Finite element analysis on acid compressor expansion turbine: Case for Fertiliser Company

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Abstract

This paper reviews the use of finite element analysis to determine the causes of the failure of the compression expansion turbine for the nitric acid plant that occurred at the company (August 2017). After an extensive literature study on the main causes of turbine failure, the researchers conducted a finite element analysis on the material of the turbine blades (Austenitic) and found out that the base metal used for the alloy may have failed to withstand the high temperatures (640°) that the turbine was subjected to. This research is going to help prevent future failure by use of material that can withstand high thermal stresses.

Keywords: compression expansion turbine, nitric acid, thermal stresses, Finite Element Analysis

1 Introduction

Nitric acid is one of the major requirements in the manufacture of nitrogen-based fertilisers. The hot waste gas from the production of nitric acid is disposed to the atmosphere through a gas turbine that recovers the energy. The other gases leaving the cooling section are then mixed with air and nitrogenous oxides from the acid solution and then compressed to a higher pressure for absorption (Ave. E van Nieuwenhuyse, 2000). Turbomachinery in the nitric acid plan consists of a motor, gear box, compressor and the expansion turbine as shown in the diagram below:

Figure 1: Layout of the turbo-machinery.

The steam turbine rotor is subjected to temperature variations in during start and stop cycle (640°C inlet and 250°C), which occurs in very short intervals of time. This variation in temperature, induces some transient thermal stresses in the rotor. This is due to very large temperature gradients. The transient stresses in the machinery occur due to the changes in the material properties such as Young's modulus, coefficient of expansion (α), thermal conductivity, and specific heat capacity (Ingle, 2016).

1.1 Background

On the 10th of August 2017, there was an extensive turbine failure in the nitric acid plant at the company nitric acid plant (North Acid compressor train). The turbine blades were ripped off from the rotor as shown in the diagram below:

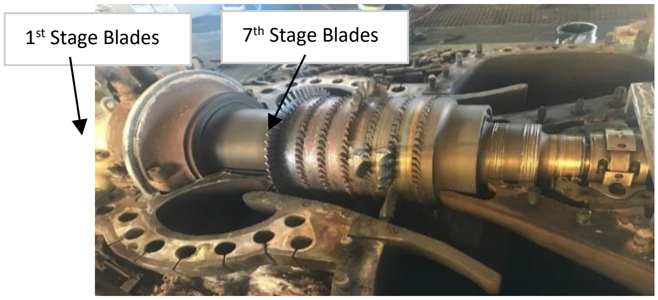

Figure 2: Damaged turbine rotor

The stages of the stator that correspond to the blades in the rotor were also ripped off except for the first stage rows only as shown below:

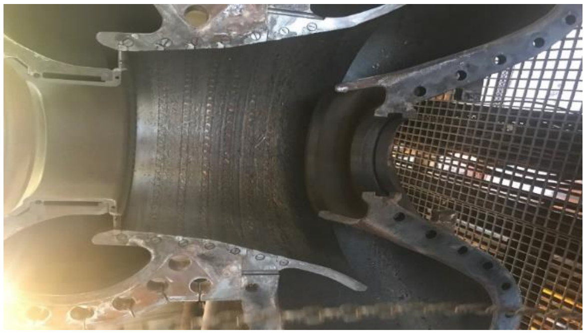

Figure 3: Damaged turbine stator

The turbine pedestal that carries the bearings was also damaged on the non-drive as well as two of its supporting legs and while the drive end remained intact. The non-drive end of the pedestal is shown in the diagram below:

Figure 4: Damage to the turbine pedestal

The Compressor, Gearbox, and Electric Motor were inspected after the incident and it was reported that they had not incurred any damages.

2 Literature review

2.1 Use of turbomachinery in nitric acid production

Nitric acid is manufactured in two stages: Firstly the ammonia is oxidized and the resulting nitrogen oxides are then absorbed.

Ammonia oxidation: Ammonia is oxidized to nitrogen monoxide /nitric oxide. This process is summarized in the equation below:

$$4NH_3(g) + 5O_2(g) \rightleftharpoons 4NO(g) + 6H_2O(g)$$

$$\Delta H^{\ominus} = -900 \text{ kJ mol}^{-1}$$

The conditions favouring the oxidation are high temperatures and pressure with excess air and a platinum and rhodium alloy as a catalyst. Using high m pressures means that the cost of equipment is also reduced since smaller sizes would now be required. The impurities are then removed from the ammonia and the resulting mixture is compressed to give an ammonia-air ratio of 1:9(Connor, n.d.). The overview of turbine machinery in nitric acid plant is shown in the figure below:

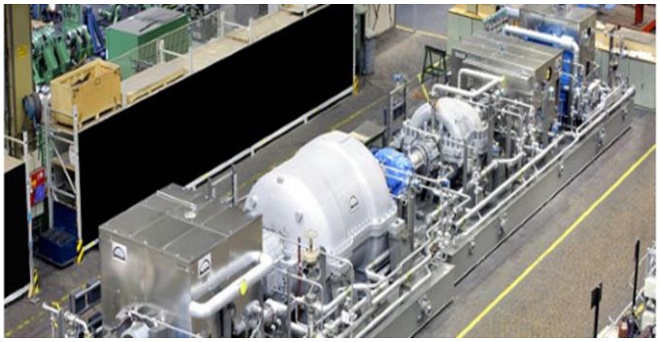

Figure 5: Turbine coupled to a motor

The turbomachinery is subjected to temperatures around 425K.

2.2 Common failure modes of turbomachinery

The turbine blades usually suffer fatigues due to the large number of stress cycles at elevated temperatures where the blades suffer from the vibrations and resonance (Alves, 2016).

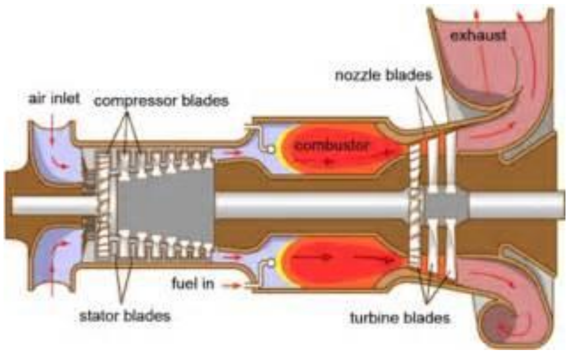

Figure 6: Turbine coupled to compressor

2.3 Factors that cause failure of turbine blades

There are various factors that cause failure of the turbine blades, however, the main factors are corrosion failure, fatigue failure and creep failures.

2.3.1 Corrosion Failure

This type of failure usually occurs when the blade material is oxidized during the chemical reactions on its surface and this is catalyzed by high temperatures and acidic conditions which are dominant in the nitric acid plant.

Figure 7: Corrosion failure in turbine blades

Low-pressure blades of a turbine were found to be more susceptible to failure compared to the intermediate and high-pressure blades. The most common failure mechanisms that occur in low-pressure blades are corrosion fatigue, stress corrosion cracking, Pitting and Erosion-Corrosion in the turbines. Corrosion due to fatigue is the most abundant mode of failure in the turbines (Sulfidation: Turbine Blade Corrosion, 2008).

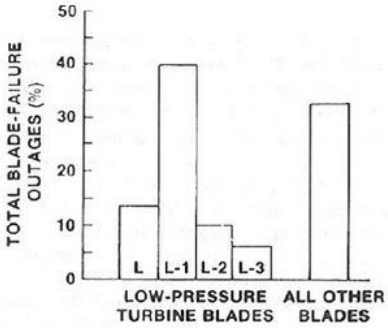

Figure 8: Distribution of failure in turbine blades

2.3.2 Fretting fatigue failure

The cracks in fretting fatigue start out small but with time spread all over the blade and lead to severe damage. Fretting fatigue can be prevented by reducing slip in the initial stages of the design process (Anon., 2002).

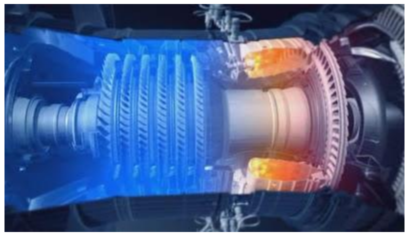

Figure 9: Fretting fatigue failure in turbine blades

2.3.3 Fatigue-creep Failure

The turbine operates under very high temperatures and is subjected to high stress levels. This is caused by the high frequency of the cycles during loading in the high pressure stages of the turbine. This high fatigue cycle contributes to most of the failures that occur in the turbine (Alves, 2016).

Figure 10: Creep fatigue failure in turbine blades

2.4 Finite element analysis on turbine blades

The finite element analysis method solves the differential equations governing the systems in matrix form. The geometry and materials of the system are taken into consideration during the pre-processing stage and computations are done in the processing stage. The visual display of the results is then done in the-post processing stage and this includes colour coded diagrams and graphs. There are many FEA software for different applications for example, Pro Mechanica, Ansys, Nastran, and Gambit (De Oliveira Vale, 2010).

3 Methodology

Creating a 3D Model: The researchers used SOLIDWORKS on the analysis of the turbine

Clean Up of the 3D CAD Model: The basic procedure for finite element analysis is shown below.

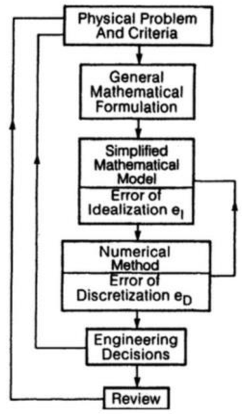

Figure 11: Finite element analysis procedure

4 : **Results**

4.1 Flow trajectory

The flow trajectory shows how the nitrous oxide gas flows from the inlet to the outlet. The flow gets more turbulent towards the outlet. Atmospheric pressure conditions where used as the end conditions.

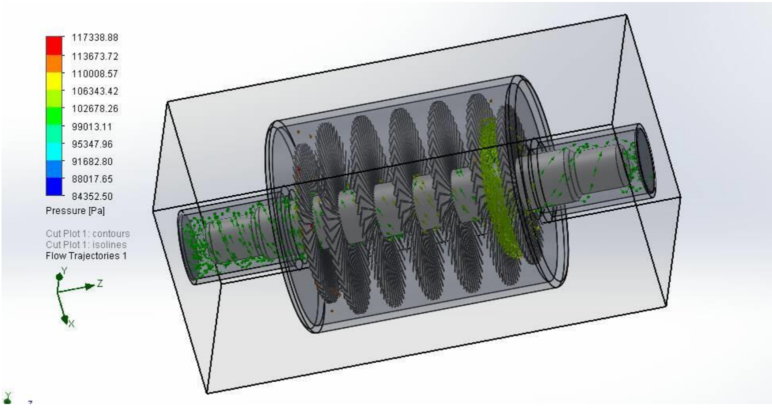

Figure 12: Solidworks drawing for the blades

4.2 Cut plot (pressure)

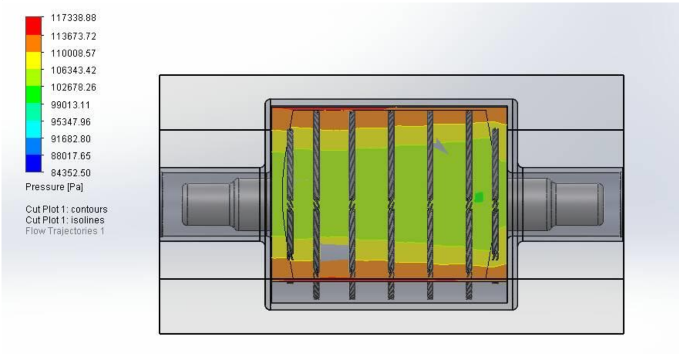

Figure 13: Pressure along the blades

4.3 Temperature simulation

The inlet temperature was 640 and the outlet temperature was 250°. The blade material was specifically designed to withstand the high temperatures.

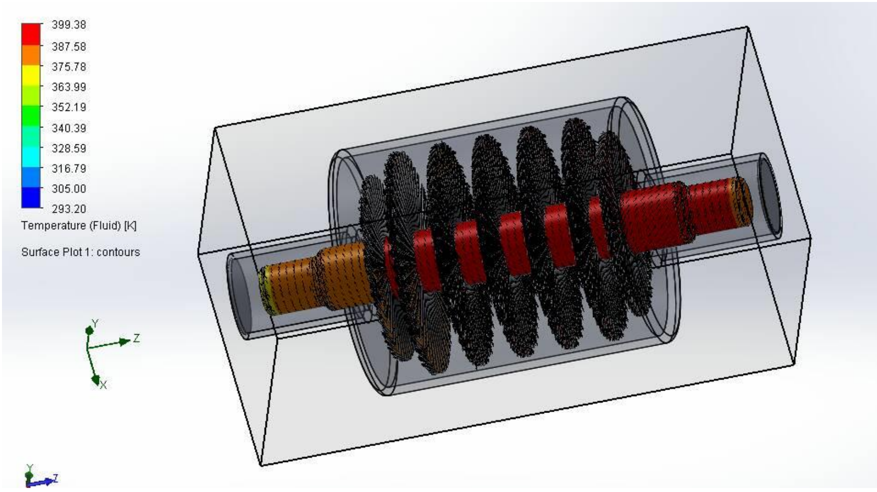

Figure 14: Temperature distribution

4.4 Shear stress analysis

The turbine blades are able to withstand the shear stress during rotation.

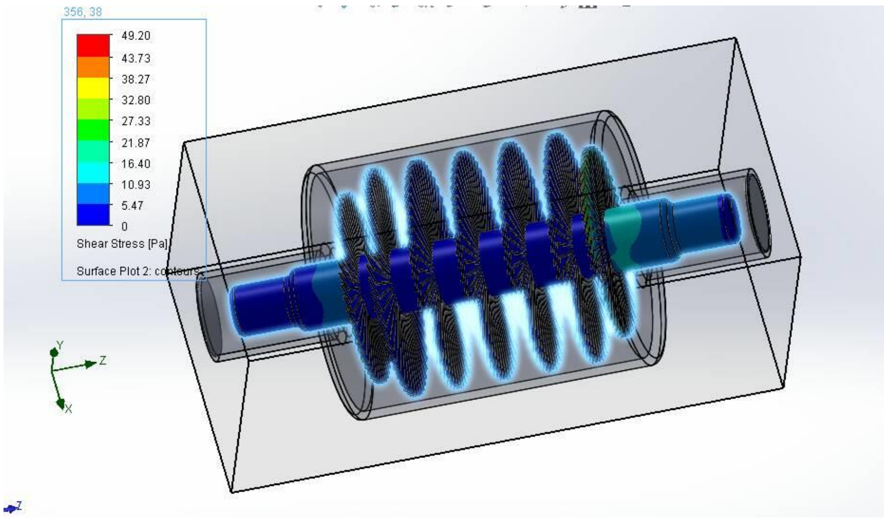

Figure 15: Shear stresses

5 : Recommendations and Conclusions

5.1 Recommendations

Since the turbine blades were exposed to high temperature as seen in the simulation there is need for material redesign to find a material more suitable for higher temperatures.

5.1.1 Material used for the turbine blades (Austenitic)

Table 1: Material used on the turbine blades.

Grade :	X2CrNiMoN17-13-3
Number:	1.4429
Classification:	Austenitic stainless steel - special grade
Density:	8 g/cm³

Austenitic is a special type of steel alloy. The chemical composition of austenitic are shown in the table below:

Table 2: Chemical composition of austenitic.

C	Si	Mn	Ni	P	S	Cr	Mo	N
max 0.03	max 1	max 2	11 - 14	max 0.045	max 0.015	16.5 - 18.5	2.5 - 3	0.12 - 0.22

The base metal in this alloy is steel so a material with better thermal properties than stainless steel may be used as a base instead.

5.2 Conclusion

The results of the finite element analysis showed the flow projections of the nitrous oxide gases in the turbine, the pressure distribution, shear and thermal stresses induced. The researcher concludes that the acid compression expansion turbine may have failed due to creep fatigue.

6 References

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Biography

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