^2}{r} \qquad (1)$$

where c_{ul} is the circumferential velocity component of the dust particle, c_r is the radial velocity, and r is the radius of curvature of the blade.

The centripetal acceleration induces a radial pressure gradient, given by:

$$\frac{dp}{dr} = p\frac{dc_u}{dt} \qquad (2)$$

This relation is valid for particles undergoing circular motion.[19] However, in the case of dust particles within the compressor flow, the trajectories deviate from perfect circularity, as the particles experience an outward radial acceleration toward the blade tip due to their higher density and inertia.

$$\left(1 - \frac{p}{p_l}\right)\frac{c_{ul}^2}{r} = \frac{d^2 r_l}{d^2 t} = \frac{d^2 r_l}{dS^2} c_a^2 \qquad (3)$$

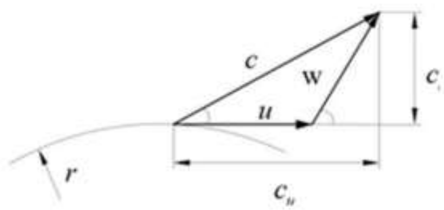

Figure 2: Diagram of air flow velocity in the clear- ance of the flow path of blade.

where:

- ρ — density of air,
- ρ_1 — density of dust particles suspended in the air,
- r_1 — radius of curvature at the position of the dust particle,
- c_a — axial velocity of the gas stream,
- c_u — circumferential (rotational) velocity of the gas stream,
- S — arc length along each S-shaped blade section,

with the time increment defined as:

$$dt = \frac{dS}{c_a}$$

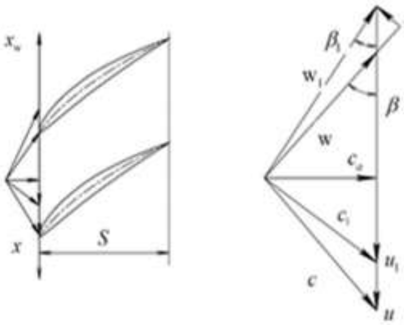

Figure 3: Diagram of velocity of dust and gas movement in flow path between blades.

in equation (3), in which it is presumed that dust particle's axial velocity is approximately equivalent to airflow's, i.e.,$c_{al} \approx c_a$. Figure 3 illustrates the velocity distribution of dust and gas particles within the blade flow channel, while Figure 4 depicts the dust concentration zones in the same region.At the inlet of the first compressor stage, the radial velocity is assumed to be:$c_{r0} \approx 0$. [20]

Thus, the radial velocity of the dust particles at any point along the S-shaped blade surface can be expressed as:

$$c_{r1} = c_{r0} + \int_0^S \left(\frac{d^2 r_1}{dS} c_a^2 \right) dS = c_{r0} + \int_0^S \left[\left(1 - \frac{\rho}{\rho_0} \right) \frac{c_{u1}^2}{r} . c_a^2 \right] dS \quad (4)$$

When dust particles move through a multistage axial compressor, their trajectory must be considered from the first inlet blade stage through subsequent rotor blades and guide vanes, primarily along the blade pressure surface. The blade radius of curvature is given by:

$$r(S) = r_{ol} + \int_0^S c_{r0} dS + \int_0^S \left[\int_0^S \left(1 - \frac{\rho}{\rho_1} \right) \frac{c_{u1}^2}{r} . c_a^2 \right] dS \quad (5)$$

where r_{0l} is the radius of the coaxial bushing.

The velocity of the dust particle in the circumferential direction is:

$$c_{u1} = \left(1 - \frac{\rho}{\rho_1} \right) c_a = u \left(1 - \frac{\rho}{\rho_1} \right) (1 - tg\beta_1 . \overline{c_a}) \quad (6)$$

($\overline{c_a} = \frac{c_a}{u}$: air flow coefficient)

and the velocity of the air flow in the direction of rotation is:

$$c_u = \frac{dx}{dS} c_a = u - \frac{dx}{dS} v_a = u (1 - tg\beta_1 . \overline{c_a}) \quad (7)$$

Substituting (5) into:

$$r(S) = r_{ol} + \int_0^S c_{r0} dS + \int_0^S \left[\int_0^S u^4 \left(1 - \frac{\rho}{\rho_1} \right)^2 \frac{1 - tg\beta_1 \overline{c_a}}{r} c_a^2 dS \right] dS \quad (8)$$

Equation (8) shows that **blade erosion is directly influenced by the separation of dust particles from the airflow within the flow path clearance**. The key factor is the rotational velocity uuu, which intensifies particle deviation due to centrifugal force, causing erosion to gradually increase from the root to the tip of the blade (Figure 4).

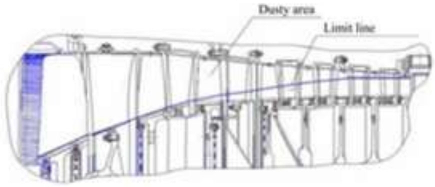

Figure 4: Distribution of dust area in the flow path.

Consequently:

a) Dust particle density rises from the root toward the tip.
b) Erosion at the first-stage root and final-stage root is minimal.
c) Observations from compressor blade disassembly and ultrasonic diagnostics confirm this distribution (Figure 2).

The **size and density distribution of dust particles** are critical parameters characterizing contamination. Dust concentration is usually measured as the mass of dust per cubic meter of air, which varies with geographic and temporal conditions.[21]

The dust density in the compressor flow path clearance is defined by the inlet airflow factor, and the corresponding dust mass flow rate is given by:

$$\frac{\pi d_1^2}{4} c_x \rho \frac{v_y}{2} = (\rho_1 - \rho) \frac{\pi d_1^3}{8} g \qquad (9)$$

where d_1 is the diameter of the dust particle; c_x is the dust density in the clearance of the flow path of the compressor; and v_y is the air speed at the inlet. Therefore:

$$\frac{\rho_1}{\rho} = \frac{c_x v_y^2}{d_1 g} + 1 \qquad (10)$$

When the rotational velocity of the air flow c_u is known, the rotational velocity of the dust particles can be determined:

$$c_{u1} = c_u \left(1 - \frac{\rho}{\rho_1}\right) \qquad (11)$$

The relative velocity of the dust particle is determined as follows:

$$w_{u1} = w_u + c_u \left(1 - \frac{\rho}{\rho_1}\right) = w_u + c_{u1} \qquad (12)$$

Movement Trajectory of Dust Particles in the Clearance of the Flow Path Between Blades

The trajectory of dust particles moving through the clearance of the flow path in compressor stages is illustrated in Figures 3 and 5.

The angle of attack of dust particles on the blade surface is expressed as:

$$ctg\beta_1 . \overline{c_a} = \left(1 - \frac{\rho}{\rho_1}\right) + \left(1 - \frac{\rho}{\rho_1}\right) .ctg\beta . \overline{c_a} \qquad (13)$$

which means that:

$$ctg\beta_1 = \frac{\left(1 - \frac{\rho}{\rho_1}\right) + \left(1 - \frac{\rho}{\rho_1}\right) .ctg\beta . \overline{c_a}}{\overline{c_a}} \qquad (14)$$

The compressor's rotor blades are generally in larger sizes compared to guide vanes or stator blades. The reason lies in the fact that contact velocities of dust particles onto rotor blades are greater compared to contact velocities of dust particles onto blades of stators.[22]

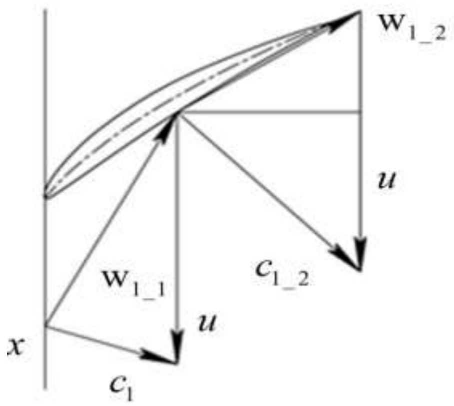

Figure 5: Diagram of the movement trajectory of the dust particle.

Figure 5 shows the diagram of the dust particle movement trajectory. When the velocity distribution $\bar{c_a}(c_a)$ is known, the relative displacement of the air flow can be determined as:$\frac{dx_{wl}}{dS}$.

Accordingly, the relative displacement of dust particles is given by:

$$\frac{dx_{w1}}{dS}c_a = \left(1 - \frac{\rho}{\rho_1}\right) + \frac{\rho}{\rho_1}\frac{dx_w}{dS}c_a \qquad (15)$$

Division into (13) by the rotational velocity u yields the following:

$$\frac{dx_{w1}}{dS}\overline{c_a} = \left(1 - \frac{\rho}{\rho_1}\right) + \frac{\rho}{\rho_1}\frac{dx_w}{dS}\overline{c_a} \qquad (16)$$

Along any trajectory, the energy of the air flow in the compressor is:

$$dL = \frac{F}{m}dx = F_{mu}.dx \qquad (17)$$

where F_{mu} is the impact force of the air flow in the direction of rotation and m is the mass flow of air.

$$\begin{aligned} &\frac{dL}{dS} = F_{mu}\frac{dx}{dS}; \\ &F_{mu} = \frac{dL/dS}{dx/dS} = u^2\overline{c_a}\frac{d^2x/dS^2}{dx/dS}; \\ &\frac{F_{mu}}{u^2\overline{c_a}}x = \frac{dx}{dS} \end{aligned} \qquad (18)$$

where $F_{mu}(S)$ is obtained according to the blade profile law, and x_w represents the coordinates of the rotor blade profile.

The degree of blade erosion is influenced by several factors, including dust particle size, velocity, material properties, and operating duration. Longer operating times result in higher erosion, altering the dust trajectory and changing blade geometry in the flow path.[23]

Table 1: Input Parameters

Parameter	Value
Absolute velocity of the air flow at the blade inlet	$c_u = 97\ m/s$
Rotational velocity of the air flow	$u = 342\ m/s$
Relative velocity of the air flow at the blade inlet	$w_u = 247\ m/s$
Axial velocity of the air flow	$c_a = 189\ m/s$
The angle of attack of the air flow	$\beta = 37^o$
Density of dust particles in the clearance of flow path of the compressor blade	$c_x = 500\ mg/m^3$
Diameter of dust particle	$d_1 = 1\ \mu m$
Average velocity of air	$v_y = 0.5\ m/s$

The variation of the absolute rotational velocity of a dust particle can be described as:

$$\frac{dc_{u1}}{dt} = \frac{\rho}{\rho_1}\frac{dc_u}{dt} = -\frac{\rho}{\rho_1}c_a^2\frac{dx_w^2}{dS} \quad (19)$$

where the acceleration of the dust particle depends on the density, axial velocity and slip of the gas flow along the blade (affected by the erosion of the blade surface). Then,

$$\begin{aligned} c_{u1} &= c_{u1}|_{t=0} + \int_0^t \frac{\rho}{\rho_1}\frac{dc_u}{dt}.dt \\ &= c_{u1}|_{t=0} + \left(-c_a^2\right)\frac{\rho}{\rho_1}\int_0^S \frac{d^2x_w}{dS^2}.dS \end{aligned} \quad (20)$$

However:

$$c_u = c_u|0 + \left(-c_a^2\right)\int_0^S \frac{d^2x_w}{dS^2}.dS$$

Therefore:

$$\begin{aligned} c_{u1} &= c_u|0 + \frac{\rho}{\rho_b}\int_0^t \frac{dc_u}{dt}dt \\ &= c_u|0 + \frac{\rho}{\rho_1}\int_0^S \frac{dc_u}{dS}dS \end{aligned} \quad (21)$$

Simulation in ANSYS

The theoretical framework is validated through 3D CAD/CAE modeling and simulations in ANSYS. Input parameters are determined according to the thermodynamic cycle of the ДР76 gas turbine engine, with boundary conditions defined as shown in Tables 1–3. The simulation results verify that higher dust density at the entrance elevates particle velocity and blade erosion speed. The velocity components in reference to the pressure surface, suction surface, and camber line are different, and the component normal to it affects material deterioration along the blade's surface.[24] The erosion along the suction surface reduces slowly and is minimal in the midportion of the pressure surface. The dust particles strike the blade normally and tangentially, losing approximately 15–19% of their velocity before collision, consistent with experimental observations.

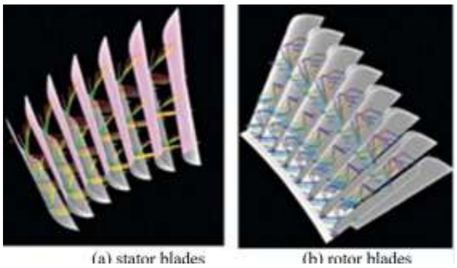

Figure 6: Motion trajectories of particles size 31μm

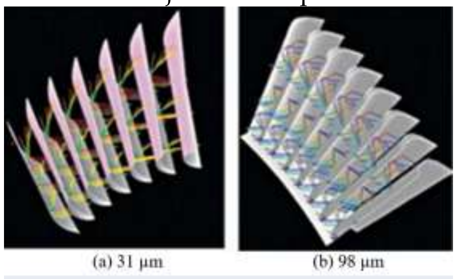

Figure 7: Movement trajectory of particles in the clearance of the flow path when changing its size.

Table 2: Information of Total Elements

Total Elements	Total Nodes	TRI_3	TETRA_4	LINE_2	NODE	QUAD_4	PENTA_6
958380	212309	56430	757532	1546	24	1516	141332

Table 3: Information of Individual Part

Part Name	Number of Elements	Number of Nodes
BODY	898864	212309
CANH1	17531	8859
CANH2	17802	8997
CURVES	1546	1534
IN	3230	1703
MAT_DUOI	4055	2586
MAT_TREN	4699	2931
OUT	3737	1951
PERIOD1	3446	1801
PERIOD2	3446	1801
POINTS	24	24

The ANSYS simulation results are presented as follows. Figures 6 and 7 illustrate the trajectory of dust particles within the clearance of the flow path between the axial compressor blades.Based on the data collected from the ДР76 engine during experimental surveys and subsequent calculations, the lower boundary of the dust concentration zone can be determined relative to the blade flow path height. It was observed that the separation of dust particles at the blade inlet progressively shifts the lower dust boundary away from the axis of rotation, as shown in Figure 4. Within this region, dust accumulation is non-uniform, with concentration increasing from the lower boundary toward the blade edge.A comparison between the simulation results (Figure 8) and the actual erosion and surface scratches observed on the ДР76 engine blades under prolonged operation in dusty environments (Figure 1) demonstrates strong agreement. The velocity distribution of the dust-laden airflow obtained through simulation aligns with the erosion patterns observed in practice, confirming the accuracy of the erosion prediction model across compressor blade stages.

4. Conclusion

This work found a solution for a dynamic dust particles motion problem in axially located compressor blade flow field and found commensurate eroding patterns for a wide variety of blade shapes. The results enable defining regions most subjected to erosion for specific shapes of bladesThe research shows that at the initial compression stage, rotor and stator blades are eroded along the entire blade height, and maximum damage is observed along the pressure surface in the region of leading and trailing edges. Conversely, for later compression stages, erosion progressively increases toward the blade-tip trailing edge as a result of centrifugation of particles. Therefore, dust concentration rises toward the trailing edge and from the rotor center, leading to local thinning and loss of material in most susceptible parts of the engine.The comparison between field measurements of eroded blades and simulation outputs validates the proposed model of dust particle motion and its erosion effects.Overall, this study provides a comprehensive understanding of dust-induced erosion in axial compressors of gas turbine engines, highlighting its impact on blade geometry, profile alteration, and engine performance. The insights gained can support the optimization of operating conditions during engine design, guide the development of protective measures against erosion, and assist in the diagnostic evaluation of gas turbine performance under dust-laden conditions.

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