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Research Article

The Effect of Surface Roughness on Thermodynamic Performance Parameter of Axial Flow Compressor

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Abstract: In axial flow compressor, blade surface roughness is affected by many failure modes such as fouling, erosion, corrosion and foreign object damage. But with development of filter performance, particles with diameter larger than 2 μm cannot enter into compressor, so fouling is the most important influence factor which results in the variation of surface roughness. This study respectively discusses the effect of surface roughness on performance parameter when surface roughness is constant and linearly distributed. Finally, based on experiment result, reverse design method is applied to reconstruct the fouled compressor by combining laser triangulation sensor with compressor fouling test rig and then reconstructed solid model is imported into ANSYS CFX to simulate flow field. Result shows that the increase of surface roughness results in the decrease of pressure ratio, mass flow and efficiency.

Keywords: Axial flow compressor, fouling, reverse design, surface roughness, thermodynamic performance parameter

INTRODUCTION

Axial flow compressor is an important device in gas turbine plant because it consumes a large portion of the total turbine work. Many researches found that approximately 50 to 60% of the total work produced in the turbine is consumed by its axial flow compressor. So maintaining high compressor efficiency is important for the plant.

In many failure modes of axial flow compressor, blade surface roughness is affected by fouling, erosion, corrosion or FOD (Foreign Object Damage). At present, because of high performance filters mounted in inlet, particles with diameter greater than 2 μm are prevented from entering into compressor. In general, particles with diameter smaller than 10 μm may cause fouling, but not erosion. Smaller particles (including dust, unburned hydrocarbons and insects) can be deposit on blade surface to form fouling when lubricating oil and water is existed simultaneously. Fouling changed compressor blade geometry and increased surface roughness so that influenced its aerodynamic performance. So, fouling is most important influence factor which results in the variation of surface roughness.

Experience has shown that axial compressors will foul in most operating environments. There are many industrial pollutants and all kinds of environmental conditions that play an important role in the fouling process. Compressor fouling is typically caused by (Table 1):

Table 1: Contaminants source

Type	Type of particle	Size (μm)
F1	Ground-dust	1~300
F2	Oil smokes	0.02~1
F3	Fly ash	1~200
F4	Salt particles in mist	Less than 10
F5	Smog	Less than 2
F6	Fume	Less than 1
F7	Clay	Less than 2
F8	Rosin smoke	0.01~1
F9	Coal dust	1~100
F10	Metallurgical dusts and fumes	0.001~100
F11	Ammonium	0.1~3
F12	Carbon black	0.01~0.3
F13	Contact sulphuric mist	0.3~3
F14	Paint pigments	0.1~5

- External contaminants
- Internal contaminants
  - Internal gas turbine oil leakage from the front bearing of the axial compressor is a common cause. Oil leaks combined with dirt ingestion causes heavy fouling problem
  - Impure water from evaporative coolers
  - Vapor plumes from adjacent cooling towers
  - Corrosion and erosion of filter panel

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Fig. 1: Geometry of NASA rotor37

Fig. 2: Computational model of NASA rotor37

Because gas turbine ingest extremely large quantities of air, study found that at a 10 ppm foul ant loading rate, 204 tones of foul ant would be ingested which reduced performance parameter such as mass flow, efficiency.

Previous research (Lakshminarasimha *et al*., 1994) found that if roughness increased from 55 to 120 μm, fuel consumption rate increased 0.13%, mass flow decreased 5% and efficiency decreased 2.5%. Another study (Kurz and Brun, 2001) found that rotor blade roughness increased from 4 to 8 μm and stator blade roughness increased to 8 μm after long time operation. Researcher (Zwebek, 2002) demonstrated that mass flow decreased 5% and fuel consumption rate increased 2.5% because of fouling.

Some researchers simulated the effect of surface roughness on performance by adding constant surface roughness. But experiments showed that fouling level is not uniform along chord length and blade span, so above methods can't reflect the real status of fouled compressor. In this study, reverse design method is applied to reconstruct solid model of fouled compressor and then flow simulation is implemented based on reconstructed solid model in order to reveal the real effect of surface roughness on performance parameter.

MATHEMATICAL MODEL

This study chooses NASA rotor37 as study object, its detailed design parameters are as following:

- **Type:** Transonic axial compressor
- **Blades:** 36 blades with tip clearance
- **Fluid:** Air
- **Working point:** Rotation speed 17188.7 rpm, Mass flow 20.19 kg/s, Pressure ratio 2.106, Adiabatic efficiency 87.7%

The geometry of rotor37 is shown in Fig. 1. 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 stream wise location near to wall and the computational model of clean rotor37 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 (Zhou and Wang, 2007; Wang *et al*., 2009; Li *et al*., 2007).

SIMULATION ANALYSIS OF DIFFERENT BLADE SURFACE ROUGHNESS DISTRIBUTION

Constant blade surface roughness: Assuming blade surface roughness is uniform in whole blade; flow simulation is implemented by ANSYS CFX based on three different surface roughnesses such as 50, 100 and 150 μm, respectively. Simulation result is shown in Table 2.

Simulation result shows that pressure ratio decreases 5.37%, temperature ratio decreases 0.49%, isentropic efficiency decreases 4.11% and output power decreases 3.69% when surface roughness increases from 0 to 50 μm. Pressure ratio decreases 5.9%, temperature ratio decreases 0.59%, isentropic efficiency decreases 4.53% and output power decreases 4.03% when surface roughness increases from 0 to 100 μm. Pressure ratio decreases 6.2%, temperature ratio decreases 0.61%, isentropic efficiency decreases 4.8% and output power decreases 4.17% when surface roughness increases from 0 to 150 μm. Simulation result simultaneously shows that thermodynamic performance parameter is dramatically reduced when blade is rough.

Table 2: Simulation results of fouled compressor when surface roughness is constant

	Blade surface roughness (micron)			
Thermodynamic parameter	0	50	100	150
Pressure ratio	2.0167	1.9085	1.8977	1.8917
Temperature ratio	1.2686	1.2626	1.2611	1.2608
Isentropic efficiency (%)	84.6359	81.1543	80.8045	80.5763
Polytrophic efficiency (%)	86.0435	82.7451	82.4111	82.1938
Output power (KW)	1627.0900	1567.1200	1561.4700	1559.2200

Fig. 3: Fouling on the IGV surface from the gas turbine

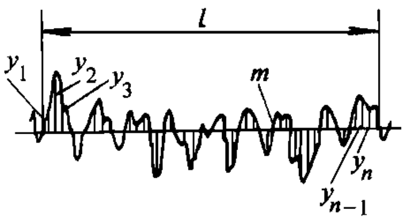

Fig. 4: Ra of contour

Linear distribution of surface roughness: Figure 3 shows the fouling on the IGV surface from the gas turbine. Fouling is not uniform in whole blade, so blade surface roughness is not constant and above result doesn't accurately reflect the real status of fouled compressor. Experiment found that contaminant particles are easily deposited on the blade root and fouling in suction surface is more severe than in pressure surface. At the same time, particles are more easily deposited in leading edge. Based on experiment result, assuming blade surface roughness in section at specified span is linear distributed from leading edge to trailing edge.

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. 4. The formula is shown in Eq. (1):

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

Table 3: Simulation results of fouled compressor when surface roughness is linear distributed

	Surface roughness in leading edge (micron)			
Thermodynamic parameter	0	50	100	150
Pressure ratio	2.0167	2.0057	1.9971	1.9884
Temperature ratio	1.2686	1.2683	1.2680	1.2678
Isentropic efficiency (%)	84.6359	84.2797	83.9816	83.6758
Polytrophic efficiency (%)	86.0435	85.7104	85.4316	85.1456
Output power (KW)	1627.0900	1622.3500	1618.6700	1615.2900

Table 4: Summary performance data of clean compressor

Quantity	Inlet	LE cut	TE cut	Outlet	TE/LE	TE-LE	Units
Density	1.1542	0.9993	1.5376	1.5422	1.5387	0.5383	[kg m^-3]
P static	94536.9000	81829.2000	151403.0000	151351.0000	1.8502	69573.9000	[Pa]
P total	112291.0000	108559.0000	229552.0000	226462.0000	2.1145	120993.0000	[Pa]
P total (rot)	112756.0000	105305.0000	101453.0000	100182.0000	0.9634	-3852.2700	[Pa]
T static	284.6910	272.5300	338.5050	338.8530	1.2421	65.9742	[K]
T total	299.6910	301.6220	380.5200	380.1980	1.2616	78.8977	[K]
T total (rot)	300.0760	300.3940	300.4100	300.3600	1.0001	0.0162	[K]
H static	-13517.9000	-25732.3000	40532.2000	40882.2000	-1.5752	66264.5000	[J kg^-1]
H total	1547.2800	3487.7000	82732.5000	82409.3000	23.7212	79244.8000	[J kg^-1]
Rothalpy	1933.9800	2253.5800	2269.8600	2220.0000	1.0072	16.2798	[J kg^-1]
Entropy	-22.1182	-1.4787	9.7369	12.9574	-6.5847	11.2156	[J kg^-1 K^-1]
Mach (abs)	0.5080	0.7300	0.7844	0.7799	1.0745	0.0544	
Mach (rel)	1.2705	1.3791	0.7248	0.7228	0.5255	-0.6543	
U	391.9840	391.3060	391.1350	390.7170	0.9996	-0.1707	[m s^-1]
Cm	171.4960	225.4720	175.9940	181.9820	0.7806	-49.4783	[m s^-1]
Cu	0.9917	-11.8294	-230.2880	-214.4570	19.4674	-218.4580	[m s^-1]
C	171.6840	240.0940	298.5870	286.2990	1.2436	58.4924	[m s^-1]
Distortion parameter	1.0663	1.0466	1.0613	1.0125	1.0140	0.0147	
Flow angle: alpha	-0.2125	2.8925	38.4182	50.0662	13.2822	35.5258	[degree]
Wu	392.9750	379.4770	160.8470	176.2600	0.4239	-218.6290	[m s^-1]
W	429.6930	442.5470	243.3650	256.5760	0.5499	-199.1820	[m s^-1]
Flow angle: beta	-66.4963	-60.1496	-46.7381	-44.5495	0.7770	13.4115	[degree]

Table 5: Summary performance data of fouled compressor

Quantity	Inlet	LE cut	TE cut	Outlet	TE/LE	TE-LE	Units
Density	1.2774	1.1092	1.5443	1.5497	1.3922	0.4351	[kg m^-3]
P static	105191.0000	92375.7000	151374.0000	151332.0000	1.6387	58998.1000	[Pa]
P total	121757.0000	116749.0000	236703.0000	232320.0000	2.0274	119954.0000	[Pa]
P total (rot)	122732.0000	113004.0000	108415.0000	106568.0000	0.9594	-4589.3100	[Pa]
T static	286.2090	275.4150	333.7480	334.1610	1.2118	58.3332	[K]
T total	299.2710	302.1120	378.0850	377.6230	1.2515	75.9737	[K]
T total (rot)	300.0030	300.7390	300.7940	300.7480	1.0002	0.0547	[K]
H static	-11993.9000	-22835.0000	35754.9000	36169.6000	-1.5658	58589.9000	[J kg^-1]
H total	1125.6200	3979.1000	80287.1000	79822.9000	20.1772	76308.0000	[J kg^-1]
Rothalpy	1860.8300	2600.6800	2655.5600	2609.5700	1.0211	54.8799	[J kg^-1]
Entropy	-44.8137	-19.5862	-6.0457	-1.5581	0.3087	13.5405	[J kg^-1 K^-1]
Mach (abs)	0.4708	0.6909	0.8118	0.8058	1.1750	0.1209	
Mach (rel)	1.2557	1.3554	0.7682	0.7644	0.5667	-0.5873	
U	391.9840	391.3060	391.1350	390.7170	0.9996	-0.1707	[m s^-1]
Cm	159.0300	211.4220	178.3260	182.8250	0.8435	-33.0965	[m s^-1]
Cu	1.8612	-13.3386	-238.7790	-216.5460	17.9014	-225.4400	[m s^-1]
C	159.5450	227.8330	312.2570	293.6420	1.3705	84.4243	[m s^-1]
Distortion parameter	1.0903	1.1100	1.0602	1.0091	0.9551	-0.0498	
Flow angle: alpha	-0.3865	3.2204	26.8658	48.9872	8.3424	23.6454	[degree]
Wu	393.8450	377.9680	152.3560	174.1710	0.4031	-225.6110	[m s^-1]
W	425.8230	435.3020	239.6200	256.5120	0.5505	-195.6820	[m s^-1]
Flow angle: beta	-68.0904	-62.0062	-48.8216	-46.0173	0.7874	13.1846	[degree]

According to Eq. (1), assuming surface roughness of leading edge is, respectively 50, 100, 150 μm; point coordinate of blade section is computed. And then, solid model is constructed. The simulation result is shown in Table 3.

Simulation result shows that the decrease of thermodynamic performance parameter when surface roughness is linear distribution is less than when surface roughness is constant. It can more accurately reflect actual situation of fouled compressor.

The application of reverse design method*:* Reverse design method is a modern design method to create a 3D virtual model of existing physical part or mechanical system. The reverse design process involves measuring an object using 3D scanning technologies such as coordinate measuring machine, laser scanners and then reconstructing it as a 3D solid model based on measured data. Because the geometry compressor blade is irregular, traditional contact measure method is difficult to measure it. At the same time, blade surface can be scratched by contact measure method (Chen *et al*., 2003, 2004, 2005).

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. Laser triangulation sensor is mounted before the compressor inlet of compressor fouling test rig to measure rotor blade profile parameter online. This study analyzes the change of thermodynamic performance parameter when compressor is operated for 20 h. Point clouds measured from sensor are reconstructed into solid model and then imported into ANSYS CFX to implement flow simulation. Simulation result shows that that pressure ratio decreases 0.97%, temperature ratio decreases 0.05%, isentropic efficiency decreases 0.77% and output power decreases 0.52% when test rig is operated for 20 h. Table 4 shows the detailed performance parameter of clean compressor and Table 5 shows the detailed performance parameter of fouled compressor. From this table can be seen that pressure and temperature at leading edge and trailing edge of fouled compressor are

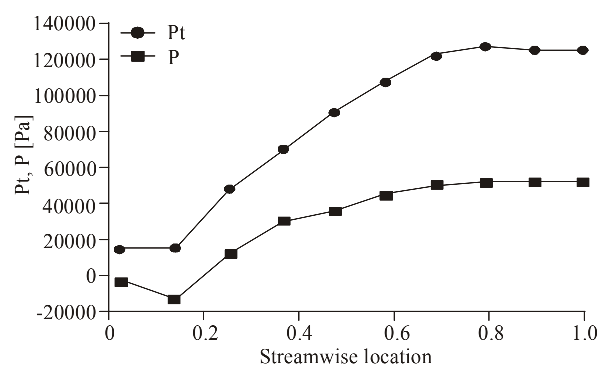

Fig. 5: Stream wise plot of Pt and P of clean compressor

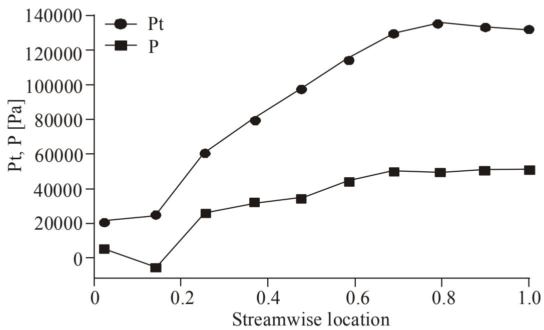

Fig. 6: Stream wise plot of Pt and P of fouled compressor

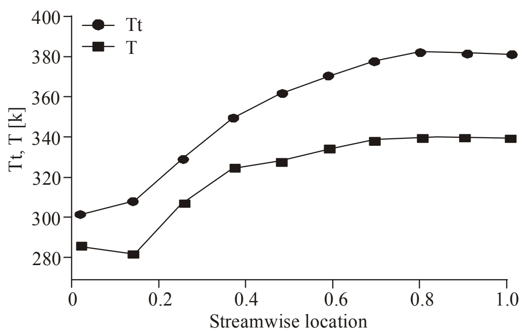

Fig. 7: Stream wise plot of Tt and T of clean compressor

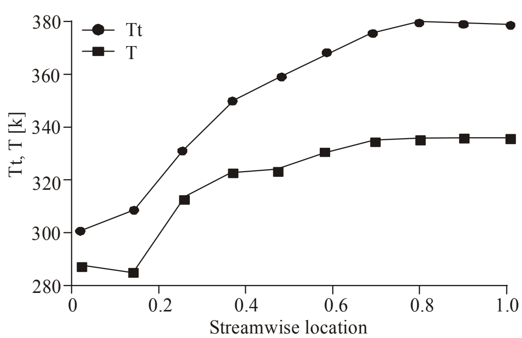

Fig. 8: Stream wise plot of Tt and T of fouled compressor

larger than these parameters of clean compressor. So the increase of surface roughness results in the increase of pressure, but the mass flow, efficiency and pressure ratio are reduced. The variation of parameter such as pressure, temperature and mach number between clean compressor and fouled compressor is shown in Fig. 5 to 10:

- **Pressure:** Stream wise plots of Pt and P show that the increase of surface roughness resulted in the increase of Pt and P in whole stream wise location
- **Temperature:** Figure 7 and 8
- **Mach number:** Figure 9 and 10

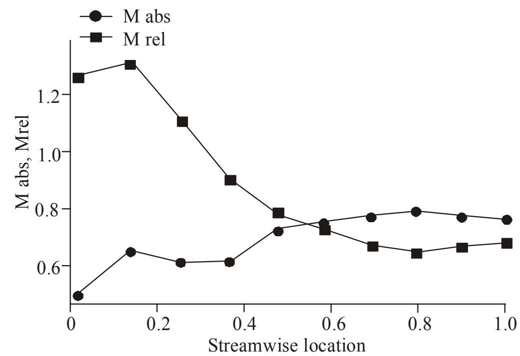

Fig. 9: Stream wise plot of absolute and relative mach number of clean compressor

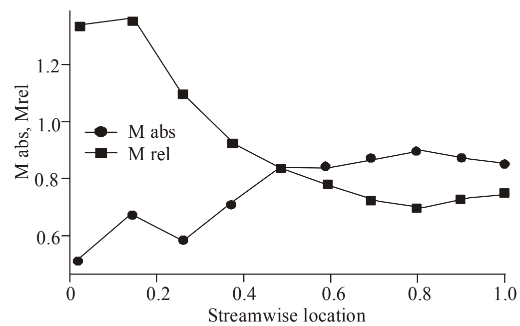

Fig. 10: Stream wise plot of absolute and relative mach number of clean compressor

CONCLUSION

Simulation analysis found that the effect of surface roughness on performance parameter is as following:

- Different distribution of surface roughness can result in different variation of performance parameters.
- Then increase of surface roughness may cause the decrease of pressure ratio, mass flow, efficiency.
- Reverse design method can be applied to reconstruct fouled compressor and simulate flow field. And this method can accurately reflect the true status of fouled compressor.

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