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Redesign of Bell Mouth Nozzles Used in Converters in Acid Plant

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Abstract:
The converters are the focal point of sulfuric acid production, in which contains series of catalytic beds which are used for the oxidation of sulfur dioxide to sulfur trioxide. The commonly used converters consists of four or five catalyst beds filled with vanadium pentoxide catalyst and the beds are having separate inlets and outlets Due to the high temperature produced during oxidation of sulfur dioxide, which is an exothermic reaction, temperature increases to a maximum of 600oC.
Bell mouth nozzles are commonly used as the inlets and outlets of catalyst beds since it allows maximum amount of SO3 gas to be drawn into the duct and also provides a thorough distribution of SO2 gas over the catalyst beds. The converters and nozzle are commonly made of carbon steel. It has been identified most of the bell mouth nozzles used in converters of chemical industries undergoes regular failure.
This thesis mainly aims at redesigning the bell mouth nozzle for improved reliability. Transient thermal analysis of nozzle was done in ANSYS by changing the material and thickness of nozzle. The effect of various nozzle exit geometries (rectangular, circular and elliptical) on stress, deformation and fatigue life was found out using transient thermal analysis and an optimum geometry of nozzle of suitable material and thickness was found out and proposed.

Keywords: *Bell mouth nozzle, ANSYS, Exit geometry*

1. Introduction

The converter is the focal point of the sulphuric acid process. Sulphuric acid is an important raw material for phosphate fertilizer production and to a much lesser extent for nitrogen and potassium fertilizers. It is in this converter which contains the series of catalyst beds which are required to convert the sulphur dioxide gas to sulphur trioxide. The converter serves the following functions: provides single or multiple beds in which the catalyst is placed, provides for the distribution of gas across the catalyst bed and also provides for the collection of gas to exit the converter. Sulphur dioxide passes through series of catalyst beds in the converter and gets oxidized to sulphur trioxide which is subsequently absorbed in water to form sulphuric acid.

$SO_2(g) + ½\ O_2(g) \rightarrow SO_3(g)\ \Delta H = -99\ kJ.mol^{-1}$(1)

The temperature inside the converter increases to a maximum of 600^oC in the converter. The converter we are dealing with has bellmouth nozzles as the inlets and outlets to the catalyst beds. The heat produced during the oxidation of SO_2 to SO_3 which is an exothermic reaction introduces thermal stresses in the material of the converter and also in the nozzle. To withstand the high temperature, the inside converter shell is brick lined. The nozzle has no such measures for withstanding the high temperature. It has been identified that most of the bell mouth nozzle undergoes failure due to the combined effect of fatigue and creep. Hence for improving reliability, the bell mouth nozzles are provided with high thickness. Cracks are formed on the body of the nozzle which results in failure. Cracks are formed at the regions near the weldments and also at the face which inserted into the shell of converter. The pressure of gases flowing through the nozzles is very low (0.0294MPa) and hence doesn't have a significant effect in causing failure. Hence in redesign, thermal stresses should be given more importance.

For withstanding the high temperature, the nozzle is provided with high thickness. The converter and nozzle is commonly made of high grade carbon steel (A 515 Gr 70). This study mainly aims at redesigning the nozzle with a suitable material and optimum thickness. Also the effect of various nozzle exit geometries on the stress, deformation and fatigue life is studied. Transient thermal analysis of the nozzle is done to find the temperature and stress distribution, deformation and fatigue life of the nozzle. The stress distribution gives an idea of the maximum stress induced and the nozzle can be designed such that the maximum stress levels would be below the design strength at the highest operating temperature of the converter. The present nozzle exit geometry is of rectangular profile. Significant differences on the thermal stresses induced were observed for rectangular, semicircular and elliptical exit configurations.

Thermal stresses, deformation and fatigue life were found out through transient thermal analysis. The three dimensional modeling is done using the CAD software CATIA. Transient thermal analysis of the nozzle is done in ANSYS. Through this redesign and analysis an optimum geometry of bell mouth nozzle using suitable material, optimum thickness and geometry is to be formed.
The dimensions of the nozzle, material details etc are taken from the drawing records of Fertilizers And Chemicals Travancore Limited (FACT), Kochi which is one of the leading fertilizer manufacturing companies in India.

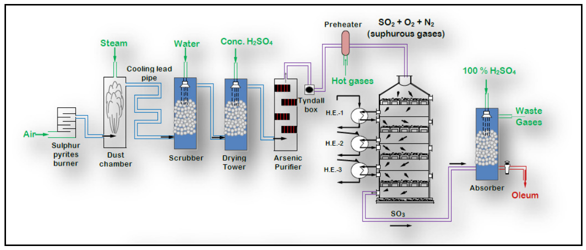

Figure 1: Manufacturing of Sulphuric acid by Contact process

2. Bell Mouth Nozzle

A bell mouth is a tapered expanding or reducing opening in the end of a ventilation duct, so named because the taper can resemble that of a bell shape. They are primarily designed and used for return the fluid or extract fluid purposes. The bellmouth cross sectional area is normally double that of the duct area, so that the air velocity entering the bellmouth is low (to reduce noise, turbulence and pressure drop), and gradually increases to the normal design velocity of the ductwork. The angle of the bellmouth is normally tapered at about 45° as a balance between keeping the bellmouth short without causing too much turbulence or excessive pressure drop. Bell mouths can be manufactured to suit either circular or rectangular ductwork sections.
The bell mouth nozzles used in converters allows maximum amount SO_3 gas to be drawn into the duct. It also provides a thorough distribution of SO_2 gas over the catalyst beds. This bell mouth nozzle undergoes regular failure due to high temperature of exothermic reaction. Bell mouth nozzles give 1-1.5% more efficiency and can also be shorter and lighter however, difficult to fabricate therefore, more expensive.

3. Methodology and Procedure

3.1. Identifying the Type and Reason of Failure

The nozzle is subjected to high temperature and corrosive environment. Fracture occurred on the nozzle due to the stresses produced from the combination of high temperature and corrosive environment. The nozzle is subjected to cyclic thermal loading. More than the corrosion, the high temperature produced during the exothermic reaction in the converter is the major reason for failure of the nozzle. Even newly installed bellmouths have failed after few stop start cycles indicating that fracture occur mainly due to fatigue. Hence fracture occurs mainly due to fatigue. The nozzle is subjected to this high temperature for hours. Hence creep may also cause failure. Creep damage occurs in metals and alloys after prolonged exposure to stress at elevated temperatures.
The failure occurs as a combination of fatigue and creep. The material of the nozzle, carbon steel A 515 Gr 70 should be replaced with a material having high temperature strength and good creep resistance.

3.2. Study of the Existing Component Drawing

The existing drawing of the nozzle is studied. In the redesign process, dimensions of the nozzle except the thickness is to be maintained constant since the converter and nozzle to duct dimensions are not varied. The thickness of the nozzle is 12mm while the duct connecting downstream equipment to the nozzle is having thickness of 6mm only. The redesigned nozzle should have the dimensions such that the ends of nozzle will accurately fit in between the converter and the duct to nozzle pipe.

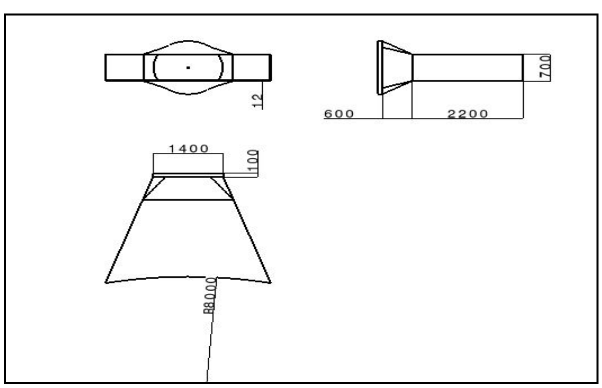

Figure 2: 2D drawing of nozzle

3.3. Selection of Material

A better knowledge of anticipated component requirements in addition to corrosion behavior provides for a better choice and the expectation of more reliable service. Materials are selected on the basis of service requirements, notably strength, corrosion resistance, formability, etc. Material availability and cost is also another design consideration. Assemblies need to be strong and resilient to the unique loads and stresses imparted on them, which can include significant temperature changes and thermal gradients for many high-temperature applications.

The present nozzle is made of carbon steel A 515 Gr 70. In this work, it is proposed to replace the material of nozzle by stainless steel. Stainless steel has better properties than carbon steel at high temperature and resistance to corrosive environment which made me to select it as the replacement material.

3.3.1. Type 309 S stainless Steel

Type 309 and 309 S are austenitic Chromium-Nickel steels that provide good corrosion resistance and also have high temperature strength and creep resistance. Type 309 S is identical to type 309 except for a lower carbon content that minimizes carbide precipitation and improves weldability. They are essentially non-magnetic as annealed and become slightly magnetic when cold worked. The lower nickel content of type 309 S improves resistance to sulfur attack at high temperatures. It is tough and ductile, and can be readily fabricated and machined. Type 309 S is the low-carbon version of type 309 stainless steel, and is recommended for applications where sensitisation, and subsequent corrosion by high temperature gases or condensates during shutdown may pose a problem.

Types 309 and 309S provide excellent general corrosion resistance. They are more resistant to marine atmospheres than Type 304. Types 309 and 309S stainless steels can be roll formed, stamped and drawn readily.

Element	**Content in Percentage**
Carbon	0.08
Manganeese	2
Phosphorous	0.045
Sulfur	0.03
Silicon	0.75
Chromium	22-24
Nickel	12-15
Iron	Balance

Table 1: composition of SS 309 S

Thermal Conductivity(W/mK)	**Mean coefficient of thermal expansion (µm/m/K)**	**Specific Heat(J/Kg/K)**
100^0C - 15.6	(0-100^0C) - 14.9	500
500^0C - 18.7	(0-315^0C) - 16.7	
	(0-538^0C) - 17.3	
	(0-649^0C) – 18	

Table 2: Thermal properties of SS 309 S

Density (gm/cm^3)	8.09
Ultimate tensile strength (MPa)	655
Yield strength (MPa)	345
Modulus of Elasticity (MPa)	200000
Poisons ratio	.29
Rockwell Hardness	B85

Table 3: Mechanical properties of SS 309 S

• High Temperature Mechanical Properties

Type 309 S has better mechanical properties at higher temperature than type 304 H stainless steel. The yield strength and ultimate tensile strength of type 309 S is very high at elevated temperatures. It has high temperature strength and creep resistance.

Temperature °F (°C)	UTS ksi. (MPa)	Yield Strength ksi. (MPa)	Elongation % in 2" (50.8 mm)
400 (204)	79 (545)	38 (262)	46
600 (316)	75 (517)	35 (238)	43
800 (427)	71 (490)	32 (221)	40
1000 (538)	64 (441)	29 (200)	38
1200 (649)	52 (359)	25 (192)	37
1400 (760)	35 (241)	22 (148)	39

Table 4: Variation of mechanical properties vs temperature.

It is clear that SS 309 S has properties that enable it to withstand the operating temperature range of the converter. Hence it is a good choice for replacing carbon steel.

3.4. 3D modeling and Thermal Analysis

After the selection of material, transient thermal analysis of the nozzle is needed to be done to calculate the temperature distribution and related thermal quantities (thermal stresses) in a system or component. For this, initially three dimensional modeling of the bell mouth nozzle is done using CATIA. The 3D CATIA model is saved as an IGS file and is imported to ANSYS for transient thermal analysis.

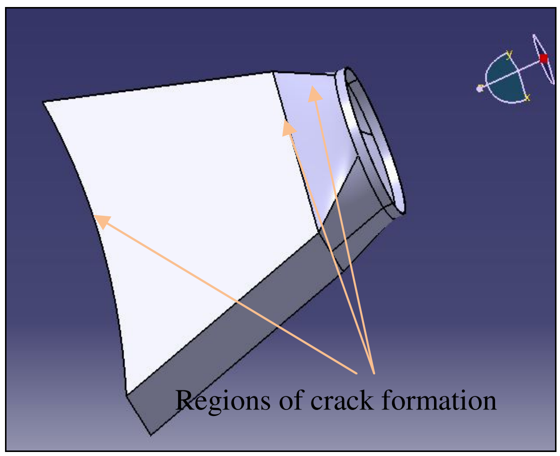

Figure 3: 3D model of Nozzle

The CATIA model is imported to ANSYS for the purpose of transient thermal analysis. The regions where cracks are formed are marked in the above figure. As said earlier, cracks mainly occur at the regions of welds and also at the face of the nozzle which is inserted to the converter shell. Nozzles of variable thickness up to 4mm were modeled for the purpose of thermal analysis. To improve the strength and to reduce the stresses, stiffeners were also modeled on the surface of the nozzle. Also, nozzle with its rectangular exit geometry replaced with semicircular and elliptical profiles of variable thickness were modeled for evaluating the effect of nozzle exit geometry on the thermal stresses induced. Finally, an optimum design of the nozzle with suitable thickness and exit profile which has better reliability is found out and modeled.

3.4.1. Transient Thermal Analysis in ANSYS

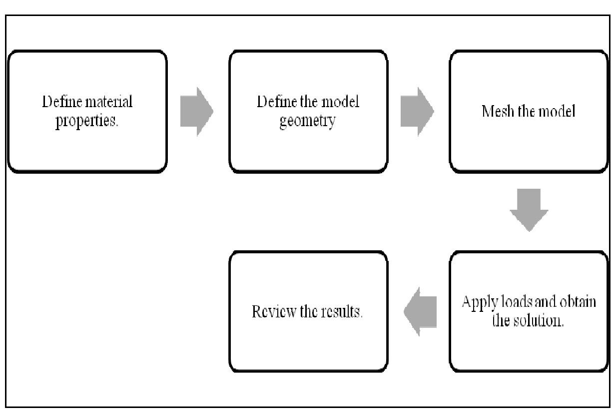

Figure 4: Flow Diagram of thermal analysis in ANSYS

Transient thermal analysis determines temperatures and other thermal quantities that vary over time. A transient thermal analysis follows basically the same procedures as a steady-state thermal analysis. The main difference is that most applied loads in a transient analysis are functions of time. To specify time-dependent loads, the load-versus-time curve is divided into load steps.

Temperature	Time interval
$22^0C – 300^0C$	8 hours
300^0C - 600^0C	½ hour
600^0C	2-3 hours
$600^0C – 300^0C$	3 hours

Table 5: Temperature cycle of the nozzle

First the transient thermal loads are applied and after that structural loads are applied. The results coming out from thermal load is applied to structural load. This is one type of thermo coupled analysis. The transient thermal analysis gives temperature distribution of the model and then static structural analysis is done. The structural loads we are concerned with is the gas flow pressure only. The gas flow pressure which is very low is about 0.0294 MPa and is applied normal to the faces of the nozzle. Regarding the boundary conditions, the rectangular end is given fixed support since it is attached to the converter at that end. The end which is connected to the circular duct is not given any support since expansion bellows are provided in between the duct and nozzle and hence is free to expand and contract. The result of transient thermal analysis is applied to structure of geometry for final result.

4. Results and Discussions

4.1. Transient Thermal Analysis of Present Nozzle Made of Carbon Steel

The bell mouth nozzle in use today is made of carbon steel A 515 gr 70 with 12 mm thickness. Here we are trying to replace the carbon steel with a material which have better properties so that the thickness can be reduced. Initially, transient thermal analysis of present nozzle is done so that the stress distribution and deformation occurring can be studied.

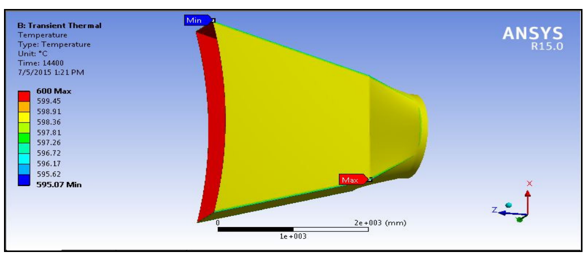

Figure 5: Temperature distribution of Nozzle made of Carbon steel (12mm thickness)

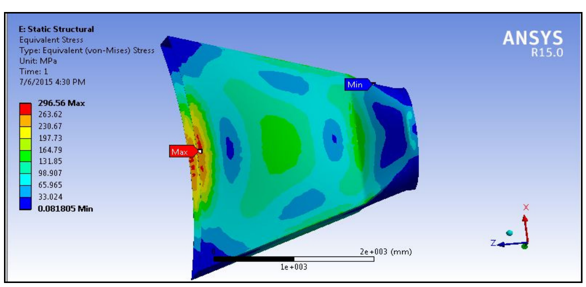

Figure 6: Stress distribution of nozzle made of carbon steel (12 mm thickness)

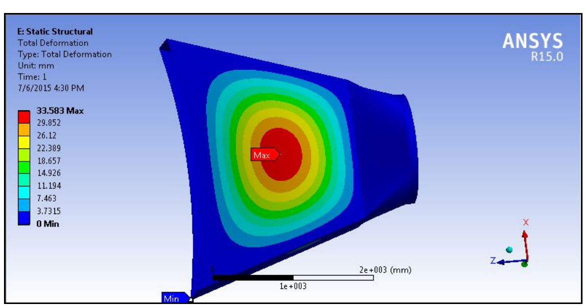

Figure 7: Deformation of nozzle made of carbon steel (12 mm thickness)

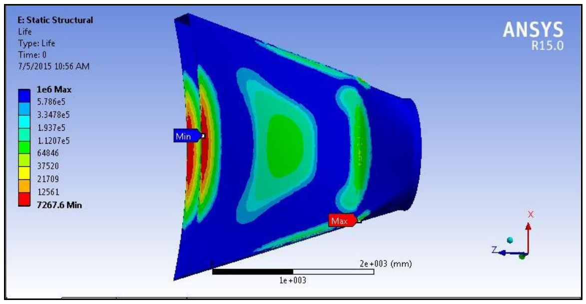

Figure 8: Fatigue life of nozzle made of Carbon steel (12 mm thickness)

4.2. Transient Thermal Analysis of Nozzle Made of SS 309 S

As described earlier, the material of the nozzle is needed to be replaced for improved reliability. Comparing with carbon steel, stainless steel has better properties at high temperature and corrosive environment. Here transient thermal analysis of the nozzle with SS 309 S as the material was conducted with the same boundary conditions which we have provided during transient thermal analysis of carbon steel. The following figures show the stress distribution, deformation and fatigue life of the nozzle of 12 mm thickness with stainless steel as the material.

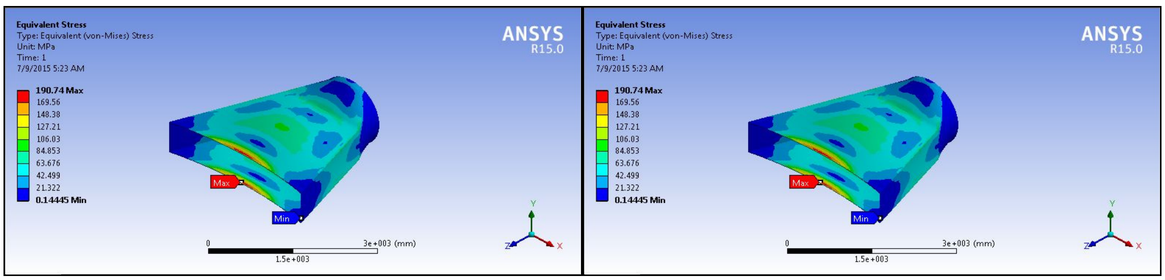

Figure 9: Stress distribution of nozzle with SS 309 S as material (12 mm thickness)

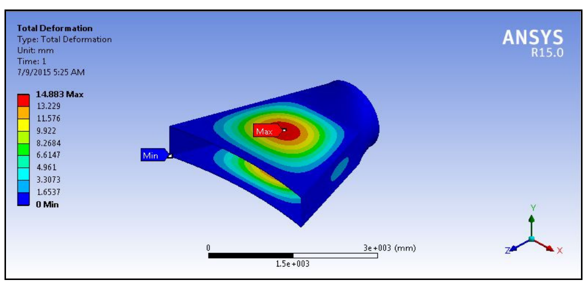

Figure 10: Deformation of nozzle with SS 309 S as material (12 mm thickness)

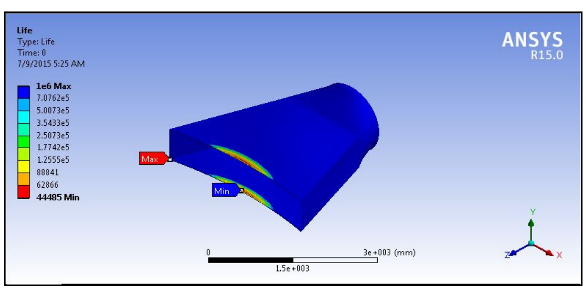

Figure 11: Fatigue life of nozzle with SS 309 S as material (12 mm thickness)

It is very clear from the above results that the stress generated decreases when the material of the nozzle, carbon steel is replaced with stainless steel. The deformation values also show good difference. Even though stress levels decreases when stainless steel is used, the maximum stress level is just below the yield strength of the material at the highest cycle temperature 600°C. Transient thermal analysis of nozzle was also conducted for variable thickness of the nozzle. Nozzles of thickness 10mm, 8mm and 6mm were modeled and transient thermal analysis were conducted for both carbon steel and stainless steel.

Transient thermal analysis was performed on the nozzles with thickness varying from 12 mm to 6mm. The variation in maximum stress, deformation and fatigue life of the nozzle with thickness is shown in figures listed below.

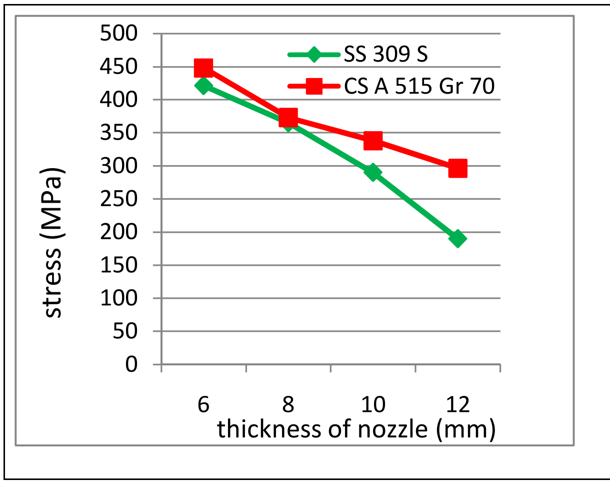

Figure 12: Maximum stress level vs thickness of nozzle

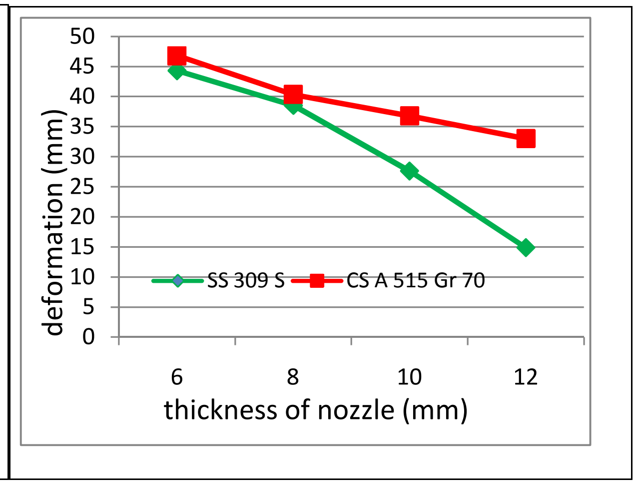

Figure 13: Deformation vs thickness of nozzle

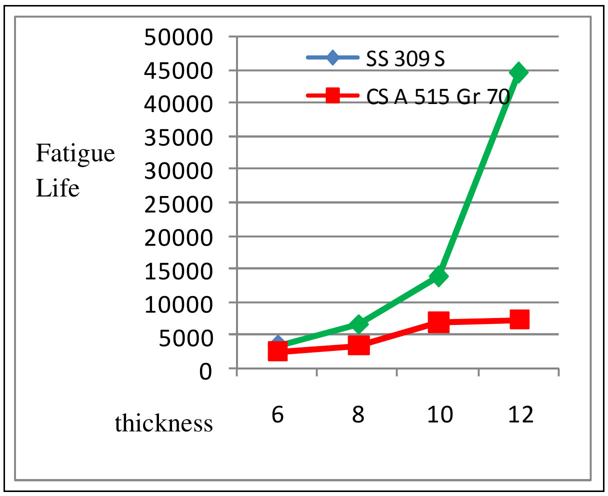

Figure 14: Fatigue life vs thickness of nozzle.

It is evident that the maximum stress level increases when the thickness decreases in case of both carbon steel and stainless steel. Also the maximum stress level is above the yield strength and below the ultimate tensile strength of the material at the maximum cycle temperature of 600˚C in case of carbon steel up to a thickness of 10mm. Below 10mm thickness, the maximum stress level is above the ultimate tensile strength. Since the material yields at this temperature at 12 mm thickness, it may gradually results in crack formation and results in fracture.

4.3. Transient thermal analysis of nozzle (SS 309 S) with stiffeners

Stiffeners are secondary plates or sections which are attached to beam webs or flanges to stiffen them against out of plane deformations. Stiffeners are commonly used for controlling local buckling and for connecting bracing or transverse beams. Here stiffeners of size 20 x 100 mm are provided on the external surface of the nozzle. Two rings of stiffeners are provided on the external surface and these two rings are joined by strips of stiffeners on the exterior of top and bottom faces. Also a sheet of plate of the same thickness of nozzle is provided internally splitting the nozzle into two parts such that it will not affect the gas flow. The sheet is having the same thickness of the nozzle.

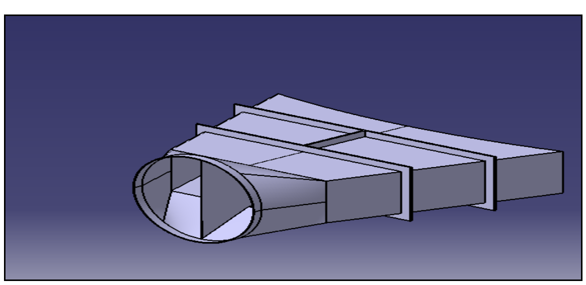

Figure 15: model of nozzle with stiffeners

Thermal analysis of the nozzle was done by providing stiffeners as shown in figure. The results showed a considerable decrease in both stress and deformation values. Since our main intention was to reduce the stress below the yield strength and to decrease the thickness, the stiffeners can be used to redesign the nozzle. Thermal analysis of the nozzle was performed for various thicknesses. It has been found that with the use of stiffeners the thickness of the nozzle can be reduced up to 6mm. As thickness decreased below 8mm without internal plate, the maximum stress level increased beyond the yield strength of the material at the highest operating temperature.

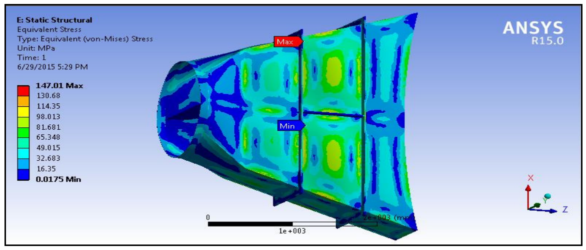

Figure 16: Stress distribution of nozzle with stiffeners (6mm thickness)

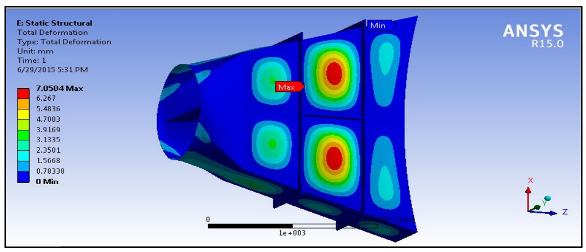

Figure 17: Deformation of nozzle with stiffeners (6mm thickness)

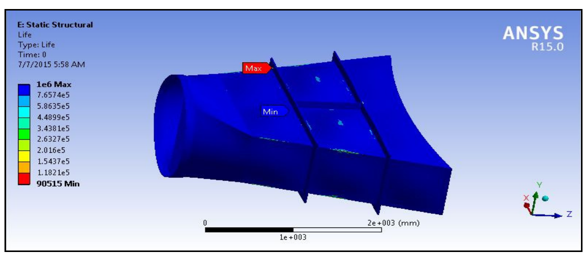

Figure 18: Fatigue life of nozzle with stiffeners (6mm thickness)

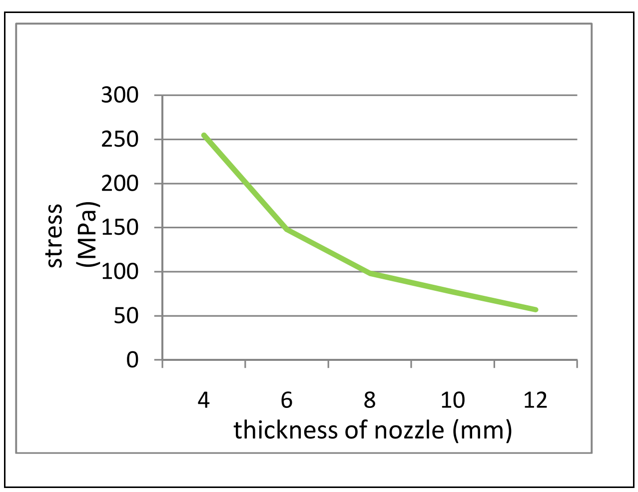

Figure 19: Maximum stress vs thickness of nozzle with stiffeners

From the results of transient thermal analysis we can accept 6mm as the minimum thickness of the nozzle by providing stiffeners as in figure. Hence I propose the nozzle with 6mm thickness and with stiffeners as the new model with improved reliability, which will have the maximum stress level below the design strengths and having very small deformation which results in better life.

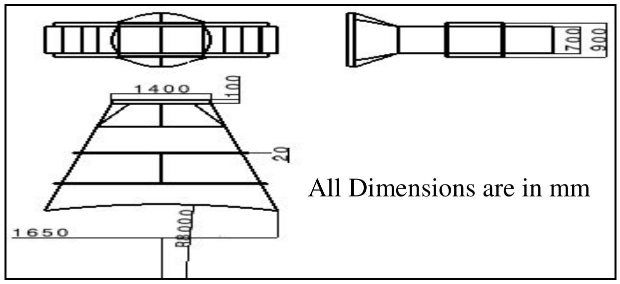

Figure 20: 2D Drawing of proposed model with stiffeners

4.4. Effect of exit geometry on maximum stress and life of nozzle

The nozzle we are dealing with is having a rectangular profile at the exit. Here I am replacing exit geometry of the nozzle with semicircular and elliptical shape so as to find the effect this change in exit geometry on the maximum stress, deformation and fatigue life of the nozzle. Transient thermal analysis of nozzle was done for nozzle with semicircular and elliptical profiles at exit geometry for thickness of 12mm and below.

4.4.1. Transient Thermal Analysis of Nozzle with Semicircular Exit Geometry

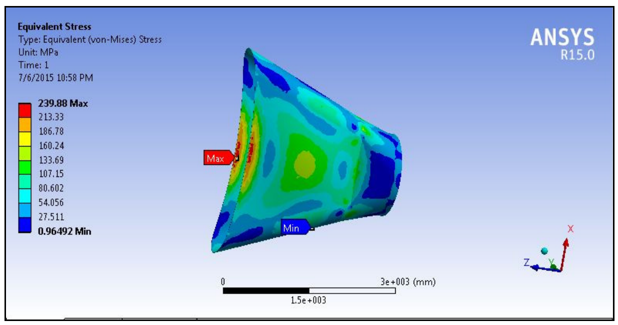

Figure 21: Stress distribution of nozzle with semicircular exit profile (8mm thickness)

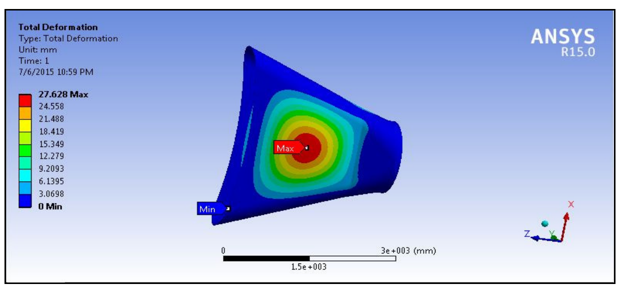

Figure 22: Deformation of nozzle with semicircular profile (8mm thickness)

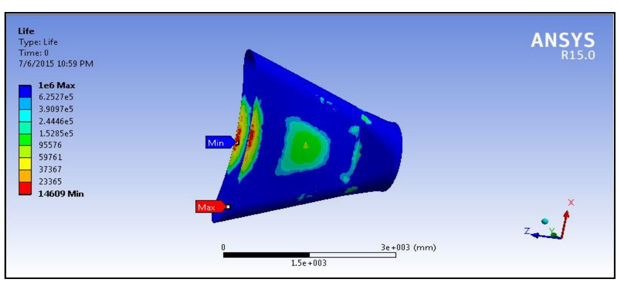

Figure 23: Fatigue life of nozzle with semicircular profile (8mm thickness)

From the results shown above, it can be understood that the maximum stress level and deformation for a nozzle of semicircular profile having 8 mm thickness is very much less than the maximum stress level and deformation induced in the nozzle of rectangular profile with same thickness. Also Fatigue life is high for semicircular exit nozzles.

4.4.2. Transient thermal analysis of nozzle with elliptical exit geometry

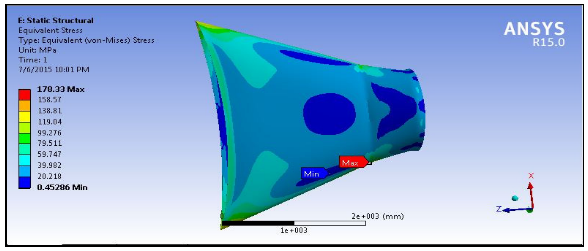

Figure 24: Stress distribution of nozzle of elliptical profile with 8mm thickness

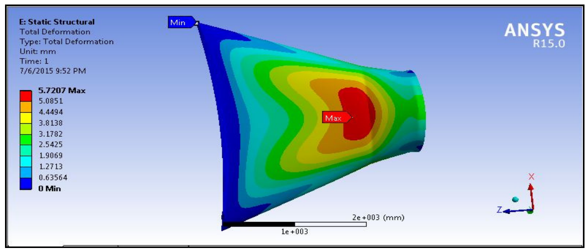

Figure 25: Deformation of nozzle of elliptical profile with 8mm thickness

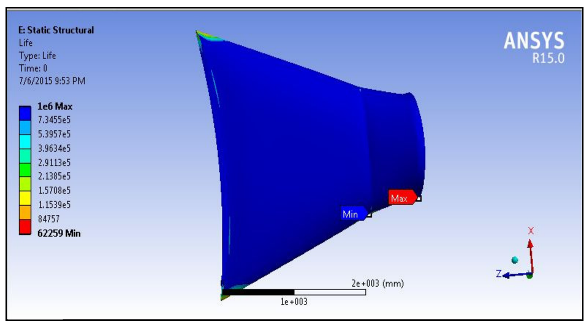

Figure 26: Fatigue life of nozzle of elliptical profile with 8mm thickness

From the above data, it is evident that the best bell mouth geometry is that with elliptical profile. The rectangular profile of the nozzle can be replaced with elliptical profile. The stress and deformation values are very much lesser for elliptical profiles compared to semicircular and rectangular profiles. The deformation value shows huge difference. Also the fatigue life of nozzle is very high for elliptical geometry. Hence the elliptical profile is the best exit geometry for bell mouth nozzle.

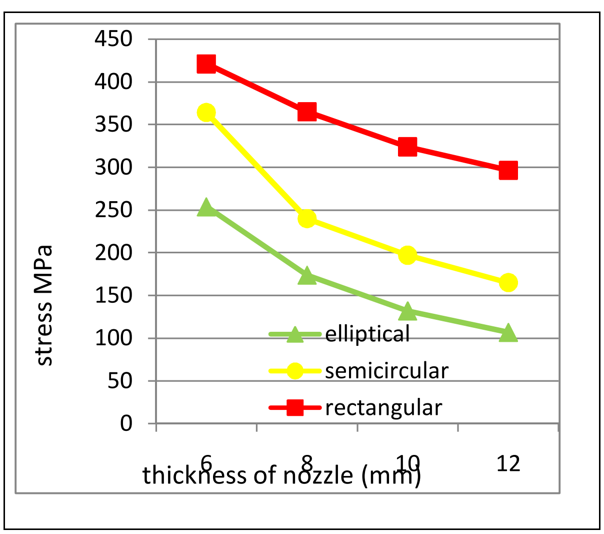

Figure 27: Stress vs thickness for various exit geometry

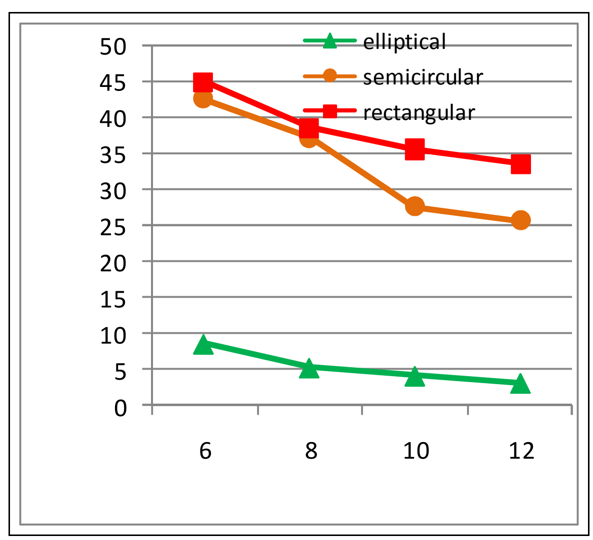

Figure 28: Deformation vs thickness for various exit geometry

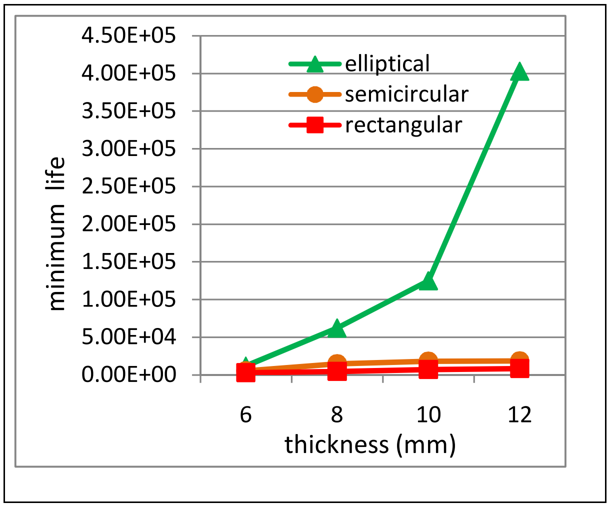

Figure 29: Fatigue life vs thickness for various exit geometry

From analyzing the results, it can be seen that the nozzle with elliptical exit geometry with 8mm thickness is suitable for this application. As thickness decreases further, the maximum stress level increases beyond the yield strength and permissible design strength at the maximum operating temperature

4.4.3 Transient thermal analysis of nozzle with elliptical exit geometry and stiffeners

The thickness can be further decreased by providing an elliptical stiffener at the neck portion, where the circular profile gets fully converged to elliptical profile in the nozzle. The following figures show the analysis results of elliptical nozzle with stiffener.

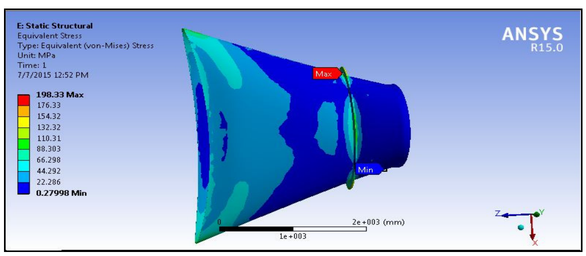

Figure 30: Stress distribution of nozzle of elliptical profile with stiffener (6mm thickness)

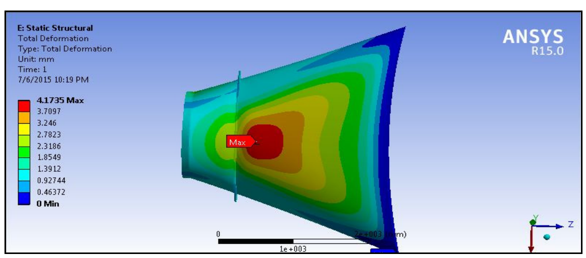

Figure 31: Deformation of nozzle of elliptical profile with stiffener (6mm thickness)

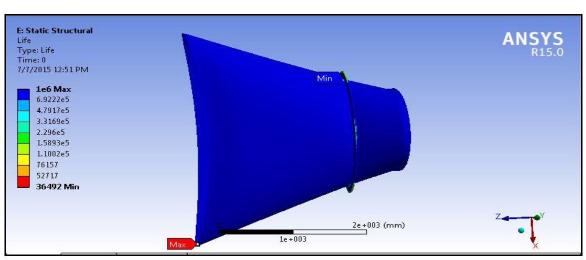

Figure 32: Fatigue life of nozzle of elliptical profile with stiffener (6mm thickness)

From the analysis results we can see that nozzle of 6mm thickness with elliptical profile and with ring stiffener can withstand the stresses at the operating temperature range of converter. Hence by using nozzle with elliptical profile, the thickness can be reduced to 6mm. The stresses and deformation produced is very much lower than with rectangular and elliptical profiles. But the problem with elliptical profile is the difficulty in forming into elliptical shape comparing with rectangular and semicircular profiles.

5. Conclusions

The failure of the bell mouth nozzle used in acid converters is mainly due to the high temperature produced during the oxidation of SO_2 to SO_3. The problem can be solved by redesigning the nozzle for improved reliability. Transient thermal analysis was done by changing material, thickness and the exit geometry of the nozzle and finally an optimum design of nozzle with suitable thickness and geometry which will provide improved reliability have been determined. The material of the nozzle which is carbon steel A 515 Gr 70 can be replaced by a type 309 S stainless steel. The properties and allowable stresses of SS 309 S are acceptable up to the maximum operating temperature of a converter. This material which offers good corrosion resistance is readily available and is easy to fabricate. The thickness of nozzle with rectangular exit geometry can be reduced up to 6mm by using type 309 SS as the material and with stiffeners. From the results it is evident that the nozzle exit geometry also has a huge influence on the maximum stress, deformation and fatigue life cycle of the nozzle. The nozzle with elliptical exit geometry has lower stress, deformation and maximum fatigue life compared to semicircular and rectangular nozzles. Hence the better design of the nozzle is the one with elliptical profile. Finally two models of 6mm thickness was proposed as result of the study, one with rectangular exit geometry of 6mm thickness with stiffeners and the other, an elliptical exit geometry of 6mm thickness and with a neck stiffener.

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