Modeling of Pressure Profiles in a High Pressure Chamber using COMSOL Multiphysics

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Dr. P. Srinivasa Rao &

Chamanooru Kartik Chandra

Indian Institute of Technology Kharagpur

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Points to be covered

- Introduction
- Significance of HPP system
- Design requirements for HPP system
- Design of cylindrical shell
- Modelling of cylindrical shell using COMSOL

Introduction

- Conventional food sterilization and preservation methods often result in a number of undesired changes in foods.
- HPP is a non-thermal food processing method
- It subjects liquid or solid foods, with or without packaging, to pressures between 50 and 1000 MPa.

Introduction

- HP Processing has potential to replace conventional heat induced sterilization and pasteurization processes.
- Need to develop and produce HPP equipment for Indian food processing sector

PROCESS DESCRIPTION

- In a HP process, the food product to be treated is placed in a pressure vessel capable of sustaining the required pressure (50-1000 MPa); the product is submerged in a liquid, which acts as the pressure-transmitting medium.
- Some pressure transmitting media used in a HP chamber include water, castor oil, silicone oil, sodium benzoate, ethanol and glycol.
- Industrial High Pressure systems are usually batch processing systems.
- The selection of equipment depends on the kind of food product to be processed.
- Solid food products or foods with large solid particles can only be treated in a batch mode.

PROCESS DESCRIPTION

- Liquids, slurries and other pumpable products have the additional option of semi-continuous production
- If water is used as the pressurizing medium, its compressibility must be accounted for; water is compressed by up to15 per cent of volume at pressures above 600 MPa.
- Once the desired pressure is reached, the pump or piston is stopped, the valves are closed and the pressure is maintained without further energy input.
- After the required hold time has elapsed, the system is depressurized, the vessel opened and the product unloaded.

Significance

- Despite of many advantages, cost of high pressure processing is high, mainly due to cost of HPP equipment.
- Import from overseas.
- This is an attempt to design an indigenous high pressure processing vessel which is heart of HPP equipment.

HPP equipment - components

- Pressure vessel
  - Cylindrical shell
  - Removable Head (cap)
  - Nozzle
  - Pressurization and decompression valves
- Vessel supports
- High pressure pump
- Cooling / heating arrangement
- Temperature, pressure sensors
- Control unit

ASME Codes

- The organization is known for setting codes and standards for mechanical devices
- Adopted worldwide for design and fabrication of pressure vessels
- For design and construction of boiler and pressure vessels - ASME section VIII, division 1 and division 2

1. Maximum stress theory

- Both ASME Code Section VIII Division 1, and Section I use the maximum stress theory as a basis for design.
- The maximum principal stress is determined applying this theory

2. Maximum Shear Stress Theory

- Yielding will start at a point when the maximum shear stress at that point reaches one-half of the the uniaxial yield strength.
- Both ASME Code, Section VIII, Division 2 and ASME Code, Section III, utilize the maximum shear stress criterion.

Lames equation

Circumferential stress,

$$\sigma_{hoop} = \left[\frac{P_i.r_i^2 - P_0.r_o^2}{r_o^2 - r_i^2} + \frac{r_i^2.r_o^2.(P_i - P_o)}{r^2.\ (r_o^2 - r_i^2)} \right]$$

Radial stress,

$$\sigma_{rad} = \left[\frac{P_i.r_i^2 - P_0.r_o^2}{r_o^2 - r_i^2} - \frac{r_i^2.r_o^2.(P_i - P_o)}{r^2.\ (r_o^2 - r_i^2)} \right]$$

Longitudinal stress,

$$\sigma_{long} = \left[\frac{P_i.r_i^2 - P_0.r_o^2}{r_o^2 - r_i^2} \right]$$

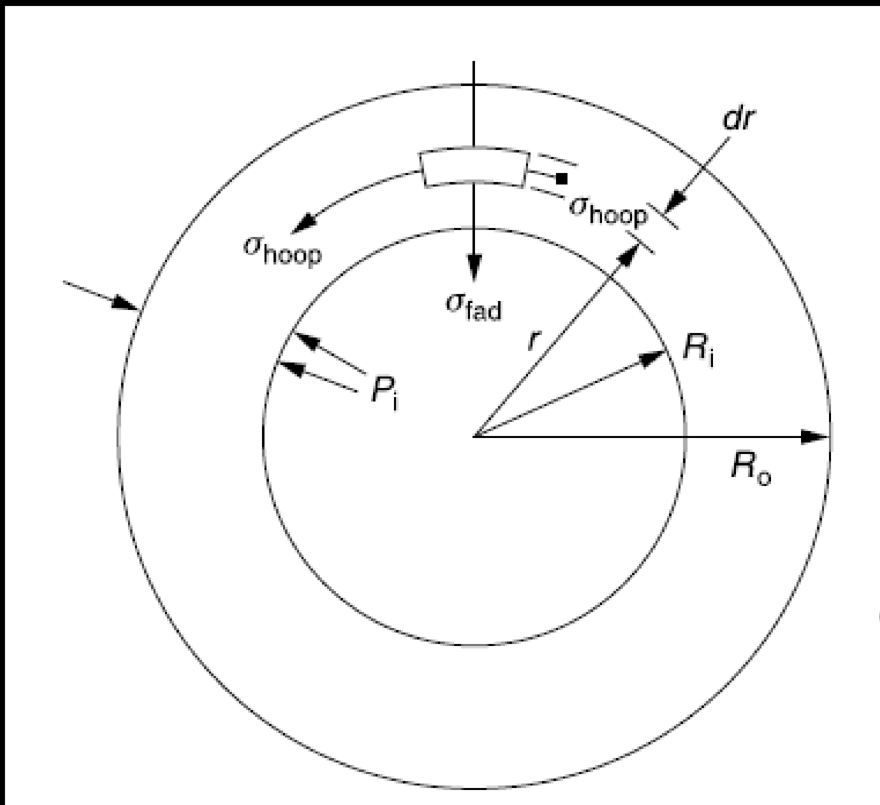


Fig. 1 Hoop and radial stresses in cylindrical shell

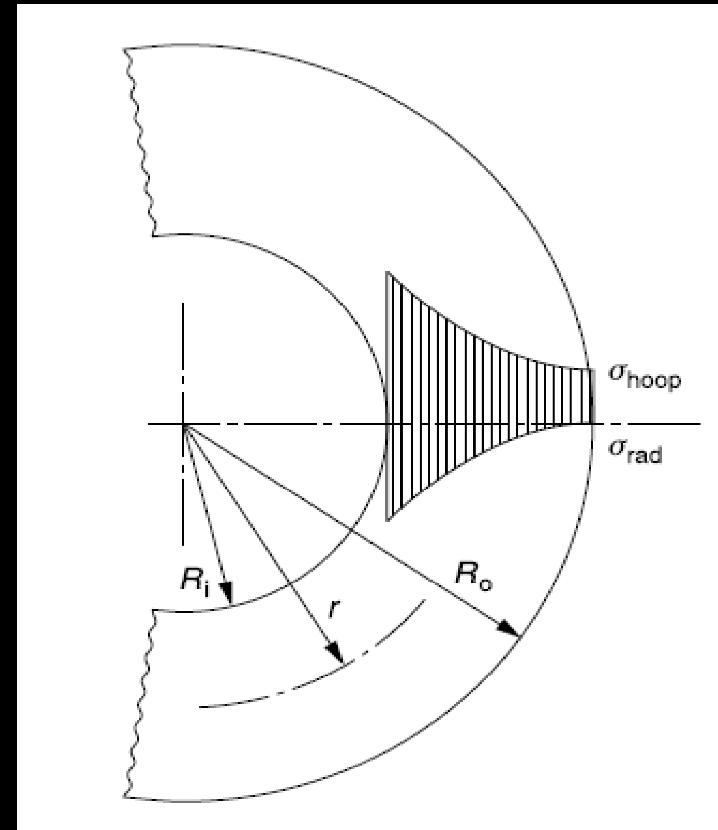


Fig. 2 Hoop and radial stress distribution in cylindrical shell

Factor of safety

- Uncertainties in load, the dimensions, and the material properties.
- 62.5 percent of the yield strength at design temperature
- European pressure vessel construction codes typically employ a factor of safety of 1.5 for the yield strength for a simple environment .

Design requirements

- Operating pressure = 500 MPa
- Capacity = 0.5 litre
- Temperature range : 10 to 100 ^{0}C
- Loading – unloading : Manual
- Indirect compression
- Batch type process

For 10 cm depth of the vessel, inside diameter of the vessel will be 8 cm.

Design of cylindrical shell

- Using ASME codes and Lames equation for calculation of principle stresses.

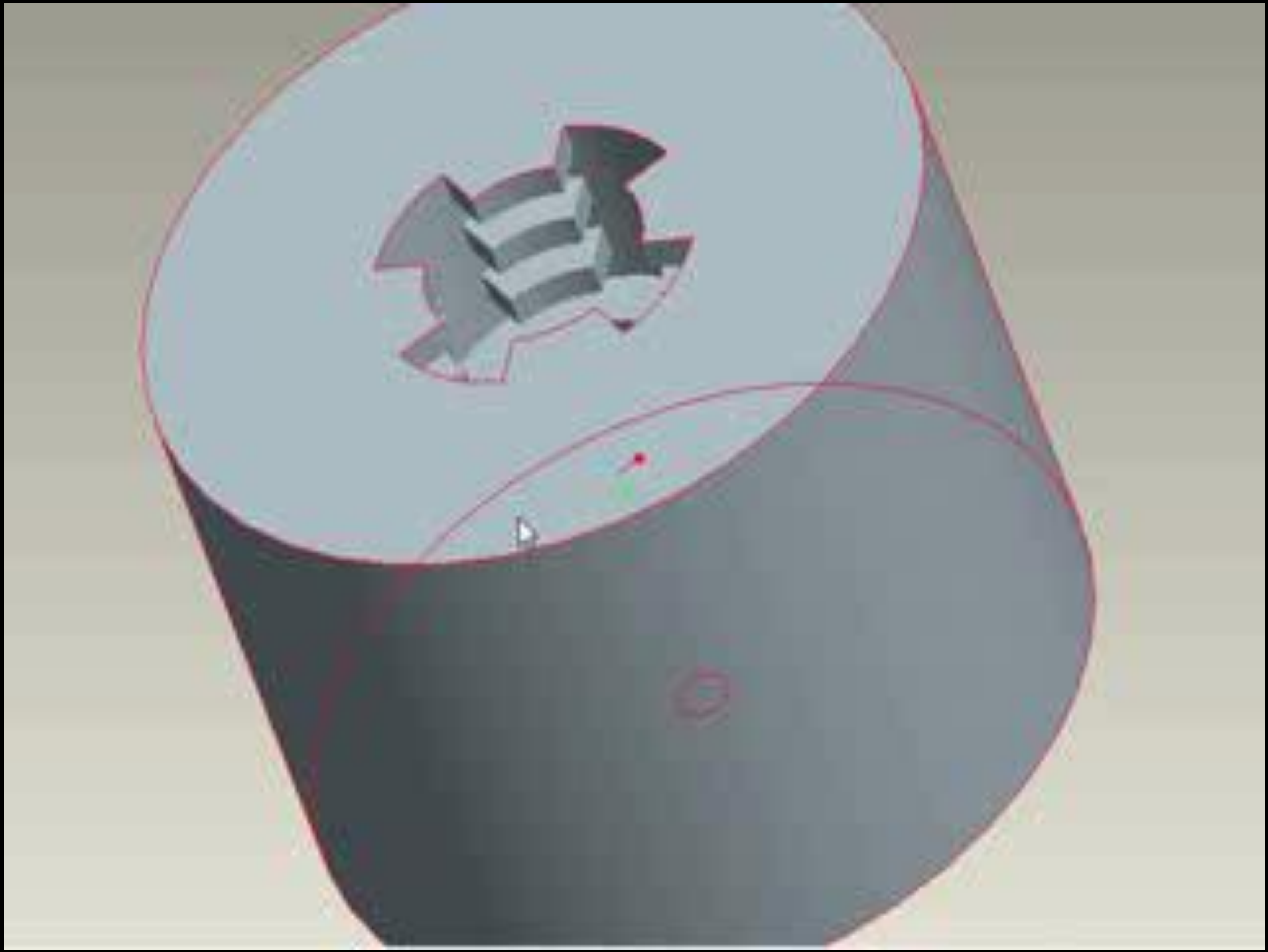
Sr. No.	Thickness (m)	σ_{long} (MPa)	σ_{rad} (MPa)	σ_{hoop} (MPa)	
				at r_i	at r_o
1	0.04 (r_o = 0.08)	166.667	500	833.33	333.33
2	0.06 (r_o = 0.1)	95.2381	500	690.4762	190.4762
3	0.08 (r_o = 0.12)	62.5	500	624.994	124.999
4	0.1 (r_o = 0.14)	44.444	500	588.889	88.889
5	0.11 (r_o = 0.15)	38.2775	500	576.55	76.55

Dimensions of cylindrical shell

Inside diameter (D_i)	0.08 m
Thickness	0.11 m
Outside diameter (D_o)	0.3 m
Depth of shell (l)	0.1 m

Considering factor of safety of 1.5, required minimum yield strength of material to be selected should be 895 MPa

Slotted cylinder arrangement



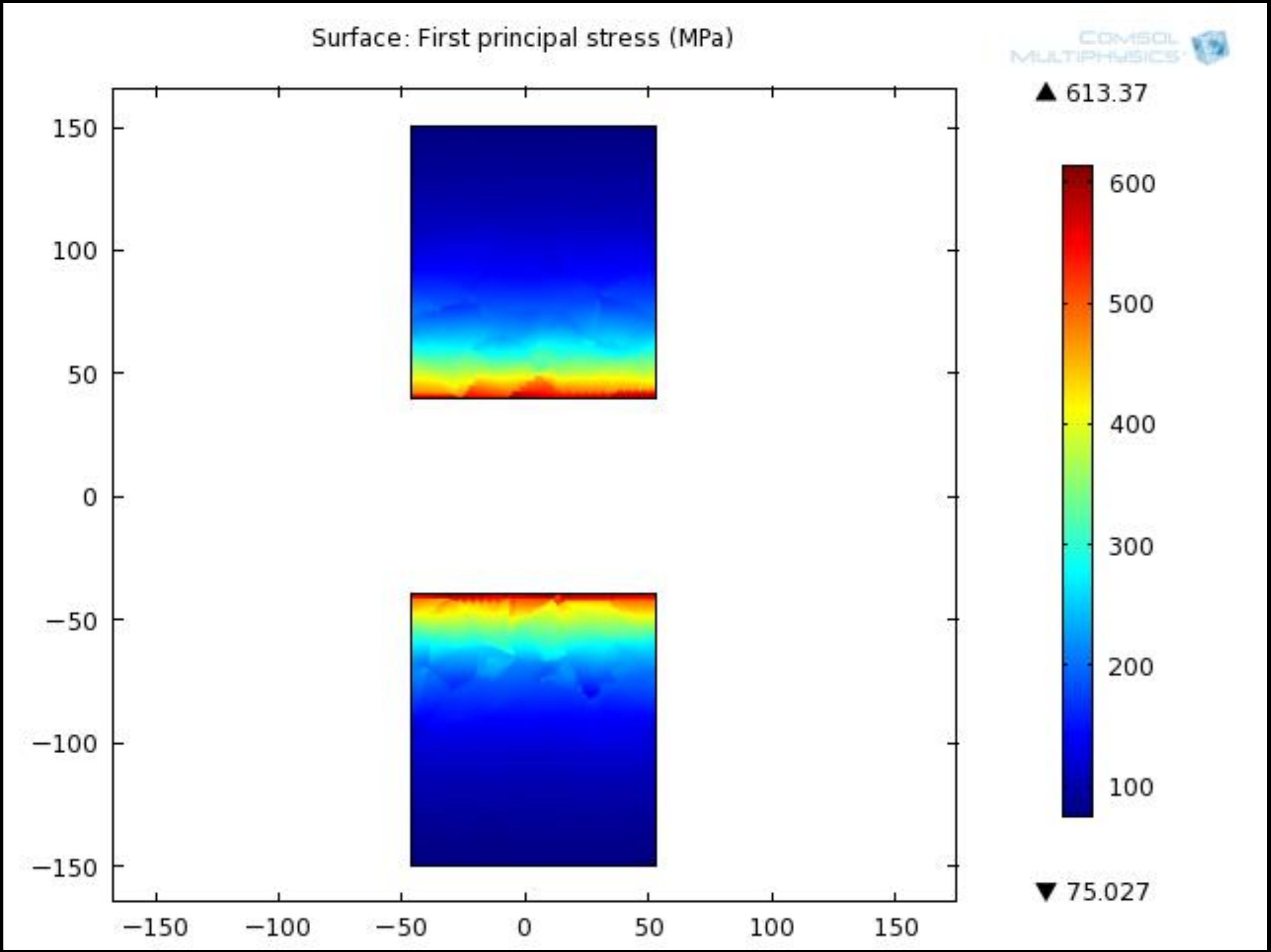
COMSOL multiphysics

- Three dimensional finite-element analysis software which uses solid elements for analysis.
- Import facilities for solid elements
- Different possible failures
- Accurate design assessment

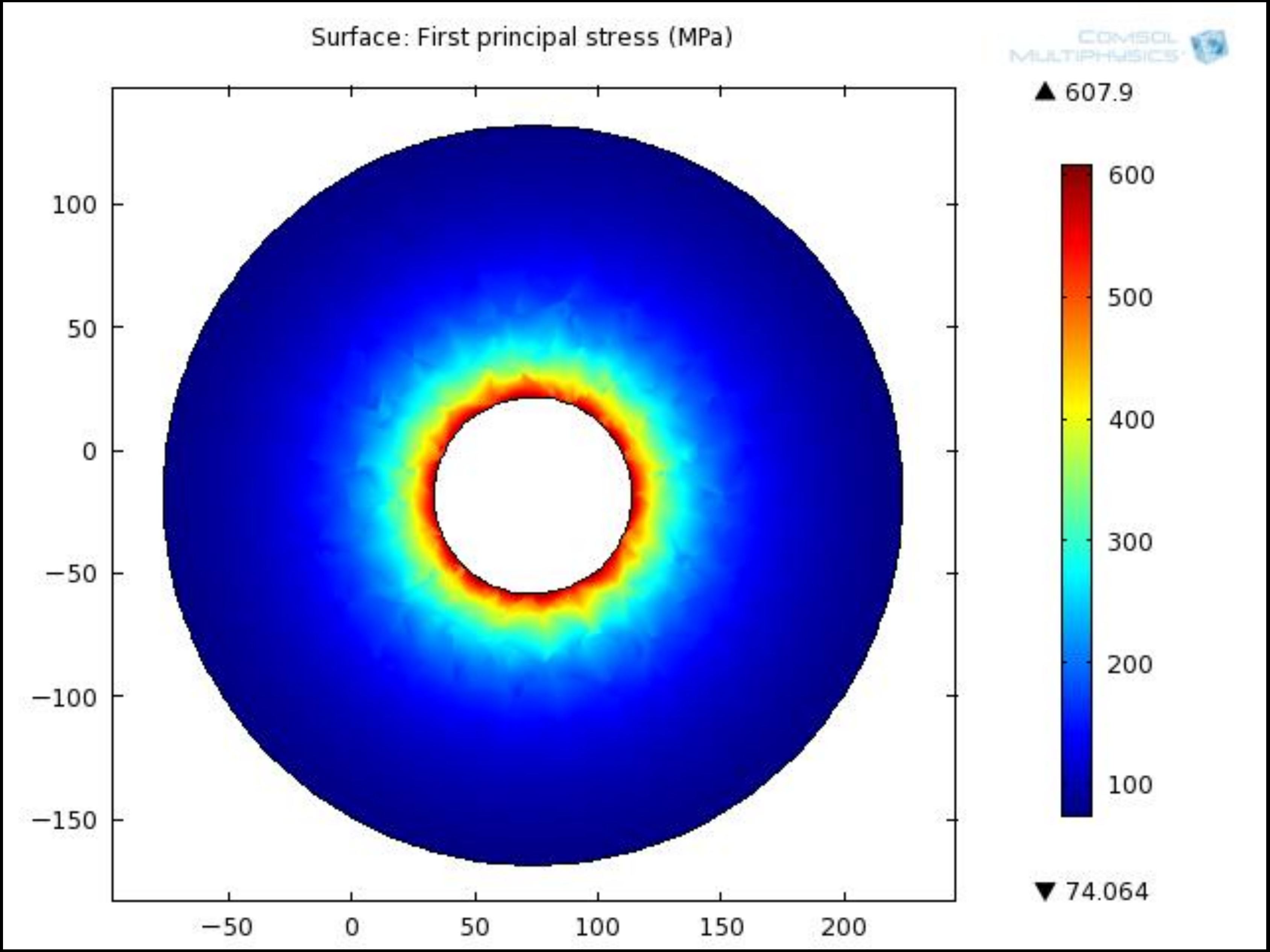
METHODOLOGY

- An FEM analysis of a hollow cylinder, and the pressure vessel used for HPP was performed.
- Surface von Mises stresses were first modelled, after which thermal stresses arising from the cylinder not being free to expand and contrast to changes to temperature were modelled together with the von Mises stress.
- Considering the compressive medium to be a fluid at 70 °C, the changes in the temperature of the vessel with time was modelled.
- A general pressure vessel has an inlet at its bottom surface for the working fluid to enter the chamber.
- The top of the vessel has constrictions for the top cap to enter and lock into the constrictions. 5 constrictions have been placed on the vessel designed in this case..

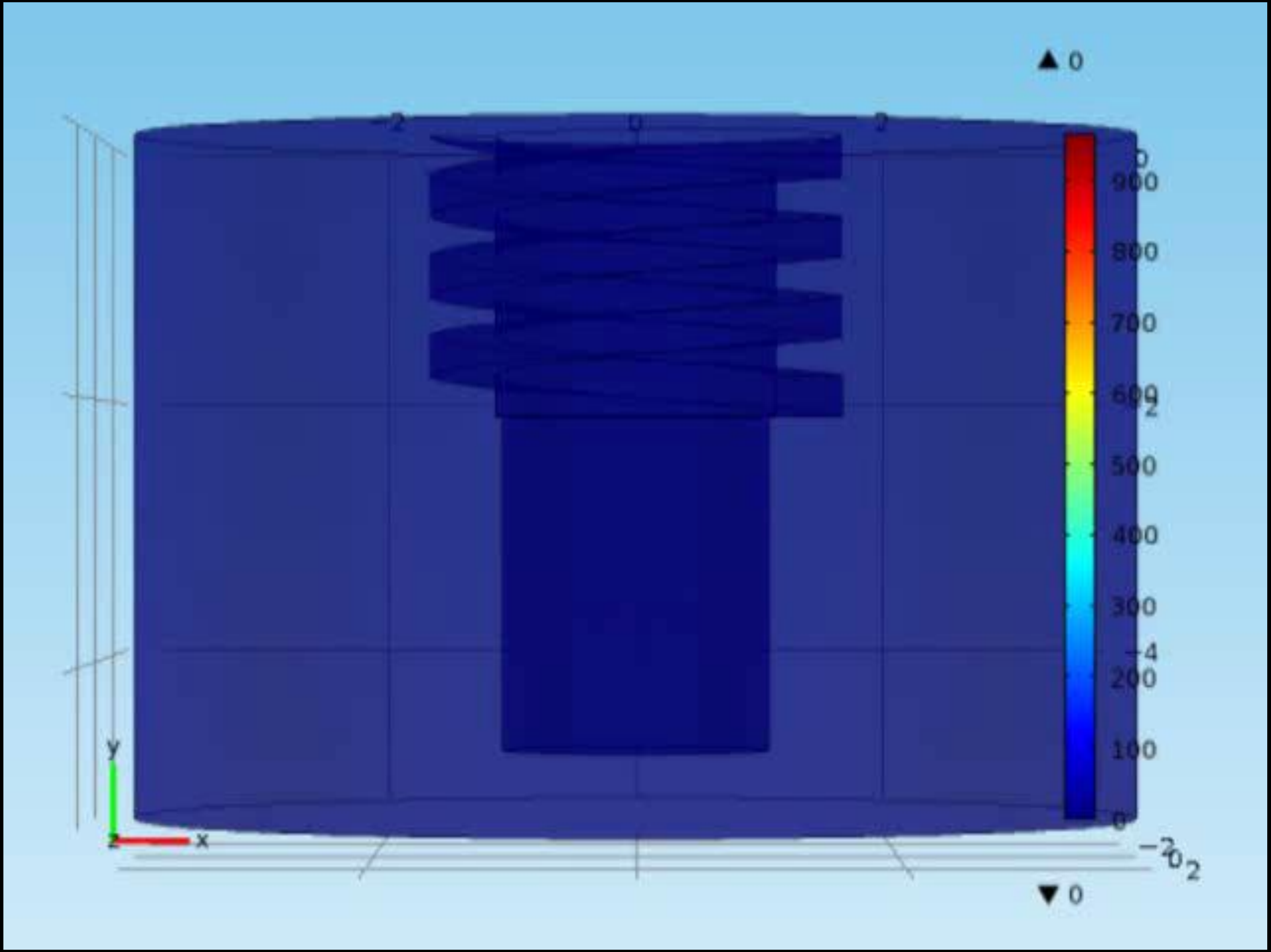
Stress distribution in cylindrical shell

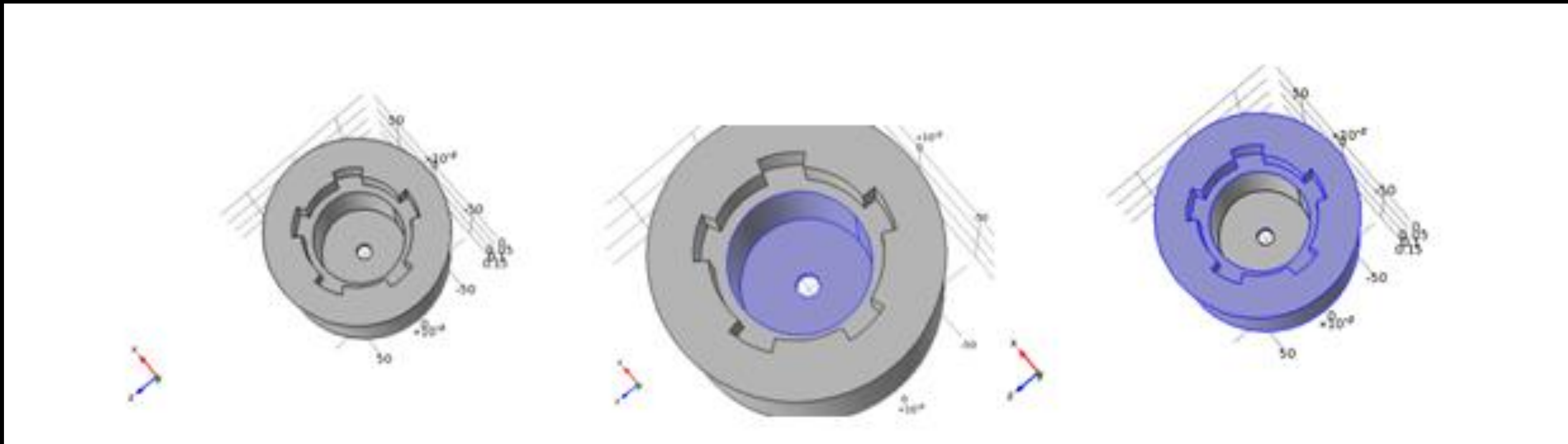


Stress distribution in cylindrical shell

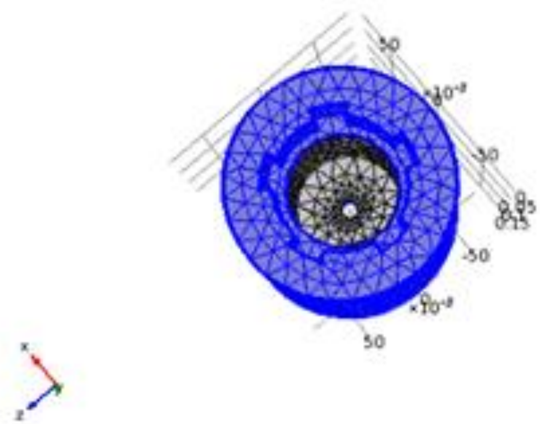


Stress in Screwed cylinder arrangement





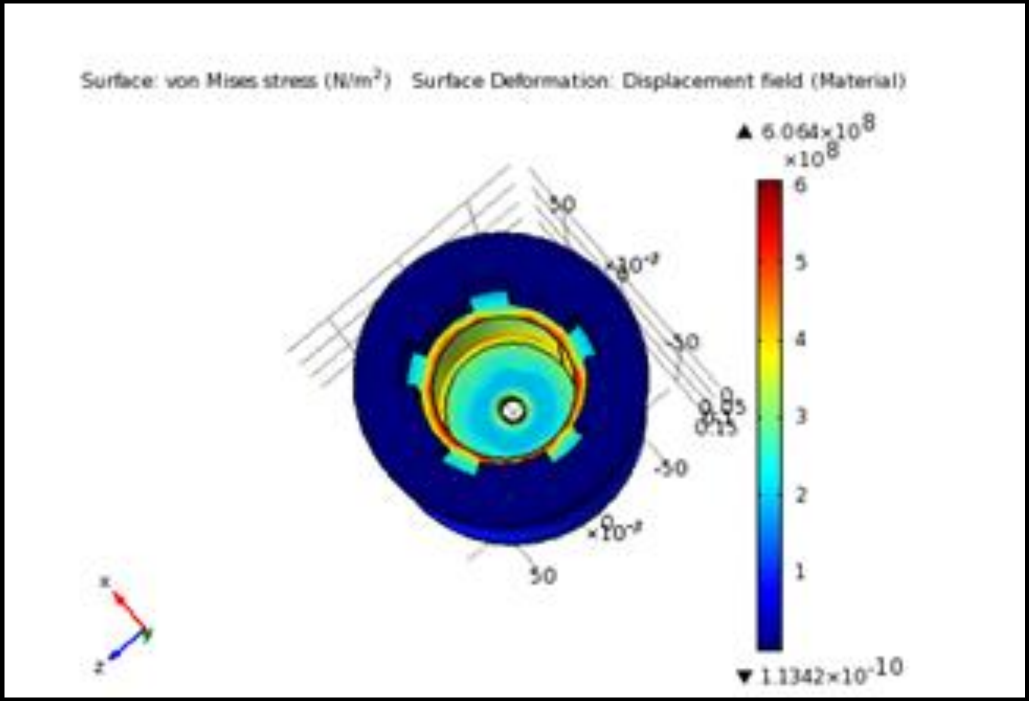
Pressure Vessel (empty) – Geometry, Loading profile and fixed constraints



MESH STATISTICS

Property	Value
Minimum element quality	0.3042
Average element quality	0.8205
Tetrahedral elements	9454
Triangular elements	2052
Edge elements	292
Vertex elements	52

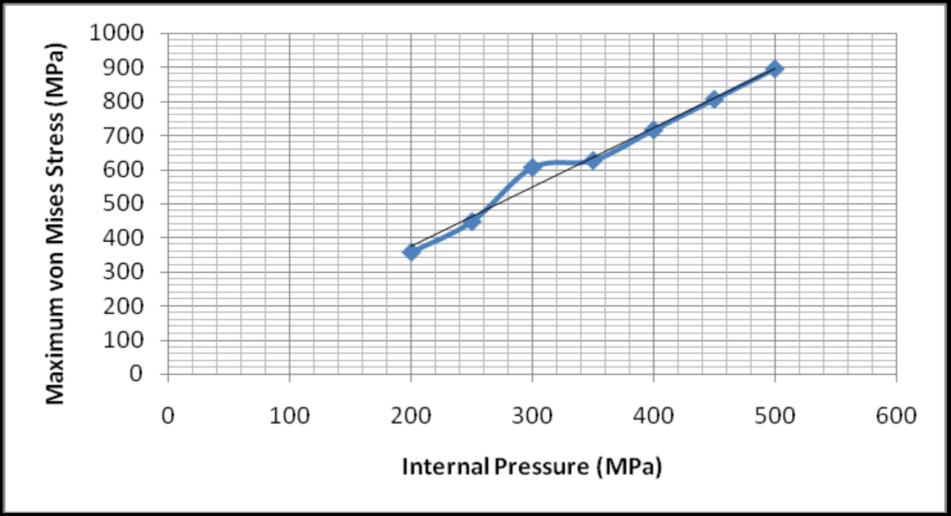
Mesh and Mesh Statistics



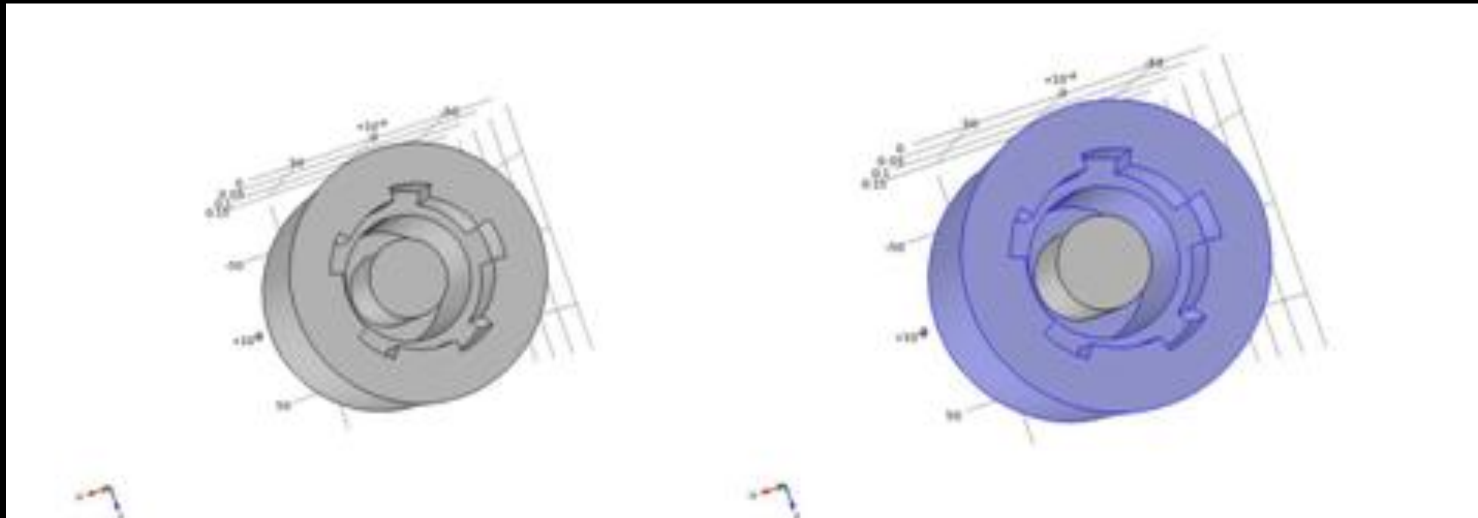
Stress Profile – Empty Pressure Vessel

Internal Pressure (MPa)	Maximum von Mises Stress (MPa)
200	358.21
250	447.77
300	606.4
350	626.9
400	716.47
450	806.03
500	895.61

Empty Pressure Vessel – Pressure vs. Stress plot

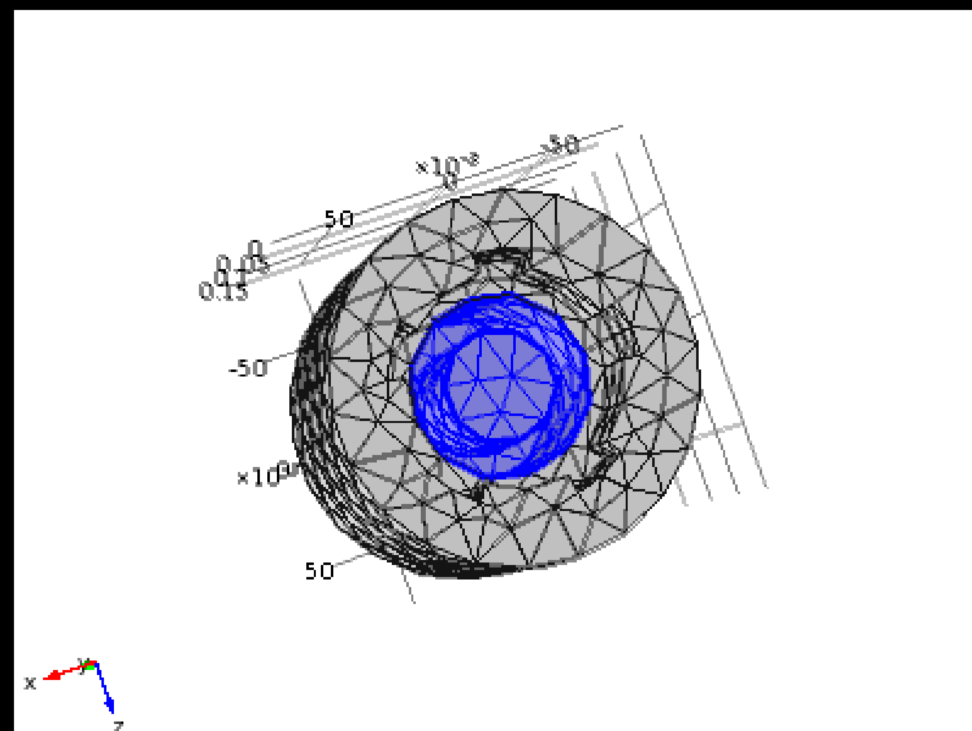


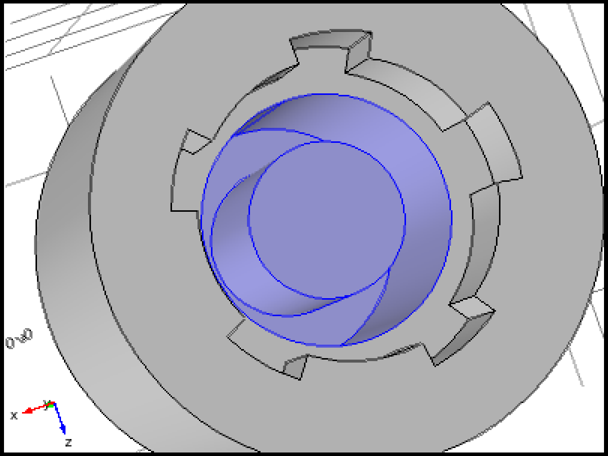
- In the case of empty pressure vessel, the plot between the internally applied pressure and the maximum von Mises stress has been found to be essentially a linear plot. This is in accordance with the theoretical findings of the plot in case of a cylinder under loading.
- The linear increase is attributed to the fact that the amount of expansive force on the surface has been increased leading to an increase in the principal stresses in the walls and consequently, in the magnitude of the von Mises stress.
- The linear increase results from the fact that within elastic range, the relation between pressure applied or stress applied results in a linear variation of the strain produced in the vessel, in accordance to the Young's relationship between stress and strain.



Pressure Vessel with polyethylene core

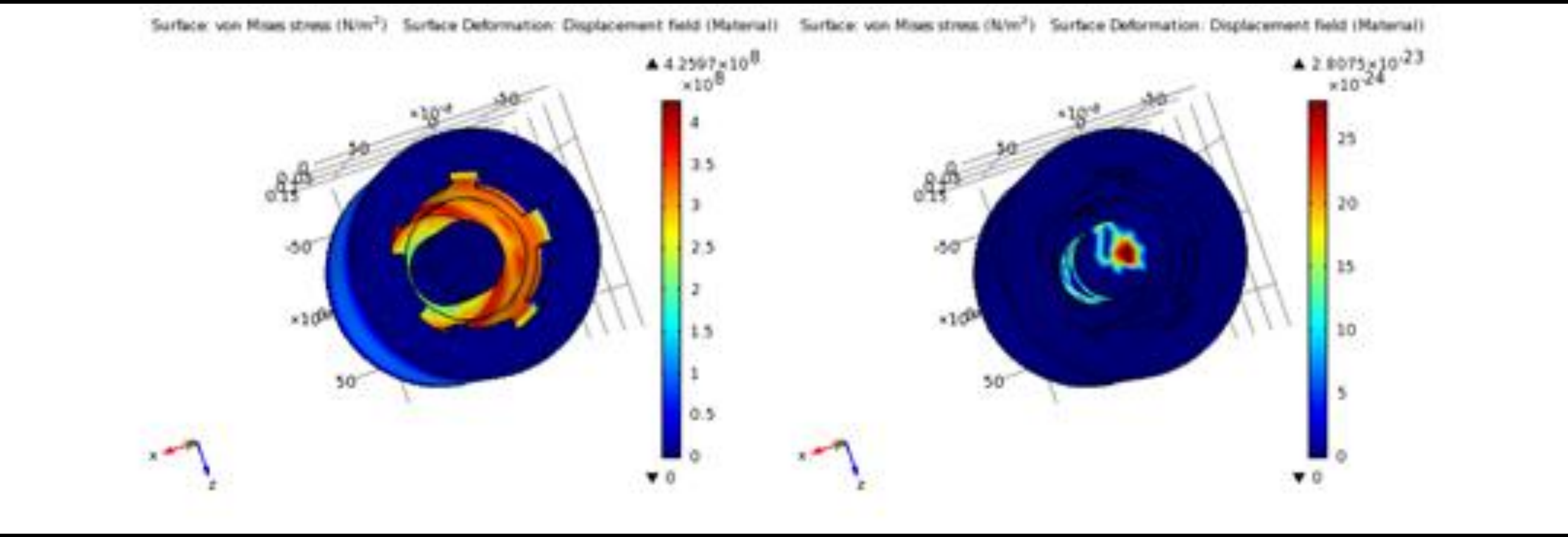
Mesh generated





Pressure Vessel with polyethylene core – Loading Profile

- The loading surfaces in the pressure vessel are the interior surfaces of the vessel and the outer surfaces of the polyethylene element.
- This is because according to Pascal's Law, pressure is transmitted uniformly throughout the element when placed in a fluid medium.
- Hence, the pressure acts uniformly on the surface of the cylindrical element.



Stress Profiles – Surface von Mises and Thermal Stresses

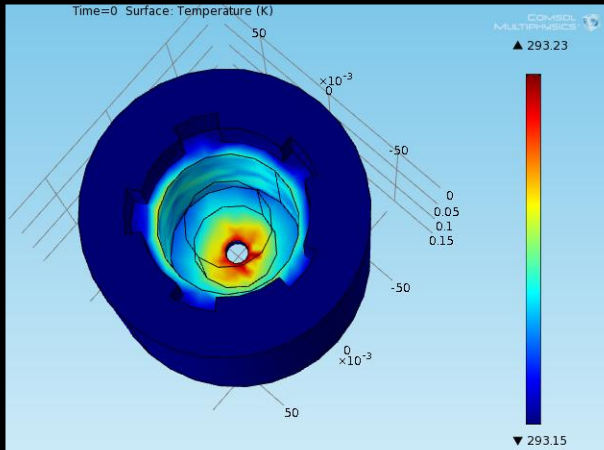
The thermal stresses are constant and do not change with temperature because the temperature difference between the working fluid and the surrounding temperature is the same under all the pressures taken in the above scenario.

Calculation of flux for Temperature – Time plots:

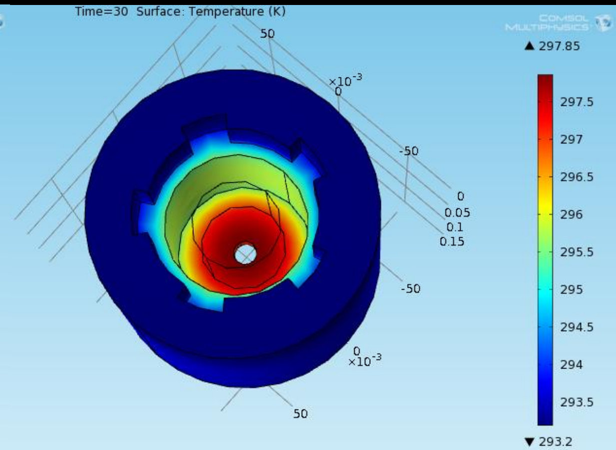
- Mass of water in the vessel = 400 g
- Specific Heat Capacity of water = 4200 J/KgK
- Holding Time = 120 s
- Surface Area of Polyethylene Core = 2prL = 2*p*0.02*0.085 = 0.010053096 m^2

- Flux = (0.4L) x (1 kg/L) x (4200 J/kgK) x (5K)/ [(120 s) x 0.010053096 m^2]

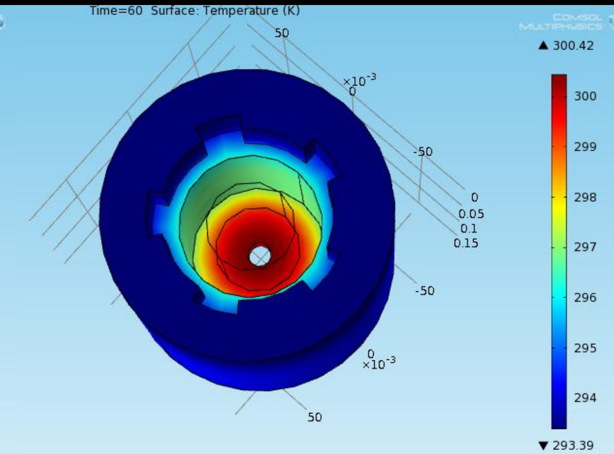
  = 6963.029101 W/m^2



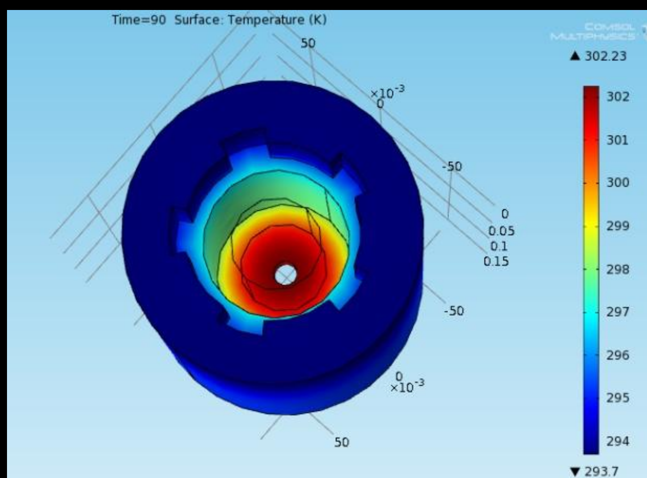
t=0



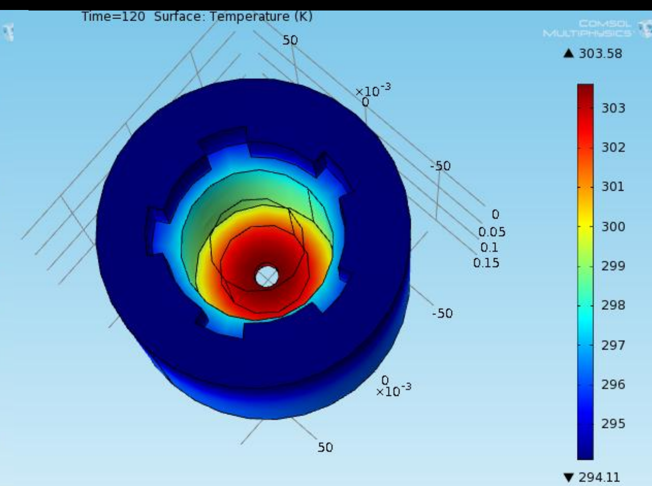
t=30s



t=60s



t=90s



t=120s

- From the temperature – time plots, it is clear that the temperature of the vessel increases with time in the radial sense indicating the movement of a flux front with time, and also from bottom to up because the fluid entering is hotter than the surroundings and the inlet is closer to the bottom.
- Also, the maximum temperature of the vessel at the inlet of the fluid increases with a falling rate as time passes by because the amount of heat absorbed by a hotter body is lesser than when the same body were cooler.
- The system is assumed to be insulated from the outside sufficiently to reduce the amount of heat dissipated. This helps in the temperature of the fluid falling back to its original inlet temperature after the processing of the material and the decompression of the system.

Conclusions

- If the system was perfectly insulated, the outlet and inlet temperatures of the working fluid would be similar. However, such a system is purely theoretical, and insulation of such high standards is not practically possible.
- The variation of the temperature of the vessel with time has been in accordance with its theoretical findings.
- Temperature of the vessel rose quickly at lower temperatures and the rate of increase started to fall with time. Also, temperature of the vessel increased radially outward with a falling rate against time.
- COMSOL was found to be very useful tool for stress analysis in such high cost equipment design.

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THANK YOU