Finite element simulation of cooling rate effects on thermal strain and stress in the shell of a de-methanizer stripper column fabricated from AISI-304L stainless steel

Abstract

De-methanizer stripper column in gas refineries is one of the most important parts of any gas train which separates methane from natural gas. Bottom of this column is operated in the range of ambient temperature, about 313.15°K(40°C), while top of the column is operated at cryogenic very low temperatures, about 183.15°K(-90°C). So, cooling down and warming up of a de-methanizer is an important and challenging matter during startup, shutdown, and normal operation of the column. In some abnormal cases such as improper startup, or malfunction of the process like problem in re-boiler of the column ,and etc, the rate of cooling down would became very high, which results high thermal strain and stress in different parts of this equipment. The fabricating material of this equipment is AISI 304L stainless steel with high thermal expansion coefficient and low thermal conductivity coefficient; So, the mentioned thermal strain and stress can cause residual stresses or may cause distortion, which may results in catastrophic damages and consequently interrupts the refinery production. In this study, a finite element approach is implemented to simulate the effects of different cooling rates on thermal strain and stress exerted in de-methanizer shell. The ABAQUS software is implemented to analyze the column and compare results in the temperature ranging from ambient to cryogenic. Furthermore, the threshold and critical strain and stress were identified and investigated. Also the mechanical behavior of the column is evaluated with simultaneously applying thermal strain/stress coupled with hoop and longitudinal stresses resulted from hydrostatic pressure. Geometrical and material properties of different parts of the column and mechanical and thermal interactions between them are considered in the model. Load cases and boundary condition were defined according to different operational scenarios. Simulation results showed that the mechanical behavior of the column's shell strongly depend on the cooling rate. Therefore, cooling rate in the range from 6 °K /hr to 8 °K /hr is recommended as a proper and safe cooling rate for de-methanizer. Based on the results, proper and practical procedures for cooling down of the de-methanizer column were investigated in the cases of unpredictable start up and shouting down. Also the results of this study were used for remaining life evaluation of the equipment and designing a reliable (RBI) Risk Based Inspection. This study is the first one in which cooling rate effects on de-methanizer column is investigated by means of finite element method; hence, the findings and approach of this study could be used for assessment of similar operation in gas production plants.

Keywords: De-methanizer; Cooling rate; Heat Flux; Thermal stress; Thermal strain; Thermal shock; Finite element; Abaqus.

Introduction

The problem domain comprises a cylindrical vessel shell, a hemispherical top head, and elliptical bottom head as shown in Figure1. The overall height of the vessel shell including the bottom head is 42350 mm. The inner radius of the vessel shell in bottom is 1000 mm and in top is 2100, and the thickness is 87 mm in bottom and 73 mm in top. The last bottom part as shell 1 is thickest part of column with 87mm thickness, 1000 mm inner radius and 2500 mm height is selected as a main geometry part.

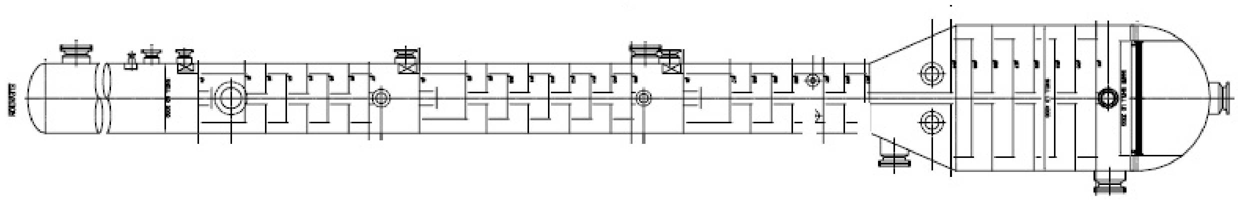


Fig.1.De-methanizer overview

Boundary conditions and loading

The outside of the vessel is exposed to air that has a constant temperature of 298.15°K (25°C). The inside of the vessel is filled with cryogenic hydrocarbon (Ethane, Methane…). Bottom of this column is operated in 313.15°K(40°C)while top of the column is operated at cryogenic very low temperatures, about 183.15°K(-90°C). During a cool-down process and in some abnormal cases such as improper startup, or malfunction of the process like problem in re-boiler of the column ,and etc, the rate of cooling down would became very high, so internal temperature in bottom shell is reduced by 183.15°K(-90°C). The hydrocarbon inside imposes a constant pressure of 3 Mpa (30barg) on the internal surface of the vessel.

Abaqus modeling approaches and simulation techniques

The objective of this analysis is an understanding of stresses near the lower vessel shell-to-bottom head interfaces. Although the assembly contains many features, such as inlet and outlet nozzles, the example ignores these details since they are far away from the vessel-to-head interface. The rest of the geometry is cyclically symmetric, which allows the example to model the entire 360° structure at a reduced computational expense by analyzing only a single repetitive sector of the model. Since there are 17 shell parts along the vessel, and the significant problem is in lowest part of the vessel .The following analysis is performed on lowest shell with 2500 mm height as shown in Fig.5.

The example also takes advantage of the fact that the thermal and mechanical responses of the vessel are only weakly coupled. Based on this fact, a sequentially coupled thermal-stress analysis is performed on the vessel. First, distribution of the temperature field is obtained through a heat transfer analysis with the temperature field specified using the results of the thermal analysis.then The mechanical response of the vessel is obtained by performing a static stress analysis and pressure.

Material Model

The material of vessel is Stainless steel AISI 304L, which is thermo elastic material that its yield stress is as a function of plastic strain in different temperature. It means that these type of materials have different Yield stresses, thermal coefficient, thermal conductivity, and heat specific in different temperatures. The heat transfer analysis requires specification of, thermal conductivity, which is 16.2 W/m.K , and specific heat, which is 0.5kJ/kg.K. The density of the material is also specified, which is 8030kg/m3.Furthurmore, The linear static structural analysis requires specification of Young's modulus, which is 193Gpa ,Yield stress which is 241Mpa, Poisson's ratio, which is 0.3,and mean thermal expansion coefficient ,which is 16.9×10^{-6} . One solid, homogenous section is used to assign material properties to the elements.

Theoretical analyze and Analyzing steps

Theoretical analyze

The fundamental calculation of stresses and strains are based on biaxial stresses. A biaxial stress system has a stress state in two directions and a shear stress typically showing in Fig.2.

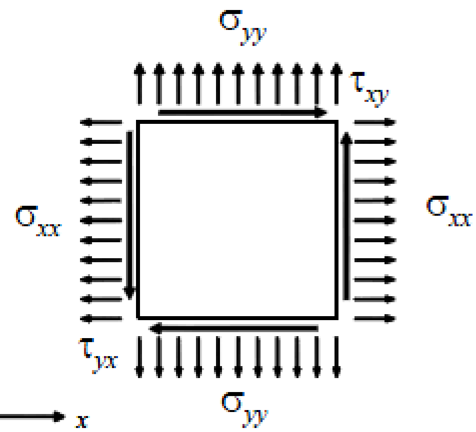


Fig.2. Element of a structure showing a biaxial stress system

The direct strain in any direction is the sum of all factors contributing to that strain:
a) Direct stresses in that direction
b) Poisson's ratio effects of stresses at right angles
c) Thermal strain
We can give the relationship between stress and strain as:

$$\varepsilon_{xx} = \frac{\sigma_{xx}}{E} - \nu \frac{\sigma_{yy}}{E} + \alpha \Delta T$$

$$\varepsilon_{yy} = \frac{\sigma_{yy}}{E} - \nu \frac{\sigma_{xx}}{E} + \alpha \Delta T$$

$$\gamma_{yy} = \frac{\sigma_{xy}}{G} = \frac{\tau_{xy}}{G}$$

If these equations are rearranged to compute the stresses for a set of given the strains, we get:

$$\sigma_{xx} = \frac{E}{\left(1 - \nu^2\right)}\left[\varepsilon_{xx_1} + \nu \varepsilon_{yy_1}\right]$$

$$\sigma_{yy} = \frac{E}{\left(1 - \nu^2\right)}\left[\varepsilon_{yy_1} + \nu \varepsilon_{xx_1}\right]$$

$$\tau_{xy} = G\gamma_{xy} = \frac{E}{2(1+\nu)}\gamma_{xy}$$

Where: $\varepsilon_{xx} = \varepsilon_{xx} - \alpha \Delta T_1$ and $\varepsilon_{yy} = \varepsilon_{yy} - \alpha \Delta T_1$. When a Biaxial Stress state occurs in a thin metal, all the stresses are in the plane of the material. Such a stress system is called Plane Stress We can see plane stress in pressure vessels.

Thin Walled Pressure Vessels

In general, thin wall refers to an inner radius to wall thickness ratio greater than 10, e.g. r/t=20, in most cases it is actually r/t > 50. If the vessels wall is thin, the stress distribution Through the thickness can be assumed to be uniform. So according to the thickness of the vessel(87mm) and inner radius(1000mm), the mentioned de-methaniser is categorized as a thin wall vessel, and the related calculation equations are following:

Cylindrical Pressure Vessels

This analysis will look at tubes with an internal pressure and closed ends. Let σ_{xx} be the Axial Stress due to the pressure on the end walls, and $\sigma_{\theta\theta}$ be the Hoop Stress due to the pressure acting on the curved surface.

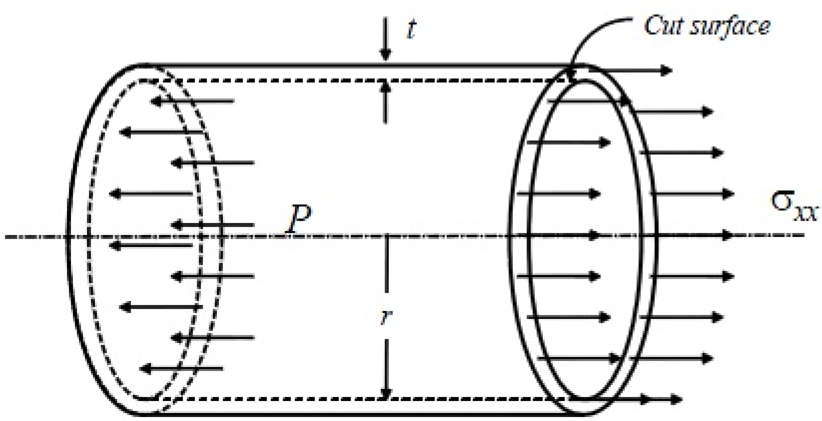


Fig.3.Axial section of a cylindrical pressure vessel

Axial Stress

Look at a FBD of the axial section as shown in Fig. 10.2 and check for the axial equilibrium.

$$\sum F_x = 0 = -P\pi r^2 + 2\pi r t \sigma_{xx} \quad \rightarrow \quad P\pi r^2 = (2\pi r t)\sigma_{xx}$$

Which gives the equation for Axial Stress (or Longitudinal Stress)?

$$\sigma_{xx} = \frac{Pr}{2t}$$

Hoop Stress

The circumferential section as shown in Fig.4:

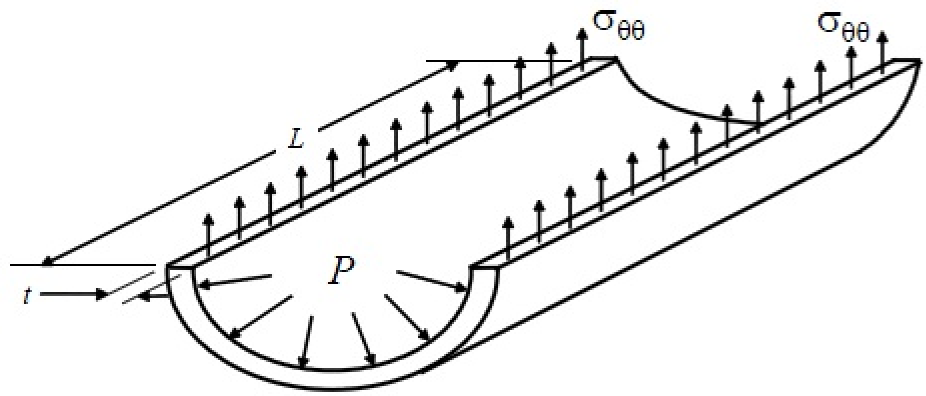


Fig.4.circumferential section of the cylindrical pressure vessel

Equating the forces vertically gives:

$$\sum F_y = 0 = -P \times (2r \times L) + \sigma_{\theta\theta} \times 2(L \times t) \quad \rightarrow \quad 2\sigma_{\theta\theta}(Lt) = 2rLP$$

Which simplifies to give the equation for Hoop Stress (or Circumferential Stress)

$$\sigma_{\theta\theta} = \frac{Pr}{t}$$

By substituting into the above biaxial strain equations, we get:

$$\varepsilon_{xx} = \frac{1}{E}\left[\sigma_{xx} - v\sigma_{\theta\theta}\right] + \alpha\Delta T = \frac{Pr}{tE}\left[\frac{1}{2} - v\right] + \alpha\Delta T$$

$$\varepsilon_{\theta\theta} = \frac{1}{E}\left[\sigma_{\theta\theta} - v\sigma_{xx}\right] + \alpha\Delta T = \frac{Pr}{tE}\left[1 - \frac{v}{2}\right] + \alpha\Delta T$$

Interactions

Conductive heat transfer is defined between adjacent/contacting surfaces. Heat flux on the surfaces is applied by film conditions. The outer surfaces are exposed to air, which has a film coefficient of 28 W/m2.°K. The inner surfaces are in contact with Ethane with a film coefficient of 124 W/m2. °K .The outer surfaces are initially associated with a sink temperature of 294.15°K and the inner surfaces, 313.15°K (40°C). During a subsequent 4.8, 9.28, and 16.25 hours cooling process, the sink temperature associated with the inner surfaces is reduced by 183.15°K(-90°C)

Analyzing steps

The vessel undergoes combination of thermal and mechanical loads ,so the analysis consists of a steady-state heat transfer step, representing the steady operation of the vessel to obtain a steady-state solution of temperature distribution in the whole model ,and followed by a transient heat transfer step, representing a 130°K rapid cool-down events last for 4.8, 9.28, and 16.25 hours.
The resulting temperatures obtained are applied to the subsequent mechanical analysis which is internal pressure applied in the first step. A predefined temperature field is also specified using the results obtained in the steady-state heat transfer step. The temperature obtained from the transient heat transfer step is specified in the last loading step, and the structure expands with the change of temperature.
The mentioned loads are following:

- Edge surface load through thickness in different direction
- Pressure load from inside of vessel
- Specified heat and cool down rate

For this target we need:

- longitudinal Actual stress calculation σ_{xx} for surface traction according to following equation :

$$\sigma_{xx} = \frac{P(D/2 + Ca) + 0.2(T - Ca)}{2E(T - Ca)}$$

σ_{xx} = *23.140 Mpa*

- Internal pressure according to design pressure:

P=3Mpa

- Different temperature boundary condition with different cooling rate:

	Cooled Temperature(Amplitude)
	(313.15-183.15) 130°K
Cooling rate(℃/hr)	27
	14
	8

Definition of loading and boundary condition:

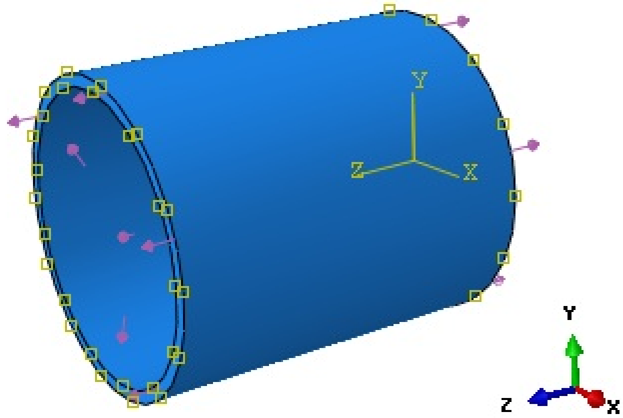


Fig.5.Loads and boundary condition

Result and Discussion

Four studies are performed in this analysis. In initial step the static mechanic and pressure is computed. Then the different interactions thermal boundary condition is imposed with different cooling time and pressure load. For assurance of accuracy in definition of step, load and condition the common situation of vessel is simulated and compared with actual hoop stress calculated according to base equation of vessel mechanical calculation .The simulation depicts that the maximum value of stress in common situation is 47.24 Mpa that it is equal to calculated according to related formula.(Fig.6)

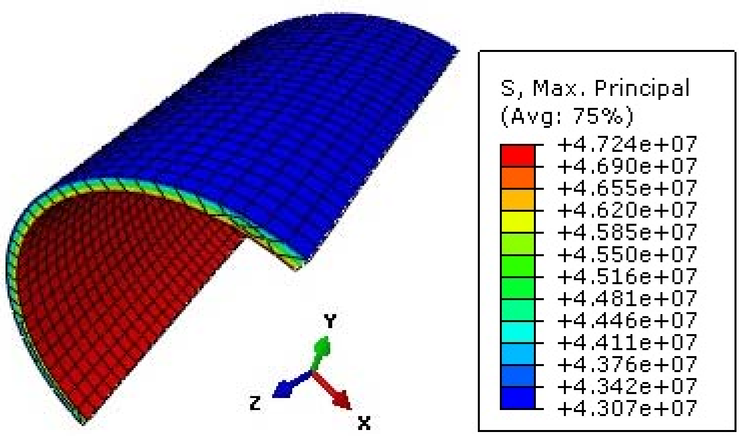


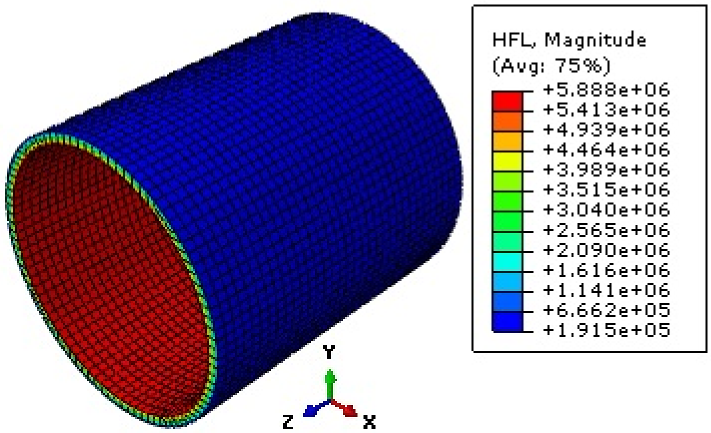
Fig.6

Hoop Stress:

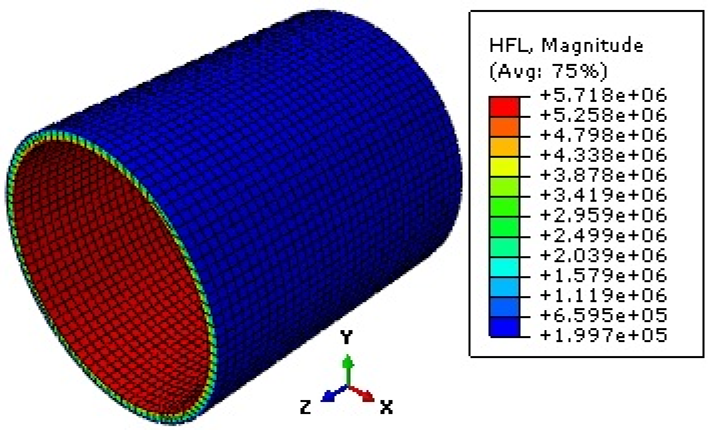
$$\sigma_{\Theta\Theta} = \frac{P(D/2 + Ca) + 0.6(T - Ca)}{E(T - Ca)}$$

$\sigma_{\Theta\Theta}$=47.812 *Mpa*

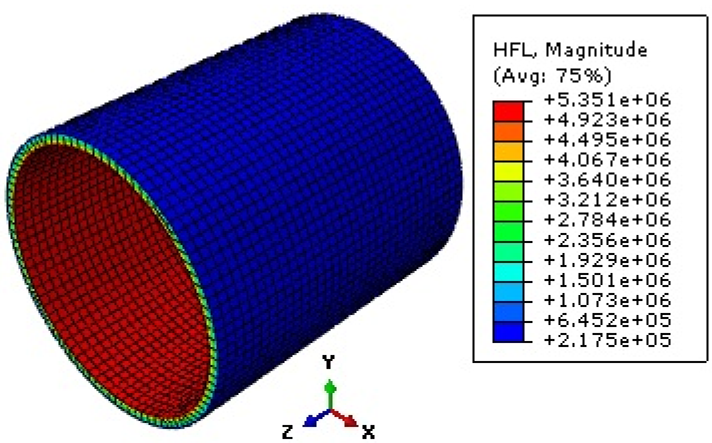
For calculation of appropriate cooling rate the different cooling times in simulation are tried to obtain HFL (Heat Flux).Fig 7. In all situation the value of reference temperature and out surface of vessel are 298.15°K (25℃) and are constant.



Heat flux values in -183.15°K with 27 (°K/hr)



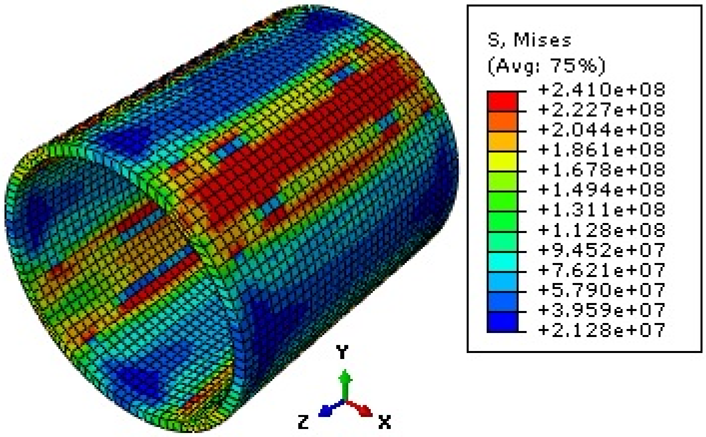
Heat flux values in -183.15°K with 14 (°K/hr)



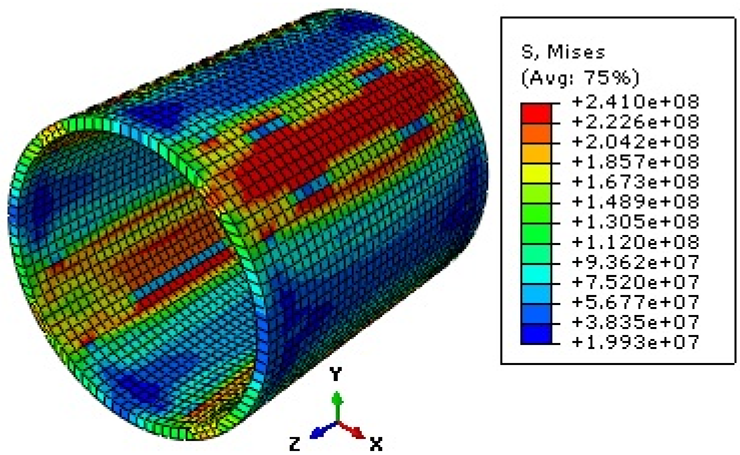
Heat flux values in -183.15°K with 7 (°K/hr)

Fig.7.HFL (Heat Flux)

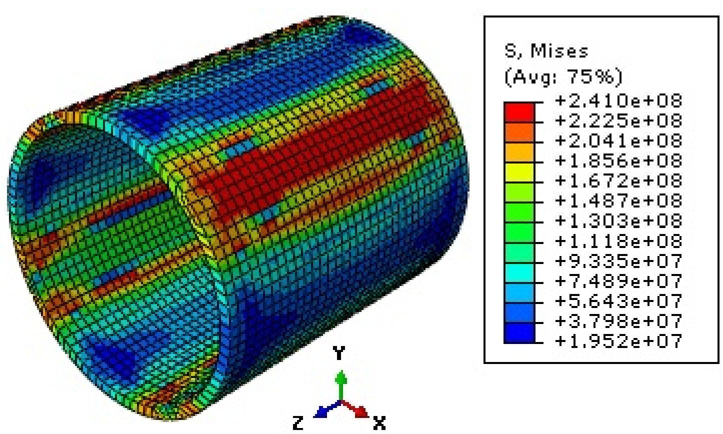
The temperature distribution calculated in the heat transfer case augments pressure loads to define the structural loading of the vessel assembly. According to Fig.8.The high heat flux values produce high values of thermal stresses.



Stress values in -183.15°K with 27 (°K/hr)



Stress values in -183.15°K with 14 (°K/hr)



Stress values in -183.15°K with 7 (°K/hr)

Fig.8.Thermal Stress

Based on all above mentioned phenomena the relation between cooling rate,HFL(heat flux), thermal stresses ,and consequently thermal strains are linear. The following chart illustrates this relationship:

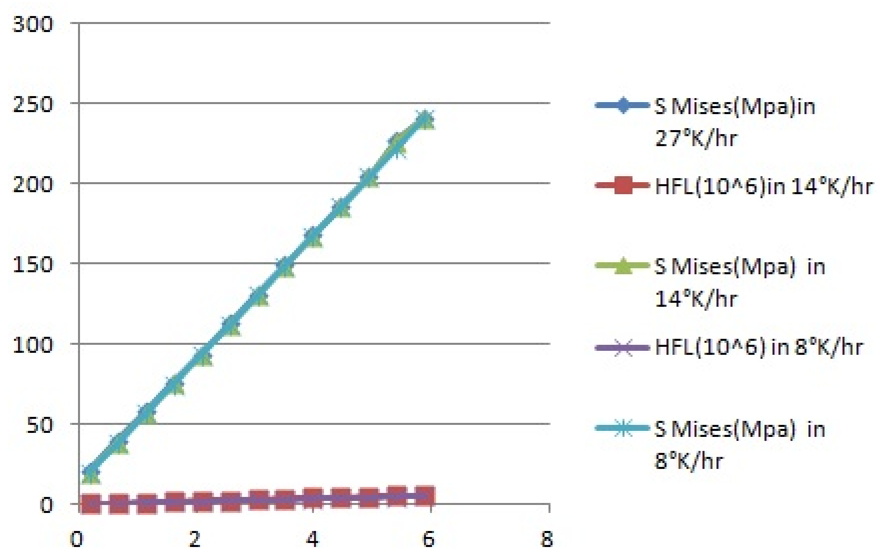


Chart: HFL and Stress different cooling rates

Conclusion

The thermoplastic materials such as Austenitic stainless steels show different mechanical and physical properties by changing temperature. Thermal stress behavior of mentioned materials is dependent of thermal expansion coefficient which is change by different temperature. So when the cooling rate of de-methanizer change the rate of thermal strain changes, consequently the rate of imposed stresses changes. In this study by increasing the cooling rate 27 °K$/hr$ to reach-183.15°K ,the value of stress increases. Thus by try and error the appropriate cooling rate is selected 8°K$/hr$. As matter of fact, this study and related finite element steps can be help full in start up and shutdown of refineries and applicable for other vessels with different situation. Undoubtedly, this study needs some experimental approval data, which can be achievable in next opportunities.

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