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Numerical Investigation of Internal Pressure in a shell and Tube type of Heat Exchanger by using FEA

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Abstract: *Shell and Tube Heat Exchangers are one of the most popular types of exchanger in heat transfer applications. Due to the flexibility, the designer has to allow for a wide range of pressures and temperatures. They are widely used in petroleum refineries, chemical plants, petrochemical plants, natural gas processing, air-conditioning, refrigeration and automotive applications. It utilizes a bundle of tubes through which one of the fluids flows. These tubes are enclosed in a shell with provisions for the other fluid to flow through the spaces between the tubes. In most designs of this type, the free fluid flows roughly perpendicular to the tubes containing the other fluid, in what is known as a cross-flow exchange. In nuclear reactors fuel rods may replace the tubes, and the cooling fluid flowing around the rods removes the heat generated by the fission process.A comprehensive Finite Element Analysis (FEA) has been performed on the critical heat exchanger components in order to validate the results of the components designed using the prescribed codes. The computational analysis helps visualize the areas of high stress concentration thereby aiding the designer to identify the failure prone regions. The regions susceptible to failure can be suitably modified to safeguard against failure. This paper aims at performing a design outputs by IBR codes of critical components of a shell and tube type heat exchanger in an attempt to show the redundancy in designing the components. Furthermore FEA shown the values of stress getting developed in the components for given operating conditions are much lesser than the allowable values of stress for those respective material. Thus the components are safe against such loading.*
Keywords: *Shell and tube type heat exchanger, IBR, tube sheet, steam drum. FEA.*

I. INTRODUCTION

A shell and tube heat exchanger is a class of heat exchanger designs. It is the most common type of heat exchanger in oil refineries and other large chemical processes, and is suited for higher-pressure applications. With the sulphur content of crude oil and natural gas on the increase and with the ever tightening sulphur content in fuels, the refiners and gas processors will require additional sulphur recovery capacity. At the same time, environmental regulatory agencies of many countries continue to promulgate more stringent standards for sulphur emissions from oil, gas and chemical processing facilities. It is necessary to develop and implement reliable and cost-effective technologies to cope with the changing requirements. Sulphur recovery units (SRU) are widely used to deal with the sulphur recovery refers to the conversion of hydrogen sulphide (H_2S) to elemental sulphur. Hydrogen sulphide is a by-product of processing natural gas and refining high-sulphur crude oils. The most common conversion method used is the Claus process. Approximately 90 to 95 % of recovered sulphur is produced by the Claus process. Packaged boiler is factory assembled, fully automatic complete with necessary auxiliaries which are more standardize, stream lined, efficient and reliable and could be transported with ease.These type of boilers are engineered, built, fire tested and guaranteed in performance by one manufacturer furnishing and assuming responsibility for all the component in the assembled unit.

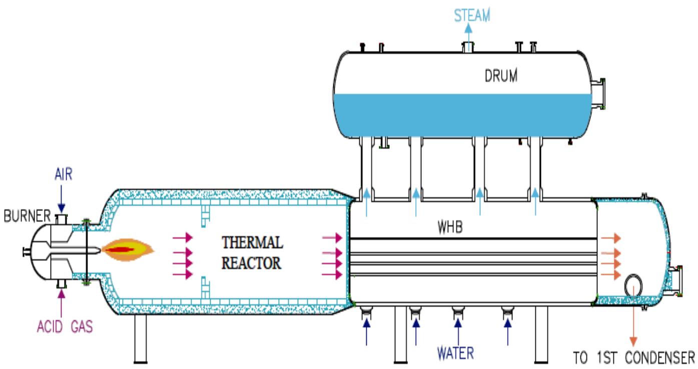


Fig.1 Schematic representation of Claus boiler

Gurpreet Singh has performed a stress analysis of boiler shell with riveted joints. By using finite element method, a stress analysis has been carried out under the application of pressure at the inner surface of boiler shell. Von-Mises stresses and maximum shear stresses are found. These stresses are compared with analytical results. *F.Vera-García* has proposed a simplified model for the study of shell-and-tubes heat exchangers (HXs) the model aims to agree with the HXs when they are working as condensers or evaporators. Despite its simplicity, the model proves to be useful to the pre-designment and correct selection of shell-and-tubes HXs working at full and complex systems. *S. V. Karmare* has performed a comparison of the tube sheet stress pattern and thickness obtained with different. Finite element analysis of the tube sheet for stress distribution and tube sheet thickness also come under the scope of their paper whose results were compared with those previously obtained from design with different standard codes. This study is to select the best configuration of the tube sheet for the design. *Hamidou Benzenine* investigate numerically to study a turbulent flow of air through a rectangular section. Two baffles were introduced into the field to produce vortices, to improve the mixture and thus, the transfer of heat. The numerical results obtained by the finite volume method, are validated and presented to analyse the dynamic behaviour of a turbulent flow using the low Reynolds number model. The highest disturbance is obtained upstream second baffle. This study showed that the undulation of the baffles induced with an improvement on the skin friction of about 9.91 % in the case of α=15°, more than 16% in the other cases. Concerning the pressure loss the undulation of the baffles was insured improvements starter from 10, 43% in all cases compared with the baffles of plane form. The investigation was carried for four cases of slopes for the corrugated baffles going from 0° up to 45°, with a step equal to 15°. It may be concluded that the purely vertical use of the waved baffles (α=0) in the geometry studied, ensures the optimal size of the zone of recirculation and thus necessary time for guarantee the improvement of heat exchange. Also this case ensures us a very high velocity in the exit of the channel, measures more than four times the reference velocity, and most significant is to reduce less the action flow induces on the pressure losses. *D.P.Naik* has an assessment of counter flow shell and tube heat exchanger by entropy generation minimization method. The design variables which are used for the shell and tube heat exchanger are tube inside diameter, tube outside diameter, number of tubes, baffle spacing and tube pitch etc. The analyses of these design parameters are very important for the better performance of shell and tube heat exchanger. Shell and tube heat exchanger performance has improved significantly by minimization of entropy generation number considering the various design variables. As the mass flow rate of shell side fluid increases, the entropy generation number increases. Therefore we can reduce the entropy generation number by reducing the mass flow rate of cold fluid by optimization. If we change tube side area heat exchanger effectiveness also change. *Sunil S. Shinde* has studied about the performance Improvement in Single phase Tubular Heat Exchanger using continuous Helical Baffles and investigated that that the performance of tubular heat exchanger can be improved by helical baffles instead of conventional segmental baffles. The use of helical baffles in heat exchanger reduces shell side pressure drop, pumping cost, size, weight, fouling etc. as compare to segmental baffle for new installations. The helix changer type heat exchangers can save capital cost as well as operating and maintenance cost and thus improves the reliability and availability of process plant in a cost effective way. For the helical baffle heat exchangers, the ratios of heat transfer coefficient to pressure drop are higher than those of a conventional segmental heat exchanger. This means that the heat exchangers with helical baffles will have a higher heat transfer coefficient when consuming the same pumping power. It can be concluded that proper baffle inclination angle will provide an optimal performance of heat exchangers. *A.E. Zohir* shown the analysis of Heat transfer characteristics in a heat exchanger for turbulent pulsating water flow with different amplitudes. The effect of pulsation on the heat transfer rates, for turbulent water stream with upstream pulsation of different amplitudes, in a double- pipe heat exchanger for both parallel and counter flows, with cold water on the shell side, was investigated. The heat transfer coefficient was found to increase with pulsation, with the highest enhancement observed in the transition flow regime. The heat transfer coefficient was strongly affected with pulsation frequency, amplitude and Reynolds number. In the counter flow, the enhancements in heat transfer rates are somewhat greater than that in the parallel flow. The heat transfer coefficient was found to increase with pulsation, with the highest enhancement observed in the transition flow regime. The results showed that an enhancement in relative average Nusselt number of counter flow up to 10 times was obtained for higher amplitude and higher pulsation frequencies. While, an enhancement in relative average Nusselt number of parallel flow up to 8 times was obtained for higher amplitude and higher pulsation frequency. The maximum enhancements in the heat transfer rates were obtained at Reynolds number of 3855 and 11570.

II. PRINCIPLE COMPONENTS OF SHELL AND TUBE TYPE HEAT EXCHANGER

The shell is the container which provides space for the exchange of heat between the two media. It houses assembly of tubes (Tube bundle) inside and remaining space for shell-side fluid. The shell has nozzles at its periphery for inlet and outlet for steam and water. The tube bundle has a large number of tubes which are decided on the basis of the capacity and purpose of the boiler for which it is designed. In a fire tube heat exchanger the hot flue gases pass through the tubes and have water or any other heat transferring fluid on the periphery. Tubes span across the length of boiler shell from the furnace side tube sheet to the channel side tube sheet. Tubes are welded to tube sheet on both the ends. Tube sheet is thick plate with multiple holes drilled in it. It has same number of holes as that of number of tubes in tube bundle. Steam drum is an external attachment which is connected to the shell through risers and down comer pipes. It holds feed water and steam generated in the process. It is a major component as it separates steam from water. Following are the major components of shell and tube type heat exchanger Boiler shell, Tube, Tube Sheet, Steam Drum.

2.1. Boiler Shell

The shell is simply the container for the shell-side fluid, and the nozzles are the inlet and exit ports. The shell normally has a circular cross section and is commonly made by rolling a metal plate of the appropriate dimensions into a cylinder and welding the longitudinal joint “rolled shells”. Small diameter shells up to around 24 inches in diameter can be made by cutting pipe of the desired diameter to the correct length (“pipe shells”). The roundness of the shell is important in fixing the maximum diameter of the baffles that can be inserted and therefore the effect of shell-to-shell baffle leakage. Pipe shells are more nearly round than rolled shells unless particular care is taken in rolling. In large exchangers, the shell is made out of low carbon steel wherever possible for reasons of economy, though other alloys can be and are used when corrosion or high temperature strength demands must be met.

2.2. Tube Sheet

Tube sheet is an important part of shell and tube type heat exchanger, which separates the tube side fluid and shell side fluid. Proper design of tube sheet is important for safe and reliable operation of heat exchanger, especially steam generators. They are generally circular with uniform pattern of holes. The study of the stresses developed in the tube sheet is of importance in order to select the tube sheet thickness. The tubes are held in place by being inserted into holes in the tube sheet and there either expanded into grooves cut into the holes or welded to be tube sheet where the tube protrudes from the surface.

2.2.1. Tube Sheet Layout

Tube pitch is defined as the shortest distance between two adjacent tubes. In our work we employ the minimum recommended tube pitch, because it leads to the smallest shell diameter for a given number of tubes. However, in exceptional circumstances, the tube pitch may be increased to a higher value, for example, to reduce shell side pressure drop. This is particularly true in the case of a cross-flow shell.

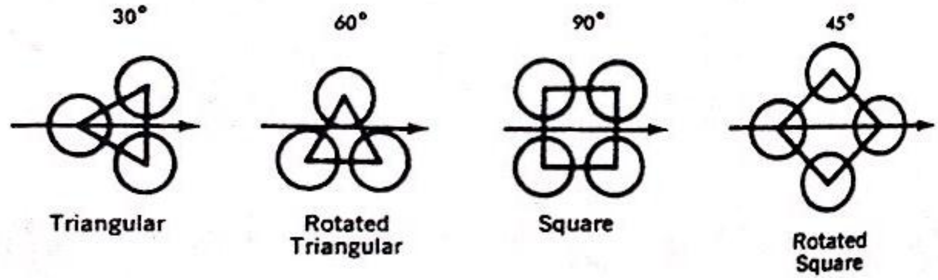


Fig.2 Schematic representation of tube sheet layout

2.3. Tubes

The tubes are the basic component of the shell and tube exchanger, providing the heat transfer surface between one fluid flowing inside the tube and the other fluid flowing across the outside of the tubes. The tubes may be seamless or welded and most commonly made of copper or steel alloys. Other alloys of nickel, titanium, or aluminium may also be required for specific applications. The tubes may be either bare or with extended or enhanced surfaces on the outside. Extended or enhanced surface tubes are used when one fluid has a substantially lower heat transfer coefficient than the other fluid. Extended surfaces, (finned tubes) provide two or four times as much heat transfer area on the outside as the corresponding bare tube, and this area ratio helps to outside heat transfer co-efficient. More recent developments are: a corrugated tube which has both inside and outside heat transfer enhancement, a finned tube which integral inside tabulators as well as extended outside surface, and tubing which has outside surfaces designed to promote nucleate boiling.[9]

2.4. Steam Drum

A steam drum is a pressure chamber of a steam boiler located at the upper extremity of steam boiler circulatory system. It is a reservoir of water/steam at the top end of the water tubes. The steam drum stores the steam generated in the water tubes and acts as a phase-separator for the steam/water mixture. Steam is separated from the water and then discharged at a position above the water level maintained there. Thermodynamically a steam drum is merely a surge tank in the circulation system to which the following parts are connected: Economizer outlet and super heater inlet pipes on one side, down comers and risers on the other side.

III. ANALYTICAL EVALUATION

Indian Boiler Regulations (IBR) are the standards in respect of materials, design and construction inspection and resting of boilers and boiler components for compliance by the manufacturers and users of boilers in the country. These regulations are being updated regularly by amending them in line with the fast changes in boiler technology by the central boilers board. The object therefore of the present legislation is a) To secure uniformity throughout India in all technical matter connected with boiler regulation. b) To insist on the regulation and inspection of all boilers throughout India. By using codes, we are calculating internal pressure for major component used in shell and tube type of heat exchanger.

3.1 Internal pressure in Boiler shell by IBR 270 [5]

- Selected design Parameters:

Parameters	Nomenclature	Range
Design pressure	P	54.72 kgf/cm^2=5.36 MPa
Design metal temperature	T	272 °C
Material specification	-	SA 516 GR 70
Allowable stress	F	1398.03kgf/cm^2=137.1MPa
Thickness of plate selected	T	90mm
Internal diameter (corroded condition)	D	3911.00mm
Corrosion allowance	C	3mm
Minimum ligament efficiency	E	1.00

Minimum required thickness of an unpierced drum shell

$$t_{min}=\frac{P\times d}{2\times f\times E-P} \qquad \text{(i)}$$

$$t_{min.}=\frac{(54.72\times 3911)}{2\times 1398.03\times 1-54.72}$$

Minimum required thickness of an unpierced drum shell t $_{min}$=78.06mm

3.2 Internal Pressure in Tube sheet by IBR 580 [5]

- Selected design Parameters:

Parameters	Nomenclature	Range
Material selected	-	SA 516 GR 70
Thickness selected	T	45mm
Maximum tube hole diameter	D	115.3mm

3.2.1 Pitch of tubes

Generally the spacing of tube holes shall be such that the minimum width in inches of any ligament between the tube holes shall be not less than:-

$$\left[\frac{D}{8}+\frac{1}{2}\right] = 1.0674'' \qquad \text{(ii)}$$

Ligament =27.113mm

Ligament provided = Pitch - tube hole diameter

= 149 - 115.3

=33.7mm

3.2.2. Cross sectional area of tube plate at tube hole

Minimum cross section of tube required

$$= (0.17D+0.025)''^2 \qquad \text{(iii)}$$

$$= 0.7968''^2 = 513.99mm^2$$

Cross section provided = Ligament × Thickness

$= 33.70 \times 45 = 1516.5mm^2$

Minimum thickness is given by = (0.125D+0.2)"

= 0.767"

Minimum thickness of tube sheet =19.49mm

3.3 External Pressure in Tube by IBR 579 [5]

- Selected design Parameters:

Parameters	Nomenclature	Range
Material selected	-	SA 210 GR A1
Thickness of tube selected	T	6.6mm
External design pressure	WP	$54.72 kg/cm^2$
Outside diameter of tube	D	114.3mm
Corrosion allowance	C	0.0mm
Allowable stress at 343^0C	F	$1196.13 kg/cm^2$

Maximum allowable external pressure $P = \frac{1.6f\times t}{D}$ (iv)

Maximum allowable external pressure P = 10.84MPa

3.4 Internal Pressure in Steam drum by IBR 270 [5]

- Selected design Parameters:

Parameters	Nomenclature	Range
Design pressure	P	$54.06 kgf/cm^2$
Design metal temperature	T	Shell side 272 °C Tube Side 343 °C
Material specification	-	SA 516 GR 70
Allowable stress	F	$1398.03 kgf/cm^2$
Thickness of plate selected	T	63mm
Internal diameter (corroded condition)	D	2606.00mm
Corrosion allowance	C	3mm
Minimum ligament efficiency	E	1.00

Min required thickness of an unpierced drum shell $t_{min} = \frac{P\times d}{2\times f\times E-P}$ (v)

$$t_{min.} = \frac{54.06\times 2606}{2\times 1398.03\times 1-54.06}$$

Min required thickness of an unpierced drum shell $t_{min=}$ 51.38mm.

IV. VISUALIZATION HIGHER STRESS CONCENTRATION AND FAILURE IN OPERATION.

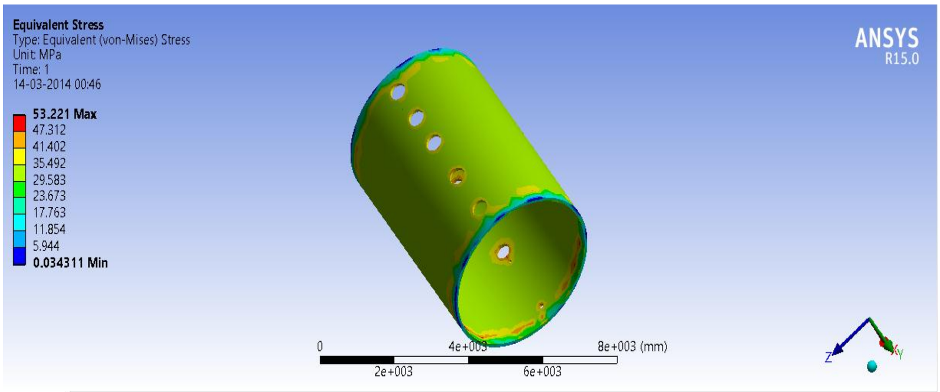
In mathematics, the finite element method (FEM) is a numerical technique for finding approximate solutions to boundary value problems for differential equations. It uses variational methods (the calculus of variations) to minimize an error function and produce a stable solution. The subdivision of a whole domain into simpler parts has several advantages such as accurate representation of complex geometry, Inclusion of dissimilar material properties, Easy representation of the total solution and Capture of local effects. In this section Finite element analysis helps us to identify and visualize the critical areas where the stress concentration is higher and which is more susceptible for failure in operation.

4.1 Boiler Shell

Design parameters:

Material: SA 516 GR 70

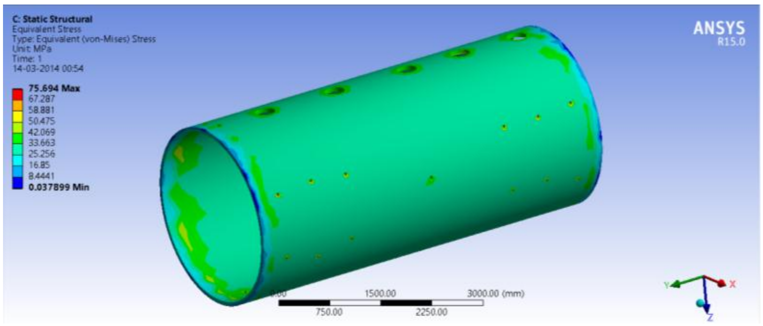
Force acting: a) Direction: Radial b) Magnitude: 5.36 MPa



The Maximum Allowable Stress = 137.10 MPa.
The Maximum Stress Developed = 75.694 MPa.
Hence the design is safe for the operating conditions.

4.2 For Steam Drum

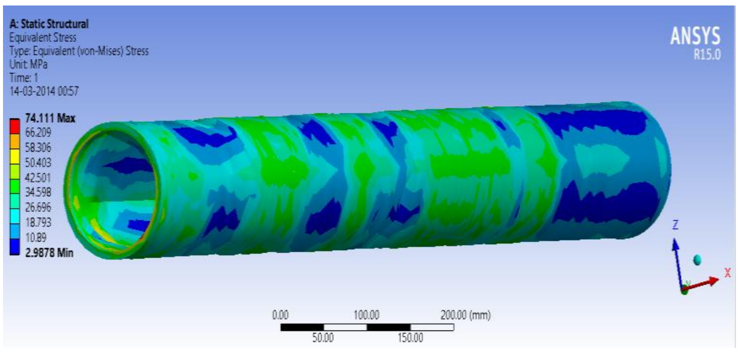
Design parameters:
Material: SA 516 GR 70
Force acting: a) Direction: Radial b) Magnitude: 5.36 MPa



The Maximum Allowable Stress = 137.10 MPa.
The Maximum Stress Developed = 53.221 MPa.
Hence the design is safe for the operating conditions.

4.3 For Tube

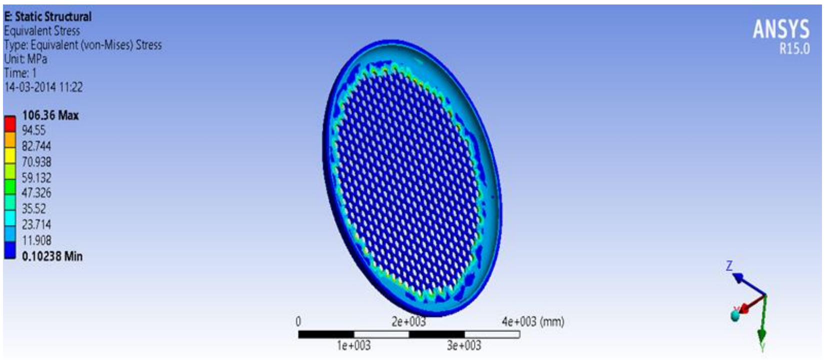
Design parameters:
Material: SA 516 GR 70
Force acting: a) Direction: Radial b) Magnitude: 5.36 MPa on external surface of tube



The Maximum Allowable Stress = 109.65 MPa.
The Maximum Stress Developed =74.111 MPa.
Hence the design is safe for the operating conditions.

4.4. For Tube sheet

Material: SA 516 GR 70
Force acting: a) Direction: Axially b) Magnitude: 5.36 MPa



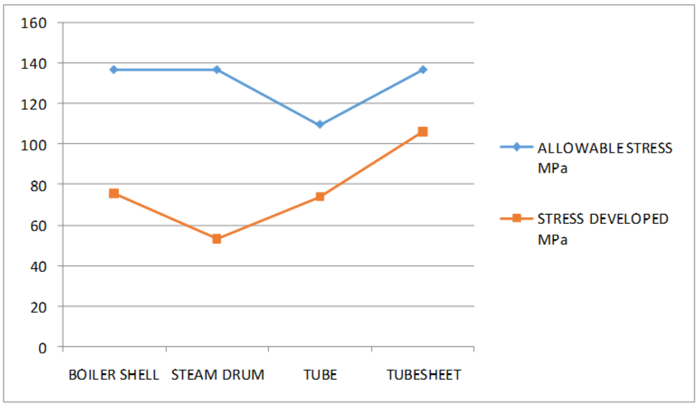
The Maximum Allowable Stress = 137.10 MPa
The Maximum Stress Developed = 106.36 MPa.
Hence the design is safe for the operating conditions.

V. RESULT DISCUSSIONS

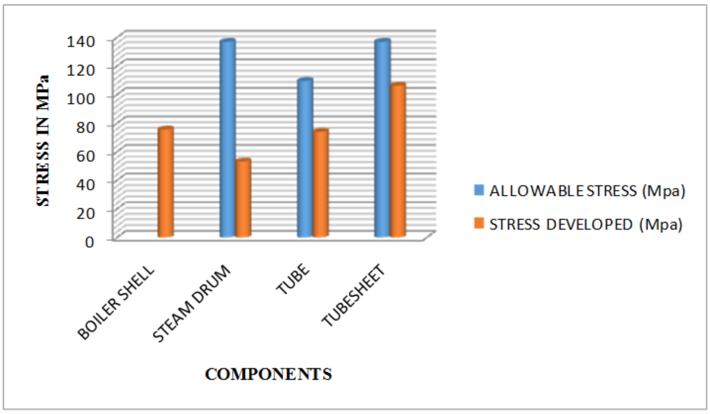
The following result shows calculated values of Allowable stress and maximum stress developed in following components.

Component	Allowable Stress (MPa)	Stress developed (MPa)
Boiler shell	137.10	75.694
Steam drum	137.10	53.221
Tube	109.65	74.111
Tube sheet	137.10	106.36

- A Graphical representation of the allowable stresses and the stresses developed is shown below. It is seen that the lines of the allowable stresses and developed stresses are non-intersecting in nature. Further it is seen that there is a sizable difference in the two stress values and therefore a high degree of safety exists.



- The bar graph shows a comparison between the stresses developed and the allowable stresses. It is seen that there is a sizable difference in the two stress values and therefore a high degree of safety exists.



VI. CONCLUSIONS

1. The above graph illustrates that the values of stress getting developed in the components for given operating conditions are much lesser than the allowable values of stress for those respective material. Thus the components are safe against such loading.
2. Finite element analysis helps us to identify and visualize the critical areas where the stress concentration is higher and which is more susceptible for failure in operation.
3. It also proves to be economical and advantageous as it acts tool to check the design before manufacturing.

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