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Research Article

The Sensitive Parameter Study of Axial Flow Compressor Fouling

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Abstract: Fouling is an important performance degradation factor of axial flow compressor. Proper fouling sensitive parameter is crucial to more effectively monitor the fouling severity. Currently fouling level and cleaning necessity are judged by the decrease degree of thermodynamic performance parameter from macro point. But simulation research of NASA rotor 37 finds that tip clearance increase also causes the decrease of thermodynamic parameters such as pressure ratio, mass flow, efficiency and output power, so these parameters can't distinguish fouling and other failure modes. Contaminated particles within air deposited on the blade surface to cause the change of blade shape and surface roughness. But from the definition of roughness, fouling and erosion can't be distinguished by surface roughness. Finally, blade profile parameters are chosen as sensitive parameter of fouling. At the same time, with the rapid development of measure technology, profile parameter can be measured by combination of laser triangulation method and CMM (coordinate measuring machine). Based on reverse engineering, measure point clouds are reconstructed into three dimensional solid model of fouled compressor. Quantitative research shows that fouling cause increase of total temperature, total pressure and surface friction coefficient, simultaneously effective flow area is decreased, thus thermodynamic performance is degraded.

Keywords: Axial flow compressor, fouling, reverse engineering, sensitive parameter

INTRODUCTION

Although high performance filters was installed in axial compressor inlet, contaminant particles (Table 1) contained in air with diameter less than 2 microns such as fly ash, oil smoke, dust, pollen etc still could enter into compressor. Because of existence of lubrication oil and water steam, particles could deposit on the blade surface which resulted in the increase of blade thickness and blade surface roughness. Thus, aerodynamics performance was influenced and thermodynamic performance was degraded (Kurz and Brun, 2001). Lakshminarasimha demonstrated that if roughness was increased from 55 microns to 120 microns, fuel consumption rate was increased by 0.13, mass flow rate was decreased 5% and efficiency was decreased by 2.5% (Lakshminarasimha *et al*., 1994). Simultaneously research found that 70% performance degradation is caused by fouling. So, it is very important to monitor the fouling level in order to run safely. Thus, sensitive parameter of fouling must be chosen (Table 1):

The sensitive parameter of axial flow compressor fouling should have some features as following:

- The parameter should be sensitive to fouling changes to accurately judge working status of compressor
- The parameter is not influenced by external environment
- The parameter should be easily measured

Table 1: Contaminant source

Type of particle	Size (μm)
Ground-dust	1~300
Oil smokes	0.02~1
Fly ash	1~200
Salt particles in mist	Less than 10
Smog	Less than 2
Clay	Less than 2
Coal dust	1~100
Rosin smoke	0.01~1

Some researchers chose thermodynamic parameter such as pressure ratio, isentropic efficiency and mass flow rate etc as sensitive parameter of fouling. Based on decrease degree of thermodynamic parameter, fouling level is judged. But research found that thermodynamic parameter was also decreased by the increase of tip clearance. So, thermodynamics parameters are not suitable as sensitive parameter because these parameters can't distinguish fouling from other failure modes.

Saravanamuttoo computed fouled axial flow compressor performance by establishing mathematical model. Author chooses parameter which is relative to pressure ratio and total temperature of inlet or outlet as

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Table 2: Design parameter of NASA rotor37

Design parameter	Value
Blade number	36
Rotation speed	17188.7rpm
Mass flow rate	20.19kg/s
Pressure ratio	2.106
Tip speed	454.14m/s
Tip clearance	0.0356cm
Aspect ratio	1.19

sensitive parameter. But this parameter is directly relate to total stage number and is difficult to measure.

Li zhao puts forward intake depression as sensitive parameter of fouling, but in simulation surface roughness is simulated by exerting random number. It is difficult to reflect real status of fouled compressor. At the same time, other failure modes may result in same changes of this parameter.

Some researchers may choose surface roughness as sensitive parameter to judge fouling level. But foreign object damage, wear and corrosion also cause same changes, so surface roughness can not uniquely characterize fouling phenomenon. At the same time, surface roughness is difficult to monitor on line.

Fouling changes the blade geometry and blade surface roughness which are considered as blade profile parameter. Different failure modes may cause different changes of blade profile parameter, so it uniquely characterizes compressor fouling. At the same time, with the development of measure technology, it is feasible to monitor this parameter on line. Thus it can be chosen as sensitive parameter of fouling.

This study chooses NASA rotor 37 as study object, respectively demonstrated the possibility of thermodynamic parameter, surface roughness and blade profile parameter as sensitive parameter of axial flow compressor fouling. Finally, blade profile parameter is chosen as sensitive parameter.

THE EFFECT OF FAILURE MODES ON THERMODYNAMIC PARAMETER

In order to verify the possibility of thermodynamic parameter as sensitive parameter of compressor fouling, the effect of each failure mode on thermodynamic parameter is discussed. Choosing NASA rotor 37 as research object, its detailed design parameters are shown in Table 2 (Lonnie and Royce, 1978) and its geometry is shown in Fig. 1.

Fig. 1: Geometry of NASA rotor37

This study simulates the flow field of axial flow compressor by using ANSYS CFX. In this simulation, J-grid is chosen and grid node number is 25 million. And then SST model is chosen as turbulent model. The grid node is refined in streamwise location near to wall and the computational model is shown in Fig. 2. Finally, compressor inlet boundary is given by mass flow rate (20.19 kg/s) and outlet boundary is given by static pressure (Wang *et al*., 2009).

Fig. 2: Computational model of NASA rotor37

The effect of fouling on thermodynamic parameter: In order to discuss the effect of fouling on thermodynamic parameter, different blade thickness changes are set to simulate axial flow compressor fouling in early stage. This study respectively simulate clean compressor and fouled compressors which blade thickness changes are respectively as 50 and 150 micron in design rotational speed. Simulation result is shown in Table 3. The result shows that fouling results in decrease of thermodynamic parameter such as pressure ratio, efficiency and output power.

The effect of tip clearance on thermodynamic parameter: Foreign object damage may cause tip clearance increase of axial flow compressor which influences flow area (Zhang *et al*., 2006). In order to discuss the effect of tip clearance on thermodynamic parameter, flow field of axial flow compressors with different tip clearance in design rotational speed is simulated. These tip clearances are as 2.5, 5 and 8% span of blade. Simulation result is shown in Table 4. By the contrast of data in Table 3 and in Table 4 can be seen that tip clearance increase simultaneously reduces thermodynamic parameter such as pressure ratio, efficiency and output power.

The effect of coexistence of fouling and tip clearance increase on thermodynamic parameter: The flow field is simulated in the condition of which fouling and tip clearance increase coexists. Compressors combined different fouling level with different tip clearance is analyzed. And simulation result is shown in Table 5.

From this result can be seen that coexistence of fouling and tip clearance increase may significantly reduce thermodynamic parameter. Data from Table 3 to Table 5 shows that fouling and tip clearance increase can cause similar changes of thermodynamic parameters, so these parameters can not uniquely

Table 3: Simulation results of clean compressor and fouled compressor in design rotational speed

Thermodynamic parameter	Blade thickness changes(micron)		
	0	50	150
Pressure ratio	2.0167	1.9081	1.8917
Temperature ratio	1.2686	1.2618	1.2608
Isentropic efficiency (%)	84.6359	81.1466	80.5763
Polytropic efficiency (%)	86.0435	82.7383	82.1938

Table 4: Simulation results of compressors with different tip clearance in design rotational speed

Thermodynamic parameter	Axial flow compressor tip clearance		
	2.5% span	5% span	8% span
Pressure ratio	1.9938	1.9227	1.8882
Temperature ratio	1.2623	1.2529	1.2465
Isentropic efficiency (%)	84.7485	83.4811	83.1863
Polytropic efficiency (%)	86.1227	84.8965	84.5755

Table 5: Compressors with different fouling level and different tip clearance in design rotational speed

Compressor			
Tip clearance	Blade thickness changes (micron)	Pressure ratio	Isentropic efficiency/%
2.5% span	50	1.8833	80.9649
	150	1.8641	80.1947
5% span	50	1.8457	80.6932
	150	1.8373	80.0586
8% span	50	1.8448	80.4888
	150	1.8325	79.8979

characterize fouling phenomenon. Thus, new sensitive parameter should be chosen to monitor fouling level.

SENSITIVE PARAMETER CHOICE

From above analysis can be seen that macro parameter can't distinguish fouling from other failure modes. So, fouling problem may be discussed from the microscopic point of view. Contaminant particles deposited on the blade surface change blade surface roughness and blade profile which significantly influence aerodynamic performance. Therefore the feasibility of these two parameters as sensitive parameter of fouling will be discussed.

Surface roughness: Based on above analysis, surface roughness increase can reduce mass flow rate, pressure ratio and efficiency which is consistent with fouling experiment result. But the definition of surface roughness shows that this parameter still can't accurately distinguish fouling from other failure modes.

Surface roughness, often shortened to roughness, is a measure of the texture of a surface. It is quantified by the vertical deviations of a real surface from its ideal form. If these deviations are large, the surface is rough; if they are small the surface is smooth. There are many different roughness parameters such as Ra, Rz, Rq, but profile arithmetic average is by far the most common which is shown in Fig. 3. The formula is shown in (1):

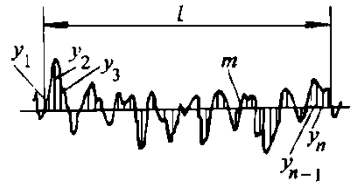

Fig. 3: Ra of contour

$$Ra = \frac{1}{l}\int_0^l |y(x)| dx or\ Ra = \frac{1}{n}\sum_{i=1}^{n}|y_i| \qquad (1)$$

According to fouling mechanism, y_i is a numeric value greater than 0 in the surface roughness formula because of fouling. But other failure modes such as corrosion and erosion can remove blade surface material so that y_i is a numeric value smaller than 0. Although y_i is different between fouling and other failure modes, the value of surface roughness may be same according to formula (1). So, surface roughness can't be sensitive parameter to uniquely monitor fouling level. At the same time, this parameter is difficult to measure online.

Blade profile parameter: Blade profile is a complex three dimensional surface. Cross section shape and size at different span is different. Blade profile parameters are blade profile and geometric dimensions which include blade thickness, blade chord length, leading edge location and trailing edge location etc., (Liu and Xing, 2000; Chen *et al*., 2005).

Sensitive parameter is parameter which can accurately distinguish fouling and other failure modes to uniquely characterize fouling level. Tip clearance increase changes tip section shape and size which reduces blade span and blade tip thickness. However, blade profile parameters in other location do not have any changes. Failure modes such as erosion, corrosion and foreign object damage can remove blade surface material which reduces blade thickness. But fouling, whether uniform or non uniform, will make blade thickness increase and change blade section shape and size. Based on above analysis, different failure modes can make different change of blade profile parameter. It is easily to distinguish fouling from other failure modes by using blade profile parameter as sensitive parameter. Traditional measurement method is difficult to monitor the changes of blade profile parameter, but with the rapid development of measurement technology, laser triangulation measurement method is demonstrated that it can be successfully applied to measure the changes of blade profile parameter. So, it can be used as sensitive parameter of compressor fouling.

QUANTITATIVE RESEARCH OF FOULING ON COMPRESSOR THERMODYNAMIC PERFORMANCE

In order to study compressor fouling mechanism and the effect of fouling on thermodynamic performance, quantitative analysis must be carried on. Fouling experiment demonstrated that more contaminant particles deposited on the suction surface than on the pressure surface and fouling in leading edge is more serious than in trailing edge. In order to accurately analyze the effect of fouling on compressor performance, high quality mathematical model of fouled compressor is critical. Many researchers apply similar model to simulate fouling phenomena which can not reflect real status. This study combines reverse design technology with traditional flow field simulation method to reconstruct accurate three dimensional solid models of fouled compressor.

Reverse design technology: With the development of computer-aided design, reverse engineering has become an important method to create a 3D virtual model of an existing physical part for use in 3D CAD, CAM, CAE or other software. The reverse-engineering process involves measuring an object and then reconstructing it as a 3D solid model. The physical object can be measured using 3D scanning technologies like CMM (coordinate measuring machine), laser scanners, structured light digitizers, or Industrial CT Scanning (computed tomography). The measured data alone, usually represented as point cloud, lacks topological information and is therefore often processed and modeling into a more usable format such as a triangular-faced mesh, a set of NURBS surfaces, or a CAD model.

Model reconstruction of fouled compressor: Laser triangulation is a non-contact active vision measurement method which has many advantages such as no influence on object surface, high precision, simple structure and strong anti interference ability.

Coordinate measuring machine is the most widely used contact type measuring device, is the use of three coordinate measuring machine probe point to obtain the measured surface point coordinate. Due to the movement accuracy of a mechanical structure continues to improve, so CMM measuring precision is very high. But it also leads to slow measurement. Measurement process requires some manual intervention and probe contact force can make the surface of an object to be measured is impaired. It is difficult to measure complex surface.

This study combines coordinate measuring machine with laser triangulation method to reduce the limitation of the object to be measured. The objects are appropriately fixed, laser multi-angle scanning of object is finished by accurate movement and rotation of coordinate measuring machine probe to acquire accurate three dimensional information of the object.

According to the experiment result, fouling is more serious in leading edge than in trailing edge. At the same time, experiment result shows that fouling is more serious in location near blade root. So this study attaches different sandpapers to clean compressor rotor blade to simulate different fouling level. Assuming fouling being linearly distributed, fouled compressor rotors which surface roughness in leading edge is respectively 50μm, 100μm and150μm are discussed.

Table 6: Quantitative result of fouled compressor

Thermodynamic parameter	Surface roughness in leading edge (micron) 50	100	150
Pressure ratio	2.0057	1.9971	1.9884
Temperature ratio	1.2683	1.2680	1.2678
Isentropic efficiency (%)	84.2797	83.9816	83.6758
Polytropic efficiency (%)	85.7104	85.4316	85.1456

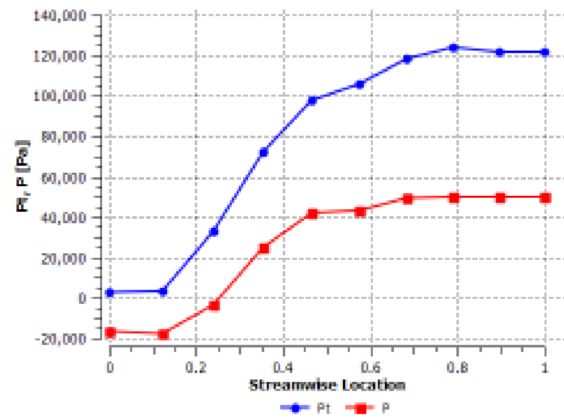

Fig. 4: Stream wise plot of Pt and P of clean compressor

Quantitative analysis: Fouled compressor rotors are reconstructed to simulate flow field based on point cloud which is obtained by above measure method. Simulation result is shown in Table 6.

Compared with data in Table 3, the reduction of thermodynamic performance parameters is much less than the former, because the former doesn't consider the fouling distribution, but consider that fouling is uniform in whole blade. But the latter is obtained by reverse technology considering changes of blade profile parameter. From qualitative point of view, pressure ratio, efficiency and output power is reduced by fouling. From quantitative point of view, pressure ratio is reduced by 0.55% and isentropic efficiency is reduced by 0.42% if surface roughness of leading edge in suction is increased from 0 micron to 50 micron. And, pressure ratio is reduced by 0.97% and isentropic efficiency is reduced by 0.77% if surface roughness of leading edge in suction is increased from 0 micron to 100 micron. Also, pressure ratio is reduced by 1.4% and isentropic efficiency is reduced by 1.13% if surface roughness of leading edge in suction is increased from 0 micron to 150 micron (Li *et al*., 2010a, b).

Pressure: The total pressure and static pressure distribution of clean compressor and fouled compressor in stream wise location is respectively shown in Fig. 4 and 5. It is demonstrated that fouling resulted in the increase of pressure.

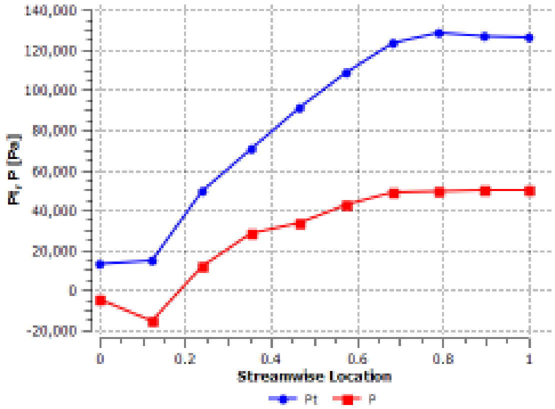

Fig. 5: Stream wise Plot of Pt and P of fouled compressor

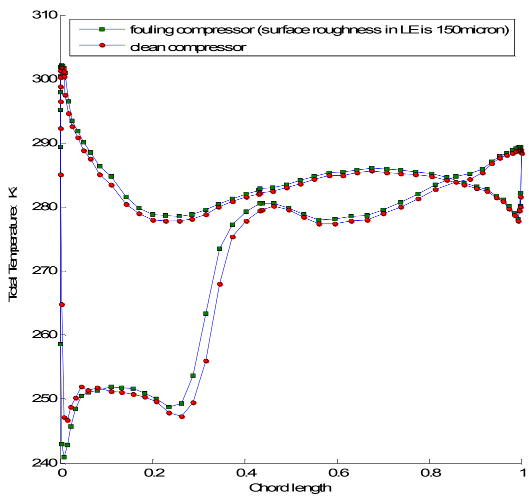

Fig. 6: Temperature contours at 20% span

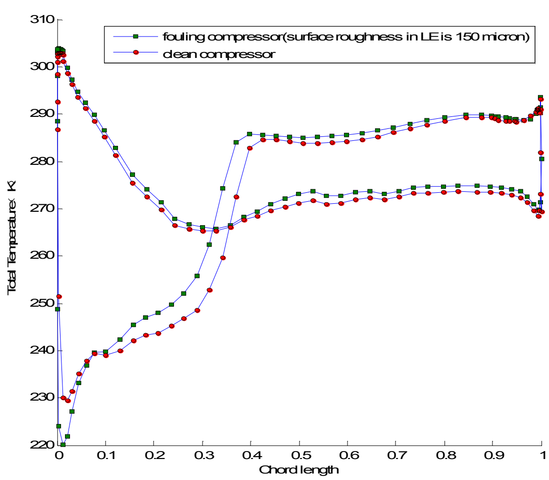

Fig. 7: Temperature contours at 80% span

Total Temperature: The total temperature distribution of clean compressor and fouled compressor in 20% span is shown in Fig. 6. And, the total temperature distribution of clean compressor and fouled compressor in 80% span is shown in Fig. 7. It can be seen from two figures that fouling can result in total temperature increases of suction surface and pressure surface. But, total temperature variation in suction surface is more obvious than in pressure surface. Simultaneously, it can be found that total temperature increase in blade leading edge is higher than other location.

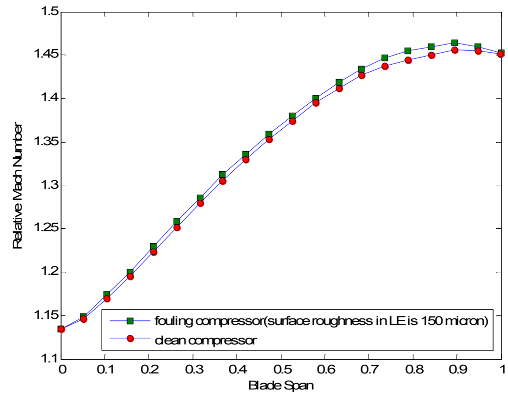

Fig. 8: Relative Mach number in leading edge

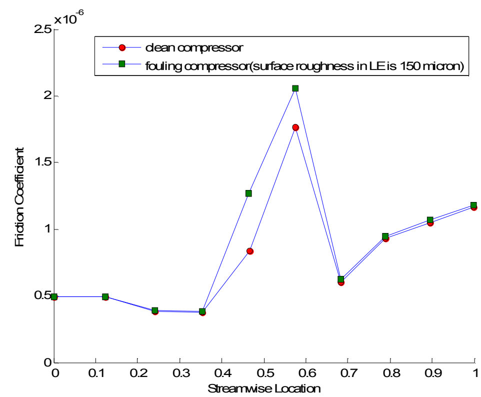

Fig. 9: Surface friction coefficient in stream wise location

Mach number: Mach number of clean compressor and fouled compressor in leading edge is computed and the simulation result is shown in Fig. 8. The simulation results show that the mach number of blade root in trailing edge is unchanged. Fouling causes the increase of mach number from 50% blade span to blade tip. Relative mach number in whole blade leading edge is increased by fouling, but the increase near blade tip is obvious.

Surface friction coefficient: From Fig. 9 can be seen that fouling obviously causes friction coefficient in middle stream wise position where blade is mounted by fouling. Thus, flow area is reduced and flow resistance is increased.

CONCLUSION

- Fouling and tip clearance increase as well as combination of both may result in the same change of thermodynamic performance parameters, so that these parameters such as pressure ratio, mass flow rate, efficiency and output power can not uniquely characterize fouling level.
- Although the most intuitive appearance of fouling phenomenon is the increase of blade surface roughness, but from the definition of surface roughness can be seen that fouling and other failure modes may cause the same roughness value. So, roughness is difficult to make a distinction between fouling and other failure modes.
- Fouling, erosion and tip clearance increase may result in different changes of blade profile parameter such as blade thickness, so it can distinguish fouling and other failure modes. At the same time, blade profile parameter is successfully measured by laser triangulation measure method. So, it can be chosen as sensitive parameter of compressor fouling.
- Based on reverse engineering, considering fouling experiment results, the quantitative simulation results show that the fouling causes total temperature increase, in particularly near blade tip position. It also shows that the total temperature increase in suction surface is greater than in the pressure surface. And mach number is increased in leading and trailing edge. Simultaneously surface friction coefficient increases and the effective flow area are reduced.

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