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An Interdisciplinary Approach to Study the Fouling Phenomenon

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Abstract

Solid particle ingestion is one of the principal degradation mechanisms in the compressor section of heavy-duty gas turbines. Foulants in the ppm range which are not captured by the air filtration system usually cause deposits on blading,which results in a severe drop in the performance of the compressor.Through the interdisciplinary approach proposed in this paper, it is possible to determine the evolution of the fouling phenomenon through the integration of several studies in different research fields: (i) numerical simulation, (ii) power plant characteristicsand (iii) particle-adhesion characteristics.This paper shows the possibility of linking the numerical results related to the impact/adhesion characteristic of the particles with the actual air contamination data and operating condition of the power units. In fact, the size of the particles, their concentrations and the filtration efficiency represent the major contributors to performing a realistic quantitative analysis of the fouling phenomena in an axial compressor.The integration of these research fields could represent a valuable support for the investigation of the relationship between compressor airfoil design and fouling rate.

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Keywords: fouling; air contaminat; filtrartion efficiency; particle's adhesion characteristics

1. Introduction

The quality and purity of the air entering the turbine is a significant factor in the performance and life of the gas turbine.For this reason, an adequate filtration system that can limit the ingestion of contaminants by the power unit is required. Depending on the type of filtration system used, small

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particles, i.e. (0.1 – 2.0) μm, can enter the engine [1]. These particles are too small to cause erosion issues but they are suitable for sticking to the blade surface and causing fouling. Particle sticking on blade surfaces results in an increase of the airfoil thickness and the surface roughness. Evaluation of fouled compressors has revealed contamination both on the suction side and the pressure side of the blades. On-field fouling detection [2, 3] has revealed that only the first stages are affected by deposits and that the absence of centrifugal force in the stator vanes leads to more severe deposits compared to the rotor. Moreover, authors in [4, 5] have reported some experimental measurements with regard to ultra-fine powder deposition on axial compressor blade surfaces. Experimental applications related to the fouling phenomenon are affected by numerous problems: (i) actual conditions of the contaminants and of the working environment, (ii) size of the experimental test bench, (iii) rotational velocity of the cascade (neglected in nearly all experimental apparatus) and finally (v) the lack of particle count, in particular, the lack of ratio between the injected particles and the stuck particles. For these reasons, the fouling phenomenon is not fully understood. It follows that the quantitative analysis of the deposits on a blade surface is strongly related to realistic (i) air contamination data, (ii) filtration efficiency and (iii) particle adhesion.

In this paper an overall analysis relating to these three strategic points is reported, highlighting the possibility of integrating these fields of research in order to estimate the fouling rate a priori. An solution can be found by using results obtained in different research fields. Interdisciplinary research can represent a new frontier for a considerable up-grade in the investigation of fouling. Climatology, filtration technology and specific studies regarding particle adhesion must be combined in order to generate a useful approach to studying the fouling phenomenon. The present paper proposes an interdisciplinary approach consisting of the combination of the three contributes previously mentioned.

2. Air contamination

Atmospheric aerosols are constituted of a suspension of a solid (smoke, fumes, fly ash, dust, etc.) or liquid (mist, fog, etc.) in the atmosphere. In general, fine particles refer mainly to a man-made action while coarse particles refer mainly to a natural phenomenon. Aerosols assume a very wide range of concentrations (from 1 $\mu g/m^3$ to 100 $\mu g/m^3$) depending on site location and time. Solid contaminants are spread from their source carried by the wind.Areas with very fine solid particles and sand are more likely to be potential source regions for dust storms or high dust concentration in the air. Given the information related to particle transportation, it is easy to understand that the particles are carried by the wind and not only the geographic area close to the power plant influences the air contamination ingested by the power unit. In [6] there is a mass characterization of the different sizes of airborne particles for the Shanghai atmosphere. It is possible to determine the mass concentration of the contaminant per unit of volume as a function of the particle diameter, as reported in Fig. 1. Since filtration systems work in different ways depending on the particle diameter, the sampled range as a function of this diameter is necessary to define which quantity and type of particles pass through the filtration barrier and enter the compressor sections. This first contributor is not related to the power plant design, but is one of the critical aspects to be considered in the fouling analysis. The only method of contrasting and reducing air contaminant concentration refers to the use of the most appropriate filtration systems.

3. Filtration system

The filtration system protects the gas turbine from harmful debris in the ambient air, which can lead toissues such as foreign object damage, erosion, fouling, and corrosion. As reported by Schroth and Cagna[7] a gas turbine with an intake volume flow of 1.5 million cubic meters per hour will swallow up to 30trillion particles of 0.5μm and greater per hour. The selection of the proper inlet filtration system coversthe following aspects: (i) characteristics of filters and filter systems, (ii) characteristics of different

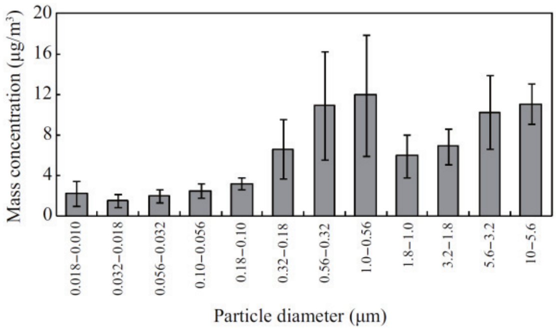

Fig.1. Mass concentrations of size-segregated particles collected in the Shanghai atmosphere [9]

environments where the gas turbine can operate, (iii) evaluation of the site where the gas turbine is or will be installed and (iv) evaluation of the combined effect due to the increment in filter pressure drop compared to the increase in filter efficiency.

In order to capture different types of particles, filtration systems use many different mechanisms. Each filter in fact has various different mechanisms working together to remove the particles, i.e. inertial impaction, diffusion, interception, sieving and electrostatic charge. The filter media, fiber size, packing density of the media, particle size, and electrostatic charge all influence how the filter removes particles. An extensive report on filtration efficiency can be found in [10], where it can be seen that conventional filtration systems will not entirely prevent particles with dimension lower than ≈ 2 μmfrom entering the gas turbine, and may therefore cause fouling [1].

Figure 2 shows a comparison of a filter's total efficiency based on the various filtration mechanisms that are applied as a function of the particle diameter. The figure also shows the effect of the electrostatic charge. Starting with the data mentioned in the previous paragraph related to contaminant concentration in the air, by using the filtration efficiency reported in Fig. 2, it is possible consider the effect of the air filtration systems for the analysis of the mass deposits on the blade surface. At this step, two contributors (contaminant concentration and filtration efficiency) have been used in order to the determine the amount of contaminant that could impact and adhere to the blade surfaces of the compressor.

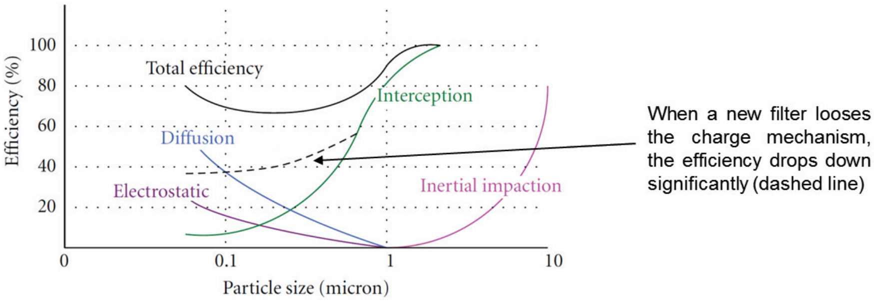

Fig. 2.Combination of filtration mechanisms to obtain filter efficiency at various particle sizes [8]

4. Particle adhesion characteristics

The capability of the contaminants to impact and adhere to the blade surface determines compressorfouling. Particle adhesion on the blade surface is a complex phenomenon that includes many aspects: (i) the material of the body in contact, (ii) the surface conditions, (iii) the particle size, (iv) the impact velocity and (v) the impact angle. All these phenomena can be studied from many points of view: (i) kinematic (velocity and direction), (ii) dynamic (velocity and mass) and (iii) energy (deformations or breaks). In almost all cases the phenomena mentioned above occur at the same time and the result of the contact depends on the combination of these effects.

Fouling phenomenon can be described by the following three phases: (i) transportation of the contaminants by the air, (ii) contact and adhesion of the first particle with the surface and (iii) repeated adhesion of subsequent particles on the contaminant previously deposited on the surface.A comprehensive study of the phenomenon of contaminant ingestion by a turbomachine must contain the resolution of the three phases of adhesion and that of rebound mentioned above.

Most of the classical approaches and the results reported in literature [9 – 12] do not provide a full understanding of the adhesion phenomena which are responsible for the fouling mechanism. This limit is largely due to: (i) different particle sizes, (ii) different material characteristics (some particle materials do not show the elastic yield limit) and (iii) the different impact velocity.

Some very interesting results and detailed analysis of micro-particle adhesion can be found in astrophysics applications related to the research of pre-planetary dust dynamics. The particles, in most cases consisting of sub-micrometric silica spheres, are the basis of the planets' origin.In this field of research, one of the studies closest to that of the fouling phenomena is [13], reporting experimental evaluations of perfectly spherical and irregular particles impacting a smooth surface (smooth as the particle surface).The uniqueness and usefulness of these studies is that the particle velocities, materials and dimensions are in the same range as those responsible for the fouling phenomenon.The sticking probability is one of the most interesting quantities used in this type of study. It compares the impact that results in sticking with the total number of impacts.

From the reported literature, it is easy to understand that in order to completely comprehend fouling phenomena, knowledge of how the contaminants hit the blade surface is essential. In this context the word "how" refers to the impact velocity and the impact angle for each particle. For these reasons, the numerical simulation could represent a valuable support for the calculation of the particle's kinetic characteristics. If the transport of contaminants (particles) is resolved by the coupling of the Eulerian and Lagrangian approaches, the kinematic characteristics of the particles are calculated at each point of the computational domain, representing the basis for the calculation of sticking probability. In literature, some studies related to particle ingestion in the axial compressor can be found [14 – 16] but, unfortunately, the particle diameter is too large to study the fouling phenomenon. Small particles are subjected to inertia and diffusion deposition and, for this reason, the capability of numerical simulation to represent their trajectories is limited. Only a few applications are reported in literature [17 – 20] for transonic and subsonic rotors. However, the numerical simulation represents the only method of discovering the kinematic behaviour of the particles in axial compressors.

5. Methodology application

In the light of the analysis reported in this paper, the fouling phenomenon can be studied by using different sources and different results provided by different research fields. Starting from the air contamination data as a function of the location and the season, knowledge of the filtration system efficiency allows the calculation of the concentration of air contaminant at the inlet section of the compressor. This concentration is calculated as a function of the particle diameter and can be integrated with the results of particle trajectories and particle adhesion characteristics. In fact, the data regarding particle adhesion characteristics could be obtained from specifically-designed experimental tests, where the sticking probability of the particle is related to its material, diameter and kinematic characteristics. Finally, the particle impact location on the blade surfaces could be calculated by using numerical CFD simulations and the kinematic characteristics of each particle calculated by using the Lagrangian strategy.

The lumped scheme reported in Fig. 3 summarizes and explains the interdisciplinary approach that can be used to improve the comprehension of the fouling phenomenon while the mass deposits contour plot represents an example of the results that can be obtained through the use of this interdisciplinary

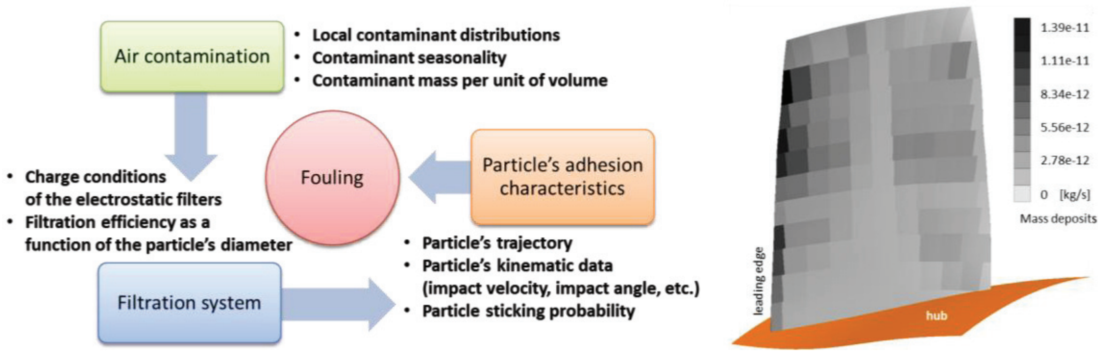

Fig. 3. Interdisciplinary approach to studying the fouling phenomenon

approach. This latter figure is an excerpt of a wider analysis presented by the authors in [21] where this methodology has been applied to a transonic rotor located in sites characterized by different air contaminant distributions.

The application of this interdisciplinary approach has demonstrated that by using realistic (i) air contamination, (ii) filtration efficiency, and (iii) particle adhesion data it is possible to calculate the contaminant mass on the blade surface, as reported in Fig. 3, and realize a quantitative analysis regarding the influence of external factors (such as season and filtration system) on a fouling rate. From these analyses, some guidelines for proper installation and management of the power plant (in terms of filtration systems and washing strategies) can be drawn.

6. Conclusions

In this paper an analysis of the contributors to the fouling phenomenon has been carried out. Compressor fouling is one of the major causesof gas turbine performance degradation. The deposits on the blade surface are linked to (i) air contaminant concentrations, (ii) filtration efficiency and (iii) particle adhesion characteristics. Through the use of an interdisciplinary approach, it is possible to determine the evolution of fouling phenomenon by the integration of (i) CFD numerical analysis (which provides the match between the design characteristic of the machine and the fluid dynamic phenomena) and (ii) power plant characteristics (air contaminant concentrations and the efficiency of filtration systems).In the future, this approach could be a support in the preliminary design phase in order to establish, a priori, cost management due to the maintenance of filtration systems, the interval for washing operations as a function of the axial compressor and the air contaminant concentration that characterizes the power plant location.

7. Copyright

References

[1] Kurz, R., Brun, K., 2012, "Fouling Mechanism in Axial Compressors", Journal of Engineering for Gas Turbines and Power, 134(3), p. 032401

[2] Tarabrin, W. P., Schurovsky, V. A., Bodrov, A. I., Stalder, J.-P., 1998, "Influence of Axial Compressor Fouling on Gas Turbine Unit Performance Based on Different Schemes and With Different Initial Parameters", ASME Paper 98-GT-416

[3] Syverud, E., Brekke, O., Bakken, L. E., 2005, "Axial Compressor deterioration caused by Saltwater Ingestion", ASME Paper GT2005-68701

[4] Vigueras Zuniga, M. O., 2007, "Analysis of Gas Turbine Compressor Fouling and Washing on Line", Ph. D. Thesis, Cranfield University, UK

[5] Parker, G. J., Lee, P., 1972, "Studies of the Deposition of Sub-Micron Particles on Turbine Blades", Proceedings of the Institution of Mechanical Engineers, 186(1), pp. 519-526

[6] Lü, S., Zhang, R., Yao, Z., Yi, F., Ren, J., Wu, M., Feng, M., Wang, Q., 2012, "Size distribution of chemical elements and their source apportionment in ambient coarse, fine, and ultrafine particles in Shanghai urban summer atmosphere", Journal of Environmental Sciences, 24(5), pp. 882–890

[7] Schroth, T., Cagna, M., 2008, "Economical Benefits of Highly Efficient Three-Stage Intake Air Filtration for Gas Turbines", Proceedings of ASME Paper GT2007-50280

[8] Wilcox, M., Baldwin, R., Garcia-Hernandez, A., Brun, K., 2010, "Guideline for gas turbine inlet air filtration systems", Gas Machinery Research Council Southwest Research Institute, Release 1.0

[9] Hertz, H., 1882, "Uber die Beriihrung fester elastischer Korper", J. reine und angewandte Mathematik, 92, pp. 156-171, (for English translation see: Jones, D. E., Schott, G. A., 1896, "Miscellaneous Papers by H. Hertz,", Macmillan, London)

[10] Johnson, K. L., Kendall, K., Roberts, A. D., 1971, "Surface Energy and the Contact of Elastic Solids", Proceedings of the Royal Society of London. Series A, Mathematical and Physical, 324(1558), pp. 301-313

[11] Thornton, C., Ning, Z., 1998, "A theoretical model for the stick/bounce behavior of adhesive elastic-plastic spheres", Powder Techonology, 99, pp. 154-162

[12] Wall, S., John, W., Wang, H. C., Goren, S. L., 1990, "Measurements of Kinetic Energy Loss for Particles Impacting Surfaces", Aerosol Science and Technology, 12(4), pp. 926-946

[13] Poppe, T., Blum, J., Henning, T., 2000, "Analogous experiments on the stickiness of micron-sized preplanetary dust" The Astrophysical Journal, 533, pp. 454-471

[14] Suzuki, M., Inaba, K., Yamamoto, M., 2008, "Numerical Simulation of Sand Erosion Phenomena in Rotor/Stator Interaction of Compressor", Journal of Thermal Science, 17(2), pp. 125−133

[15] Suzuki, M., Yamamoto, M., 2011, "Numerical Simulation of Sand Erosion Phenomena in a Single-Stage Axial Compressor", Journal of Fluid Science and Technology, 6(1), pp. 98-113

[16] Ghenaiet, A., 2012, "Study of Sand Particle Trajectories and Erosion Into the First Compression Stage of a Turbofan", Journal of Turbomachinery, 134, p. 051025

[17] Suman, A., Kurz, R., Aldi, N., Morini, M., Brun, K., Pinelli, M., Spina, P. R., 2015, "Quantitative CFD Analyses of Particle Deposition on a Transonic Axial Compressor Blade, Part I: Particle Zones Impact" Journal of Turbomachinery, 137(2), p. 021009

[18] Suman, A., Morini, M., Kurz, R., Aldi, N., Brun, K., Pinelli, M., Spina, P. R., 2015, "Quantitative CFD Analyses of Particle Deposition on a Transonic Axial Compressor Blade, Part II: Impact Kinematics and Particle Sticking Analysis", Journal of Turbomachinery, 137(2), p. 021010

[19]Aldi, N., Morini, M., Pinelli, M., Spina, P.R., Suman, A., 2015, "Comparative analyses of micro-particle impact between transonic and subsonic axial compressors", 11th European Turbomachinery Conference, 23–27 March, Madrid, Spain

[20] Suman, A., Kurz, R., Aldi, N., Morini, M., Brun, K., Pinelli, M., Spina, P. R., 2016, "Quantitative CFD Analyses of Particle Deposition on a Subsonic Axial Compressor Blade", Journal of Engineering for Gas Turbine and Power, 138(1), p. 012603

[21] Suman, A., Morini, M., Kurz, R., Aldi, N., Brun, K., Pinelli, M., Spina, P. R., 2016, "Estimation of the ParticleDeposition on a Transonic AxialCompressor Blade",Journal of Engineering for Gas Turbine and Power, 138(1), p. 012604

Biography

Alessio Suman graduated cum laude from University of Ferrara (Italy). Recently, he has been awarded the Best Papers by the Oil and Gas Committee of the ASME Turbo Expo 2014.