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Reliability Improvement in FCC Hot Gas Expander using CFD Modeling

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Abstract

Hot gas expanders play important role in improving energy efficiency of Fluid catalytic cracking (FCC) by recovering pressure energy from flue gases. Hot gas expanders face several reliability challenges because of high speed and presence of fine particles in the flue gases. The expander under study faced reliability issues in the form of high vibrations. The present study investigates the fundamental forces contributing to vibrations to arrive at long term solution.

A detailed 3D CFD analysis was carried out to understand the flow and particle behavior inside the expander. Analysis results showed that velocity in both stator and rotor region were approaching sonic value. The identified locations of erosion and deposition potentials agreed well with published data on similar expanders.

The model was used to evaluate flow field for two cases showing distinct vibration phenomena. The case with more variation in tip clearance was found to have parabolic pressure profile w.r.t. angle of rotation. This will exert an extra pressure force on the rotor. The additional force can make expander susceptible to high vibrations.

Based on analysis recommendations, rotor tip clearances for expander under study were made uniform in the field. It showed significant improvement in vibration phenomena and reliability of the expander.

Keywords
Expander, Vibration, CFD, Tip clearance

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Introduction

A fluidized bed catalytic cracking (FCC) process is a unit that converts heavy distillates like crude oil or residue to lighter petroleum fractions like gasoline or LPG. Considering its economic importance, it is widely known in petroleum industry as heart of refinery. The economic efficiency of the FCC unit and hence, the complete refinery can be significantly enhanced by recovering the pressure and heat energy from the exiting flue gases. The unit to recover the same is known as Pressure recovery train (PRT). The PRT unit consist of various equipment like expander, air blower and steam turbine. The same is shown schematically in エラー！参照元が見つかりません。. The expander is primary component to convert the pressure energy into mechanical energy. As expander and air blower are mounted on the same shaft, the kinetic energy is used to run the blower as well. Hence, it saves significant energy which would have been required to run the blower. The steam turbine is used for startup or for cases when power generated by expander is below required capacity.

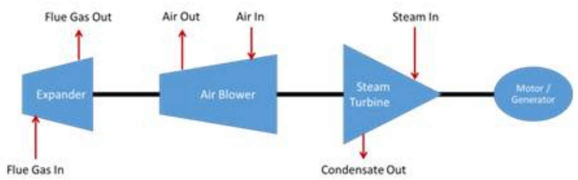

Figure 1

The Flue gas conditions at expander may vary in temperature from 650 ^{0}C to 760 ^{0}C, Pressure ratio of 1.4 to 3.5, and flowrates upto 635 Tons/hr. The estimated power ratings are in order of 20-40 MW. However the main challenge in operating expander comes from the particles in the flue gas. The flue gas is typically laden with about 100 ppm catalyst particles, which are of alumina / silica base with fine particles of ceramic known as zeolite. The particles may erode the blades because of high velocity or sometime deposit on the blade surface causing more complex issues.

The expander under study had radiation vibration sensors installed as a reliability measures. The operating principle is to ensure that the vibration level should remain below 0 to 80 microns to prevent any structural failures. Various methods like abrasive cleaning and thermal cycling is used to control the vibration level. However, this methods are known to give short term relief and a detailed analysis is needed to understand the underlying physics.

1. Method

A detailed 3D CFD analysis has been carried out to understand the flow and particle physics in the expander. The flue gas flow is solved in Eulerian frame by numerically solving the Navier-stoke equation. Catalyst particle is treated in Langrangian frame to determine the particle trajectory and its interaction with flow field. The computational model included different parts of expander including the nose-cone, shroud, struts, stator blades, rotor blades, diffuser, inner and outer exhaust casings. The flow domain is shown in Figure 2. In order to accurately model the flow field, it is necessary to capture the instantaneous stator rotor interaction. The same has been achieved using the sliding mesh technique, i.e., modelling the actual motion of the rotor in unsteady manner. This approach is more accurate than periodic assumptions made in some of the previous efforts [3] on CFD modeling of expander. Special care has been taken to ensure good mesh quality and flow aligned grid to reduce the numerical error. Density variation of flue gas with temperature and pressure has been accounted using ideal gas law.

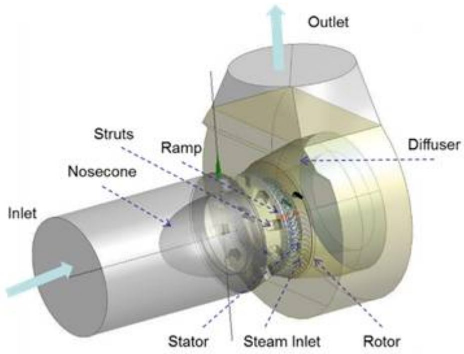

Figure 2

2. Results

2.1 Flow Profile

Figure 3 shows the contours of velocity magnitude on a vertical plane passing through inlet and outlet. It can be seen that flow is slowly accelerating as it passes through nose-cone region. The sharp increase in velocity in stator region can be attributed to change in directions provided by stator blades. It is important to note that no boundary layer separation was observed in the divergent section. Thus ruling out one of the major root cause as demonstrated by Drosjack et. al [3]. The velocity in both stator and rotor region was seen approaching sonic velocity confirming the fact that expander are operating in severe conditions. Major component of velocity in rotor region is tangential velocity. The swirl effect can be seen in divergent section downstream of expander as well.

エラー! 参照元が見つかりません。Figure 4 shows the distribution of normalized pressure ($P_n = P / P_{in}$) from inlet to outlet on the center plane. The pressure first decreases in nose cone region because of conversion of pressure energy to kinetic energy. As work is done by expander, significant pressure drop occurs across the rotor and then recovers slowly in diverging section due to conversion of kinetic energy to pressure energy.

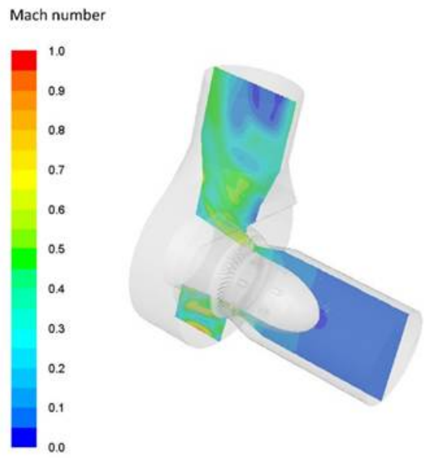

Figure 3

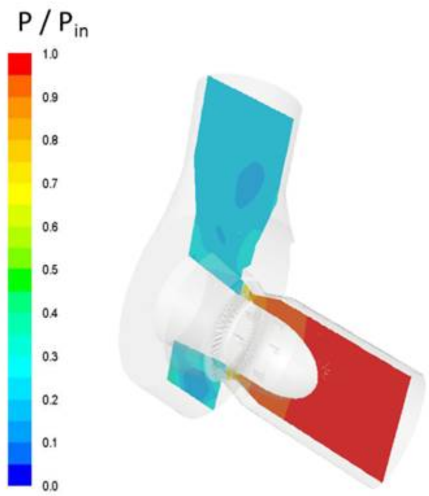

Figure 4

2.2 Particle Trajectories

Ideally, the particles entering the expanders would be 2 to 5 microns in size. Larger particles will tend to cause erosion while smaller particles will have potential to deposit [2]. The particle size distribution used in this analysiswas based on iso-kinetic sampling and had maximum diameter of 15 micron. The particle equation was solved in Langrangian frame of reference in an unsteady manner. It is interesting to see that most particle hit rotor blades, many small particles are able to pass through gap between rotor tip and shroud.

It is important to investigate the erosion and deposition potential to study the effect of the particle flow behavior on the rotor vibration. The erosion rate was calculated based on following equation.

$$R_{erosion} = \sum_{n=1}^{np} \frac{\dot{m}_p \, C(D_p) f(\alpha) V^{b(v)}}{A_{face}} \ldots \qquad 1$$

In the equation 1, $R_{erosion}$ is the rate of erosion on the wall surface and total erosion on any surface element is found by adding the erosion rate due to individual partice. The erosion rate due to individual particle is function of different parameters like mass of particle (m_p), Particle diameter (D_p), angle of incidence (α) and relative velocity (V). The equation stats that erosion rate will be higher for fast moving large particles.

Prediction of deposition potential is more challenging as there is no single matrix which will tell whether particle will stick or reenter with the flow after hitting the solid boundary. The probability of the deposition will be maximum when the flow tries to push particle on the blade. As tangential velocity is dominant component for the rotor region due to high rotational speed, particle heating the blades with tangential velocity higher than the tangential velocity of rotor itself will have higher probability of deposition. Hence, in this study, a new matrix has been proposed for assessing the deposition potential. The new matrix is defined as per following equation:

$$\text{Deposition Potential} = U_t - \frac{2\pi n r}{60} \ldots\ldots\ldots\ldots \qquad 2$$

In the equation 2, U_t is the tangential velocity, n is the rotor speed (in rpm) and r is the radial distance from the center of rotor axis.

The predicted erosion and deposition potential is shown in the Figure 5. It is expected that erosion will be high on the leading edge while deposition is expected in the concave region of blade. Figure 6 shows erosion and deposition on blades on similar expander as shown by Carbonetto et al[3].

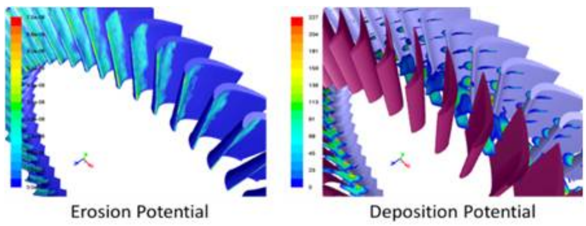

Figure 5

Figure 6

2.3 Effect of Tip Clearances

Further, the model has been extended to study effect of rotor tip clearance on the vibration phenomena. Drosjack et al [3] had earlier correlated the vibration phenomena with particle deposition on gap between rotor tip and shroud. The blades rub with deposit and causes the vibration. However, for expander under study, velocity are very high in the clearance region ruling out the probability of the tip rubbing. The data shows a reverse trend for current expander where higher vibration levels are observed for a case with ~11mm tip clearance (Case-1) than a case with ~8.5mm tip clearance (Case-2).

CFD analysis were carried out for this two cases. The results did not show any significant difference on the flow field. Figure 7 shows the schematic representation of two cases and angular pressure distribution on the rotor. It can be seen case-2 with lower tip clearance has higher average pressure on rotor than the case-1. The lower pressure in case-2 can be attributed to the leakage of flow through the higher clearance. The higher clearances also results in lower expander efficiency.

As next step of analysis, the non uniform tip clearance has been modeled for two cases. In case-1, the non-uniform tip clearance varies from 11.1 to 12.5 mm and in case-2, from 8.1 to 9.1 mm. The schematic representation and obtained angular pressure profile are shown in Figure 8. Similar to uniform clearance case above, pressure on rotor is higher for case-2 than case-1. When a trend line is draw, it showed a significant parabolic nature in Case-1, which has higher tip clearance as well as higher tip-clearance variation. The non-uniform pressure profile is attributed to different leakage flow in the regions of different rotor tip clearances. Higher variation in tip clearance will result in higher curvature in pressure profile. The non-uniform pressure profile will exert additional pressure force on the rotor. The additional pressure force can affect the vibration characteristic of the expander.

3. Conclusion

The CFD modeling was used to better understand the performance of expanders and factors affecting vibrations in particular. The velocity and pressure profiles provided significant insight into working of the expander. The velocity was found to approach sonic value at a few locations in both stator and rotor region. The erosion and deposition potentials predicted by model qualitatively agree with the plant observation as well as the available literature for similar expanders. The rotor tip clearance variation is found to be an important factor than tip clearances itself. Higher non-uniformity will lead to presence of an extra pressure force on the rotor. Based on the analysis, the expander clearances were modified in the plant during shutdown and it showed significant improvement in the vibration characteristic of expander

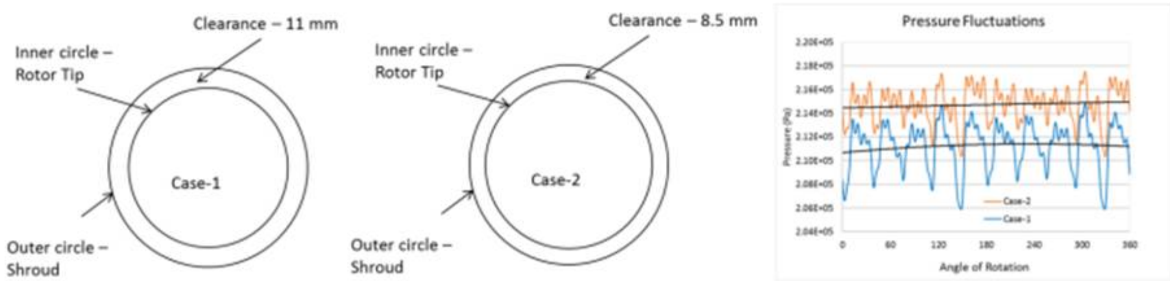

Figure 7

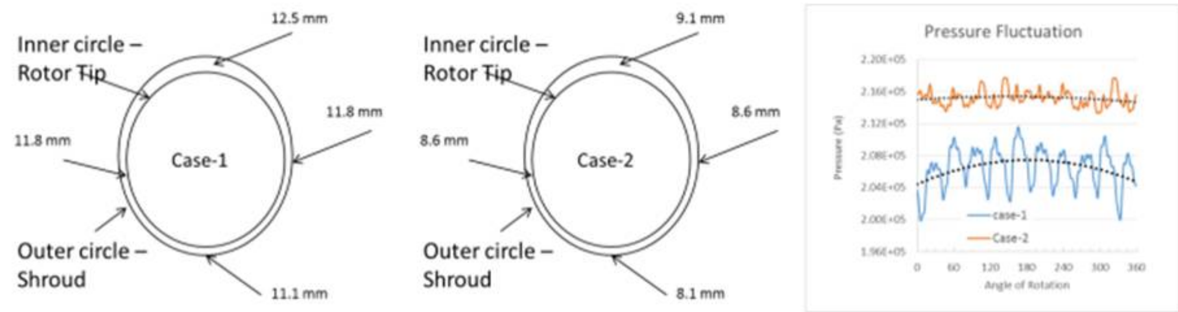

Figure 8

4. References

1. B. Carbonetto, and G. Hoch., *"Advances in Erosion Prediction of Axial Flow Expanders",* Proceedings of the Twenty-Eight Turbomachinery Symposium, 1-8, 1999
2. B. Carbonetto, *"Online techniques to mitigate the risks that limit expander reliability*", Proceedings of the Thirty Second Turbomachinery Symposium, 179-188, 2003
3. Drosjack M., Felten J., Seamon G., Griffin T., *"What to do when classic RCA doesn't give the answer – Apply detailed engineering analysis",* Proceedings of the Thirty Fifth Turbomachinery Symposium, 7-18, 2006