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# Design of vacuum impregnation chamber for soaking of *Gulabjamun* in sugar syrup and optimization of wall thickness by Finite Element Analysis (FEA)

Maheshkumar G.[1] , Menon Rekha Ravindra[2]

[1]Asst Professor of Dairy Engineering, Dairy Science College, Hebbal, Bengaluru, India
[2]Senior Scientist, SRS-NDRI Bengaluru, India

***Abstract***— *The application of vacuum impregnation technique for soaking of Gulabjamoon in sugar solution was conceptualized and the equipment was designed and developed. Vacuum impregnation unit (VIU) was operated under vacuum and hence the design of its wall thickness was of critical consideration. VIU facilitated rapid soaking of Gulabjamun in sugar syrup under full vacuum in cyclic process. VIU is cylindrical in geometry, designed to work at 65-80 ºC at 5 kPa pressure (vacuum) on the inside and was exposed to atmospheric pressure on the outside. This leads to compressive forces acting on inside of the cylinder wall. The shell thickness will have direct bearing on stresses developed. There will be implosion (due to compressive forces) of VIU when Von Mises stress generated is more than yield stress of stainless steel (205 MPa). Wall thickness of cylinder of VIU was optimized by Finite Element Analysis (FEA) by modeling and simulation using Pro/ENGINNER. ANSYS-14 was used for analysis of Von Mises stress, deformation and factor of safety. The wall thickness of shell was analyzed by hyper tetrahedron meshing. To validate, design software developed by ASME was used for shell thickness determination. The model prediction was shown to be in good agreement with the analytical calculation. The FEA resulted in Von Mises Stress of 135.79 Mpa, deformation of 1.55 mm and factor of safety of 1.5. VIU was fabricated as per FDA C-GMP standards from 4.00 mm thick AISI-316 SS material. The working drawings were developed and actual fabrication was carried out adopting the prescribed sanitary standards. The unit was subjected to various safety tests and it successfully passed out all of them. Satisfactory production of Gulabjamoon was carried out in the newly designed and developed equipment resulting in a product of excellent quality confirming validity of the design.*

***Keywords—Vacuum impregnation unit (VIU), ANSYS, PRO/ENGINEER.***

## I. INTRODUCTION

Vacuum impregnation is a new process to be adopted in dairy industry for faster impregnation of sugar syrup into *Gulabjamun* under pulsed full vacuum condition. VIU was to be fabricated as per FDA C-GMP standards from AISI-316 SS. It is cylindrical in geometry designed to work at 65 ºC to 80 ºC and 5kPa pressure (vacuum).

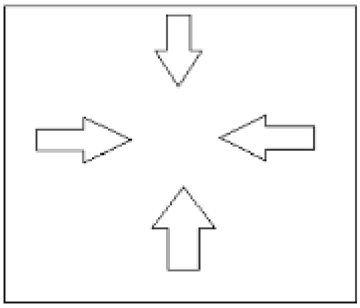

*Fig.1: Forces acting inside vacuum impregnation unit (Buckling*

VIU is exposed to atmospheric pressure on the outside which leads to compressive forces acting on the inside of the vessel that results in buckling when wall thickness is lower than the critical value (Fig 1). The mechanical strength of the VIU as determined by its thickness of the metal sheet (wall thickness) used in its fabrication is the critical design parameter. There will be implosion due to compressive forces when stress developed is more than yield stress of SS-316, the material used for fabrication of VIU. The following design steps elaborate the procedures adopted for FEA and optimization of shell thickness of VIU.

## II. MATERIALS AND METHODS

VIU is a cylindrical vessel with hemi spherical cover on bottom side and flat circular plate on top side. These covers are joined to the cylindrical chamber by welding. VIU was designed to work in full vacuum of 5kPa and the

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outside operating pressure being 101kPa (NTP). Following design data (Hauviller1993). viz., composition of material, mechanical properties, dimensional drawing, boundary conditions required for FEA for stress analysis are shown in Table 1 & 2 . Though AISI 316 was used for the VIU in this study, for comparison AISI 304 SS is also given in these Tables. The size of the unit was designed based on capacity of processing and the major dimensions are shown in Fig 2 which also describes the other constructional features of VIU.

*Table.1: Composition of stainless steel*

| ***Element*** | ***Unit*** | ***AISI-304 SS*** | ***AISI-316 SS*** |
|---|---|---|---|
| ***Carbon*** | *% max* | *0.08* | *0.08* |
| ***Manganese*** | *% max* | *2.00* | *2.00* |
| ***Phosphorus*** | *% max* | *0.045* | *0.045* |
| ***Sulphur*** | *% max* | *0.030* | *0.030* |
| ***Silicon*** | *% max* | *1.00* | *1.00* |
| ***Chromium*** | *% max* | *18-20* | *18-20* |
| ***Nickel*** | *% max* | *8-10.5* | *10-14* |
| ***Molybdenum*** | *% max* | *-* | *2-3* |
| ***Source:*** *www.sail.co.in* | | | |

Stainless Steel AISI 316 is the preferred metal for food processing equipment that comes in direct contact with the food providing an excellent corrosion resistance due to its alloying components of high nickel and molybdenum (Table 1). Important mechanical properties of AISI 316 are summarized in Table 2

*Table.2: Mechanical Properties of AISI-316 SS*

| | **Properties** | **Stainless steel grade** | | |
|---|---|---|---|---|
| A | Mechanical properties | Unit | AISI-304 | AISI-316 |
| | Ultimate tensile strength (UTS) | Mpa | 515 | 515 |
| | Yield stress | Mpa | 205 | 205 |
| | Young Modulus of elasticity | Mpa | $1.93x10^5$ | $1.93x10^5$ |
| | Density | $Kg/m^3$ | 8006 | 8006 |
| | Poisson ratio | - | 0.27-0.30 | 0.27-0.3 |
| | Hardness | $HR_B$ | 92 | 95 |
| **B** | **Thermal properties** | | | |
| | Coefficient thermal expansion | $10^{-6}/^{\circ}C$ | 19.8 | 19.8 |
| | Specific Heat | j/kg K | 500 | 500 |
| | Thermal conductivity | w/mK | 16.2 | 16.2 |
| | **Source:** www.sail.co.in | | | |

The design boundary conditions required for stress analysis by FEA are given in the Table 3. The size of the VIU, diameter and height, were arrived at based on the desired processing capacity as given in the following Table 3. The normal physical conditions required during syrup impregnation are also shown in the Table 2 . A wall thickness of 4.0 mm was considered based on the design equation of ASME, 2011. The operating vacuum inside the cylinder was assumed to be at 5000 Pa fand for the analysis. The inside temperature was assumed to be at 80C and the Table 2 describes all other parameters.

*Table.3: Design Data and boundary conditions*

| **Description** | **Unit** | **Value** |
|---|---|---|
| Material of construction | SS | AISI-316 SS |
| Inner diameter of chamber | mm | 400 |
| Length of vacuum changer | mm | 750 |

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| | | |
|---|---|---|
| Wall thickness | mm | 4 |
| Operating pressure ( inside) | kPa | 5 |
| Operating pressure ( outside) | kPa | 101.325 |
| Operating Temperature inside | º C | 80 |
| Operating Temperature outside | º C | 25-30 |
| Fixed support | VIU was permanently mounted on SS frame. | |

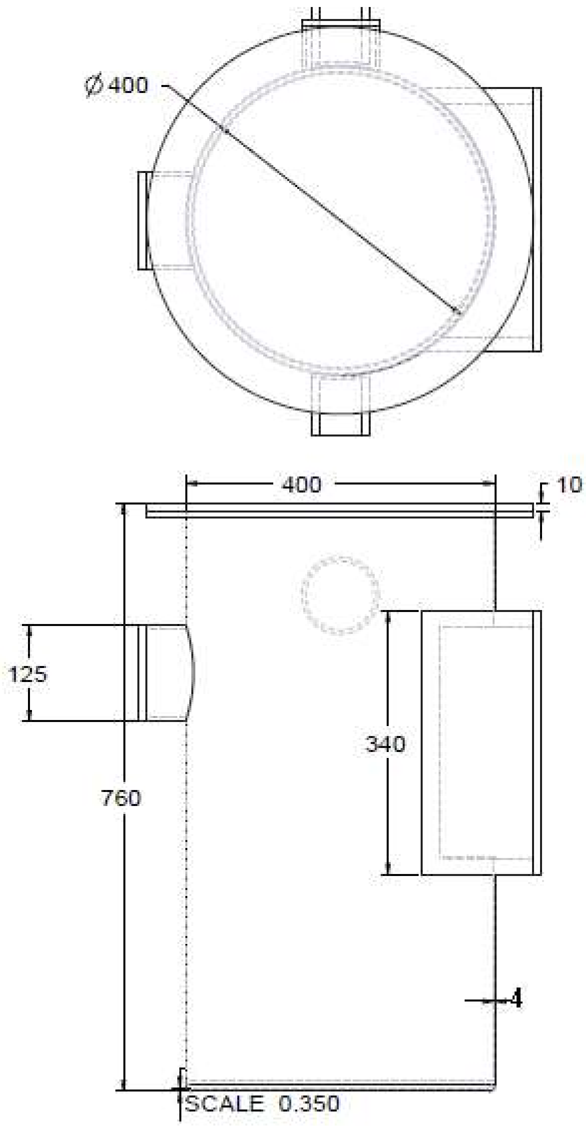


*Fig.2: Dimensional drawing of Vacuum imprenation unit (all dimension are in mm)*

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**2.1 3-D Model Generations**

The 3-D model of the VIU **was** developed using Pro/ENGINEER software (Tickoo & maini , 2009) The stress (FEA) analysis using ANSYS-14.( ANSYS, 2007) The 3-D modeling procedure ,cycle and steps are explained in Fig. 2 and 3.

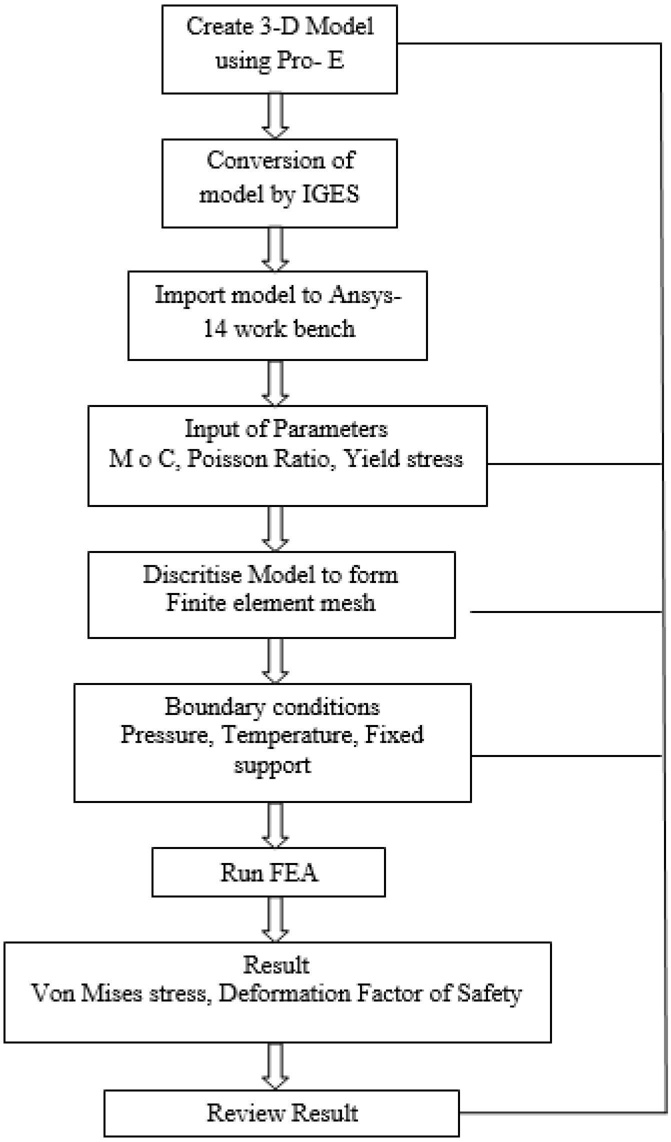


*Fig. 3: Stress analysis cycle*

**2.2 Thermal stress analysis cycle (FEA)**

In order to optimize the wall thickness of VIU, the stress analysis was performed using design software (PRO-ENGINEER and ANSYS-14) by following the procedures as detailed by Kraan *et al.,* 2004; Gajjar *et al.,* 2011; Chand *et al.,* 2012.; Abdhul 2013. The stress analysis cycle is shown in Fig 3.

**2.3. 3-D modeling for Stress analysis (FEA)**

The 3-D modeling of the VIU **was** performed using Pro/ENGINEER soft ware. The assembly 3-D model of equipment was saved in IGES-(Initial Graphics Exchange Specification) format to import to ANSYS-14 workbench for stress analysis. The operating parameters, material properties and boundary conditions were fed to Anysys-14 work bend for stress analysis. The stress (FEA) analysis procedure and steps are explained in Table 4

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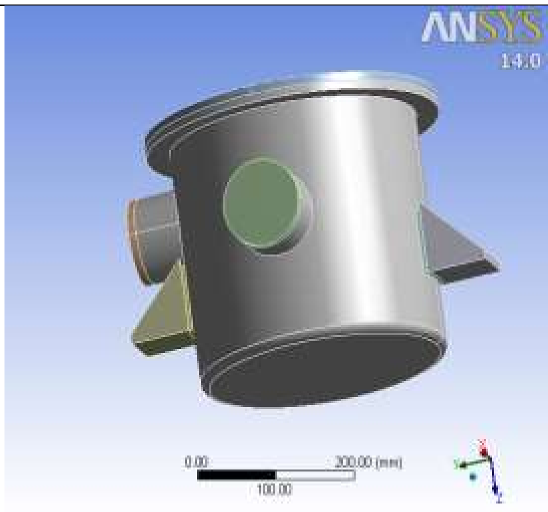
*Table.4: Modeling and Finite Element analysis using Pro-E and ANSYS-14*

**i. 3-D model Generation using –PRO-E**

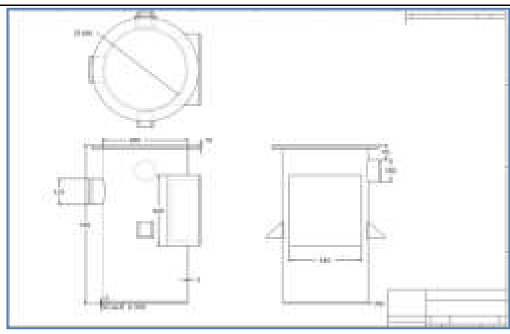
The 3-D modeling of the Vacuum impregnation unit was done in Pro/ENGINEER soft ware. The assembly 3-D model of equipment was saved in IGES-(Initial Graphics Exchange Specification) format to import to Ansys-14 workbench for stress analysis.

| | |
|---|---|
| Moc | - AISI-316 SS |
| Diameter | - 400 mm |
| Length | - 750 mm |
| Wall thickness | - 4 mm |



3-D Model of VIU

**ii. Dimensional Drawing of Equipment**


Dimensions of VIU in mm

**iii Defining FEA model**

Model was defined by feeding

a. Mechanical properties of AISI-316 Stainless steel
b. Wall thickness 4 mm

**stainless steel > Constants**

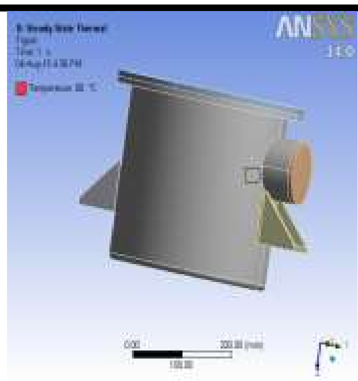
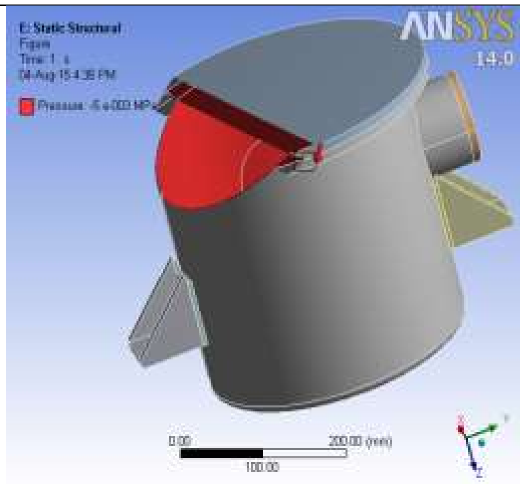
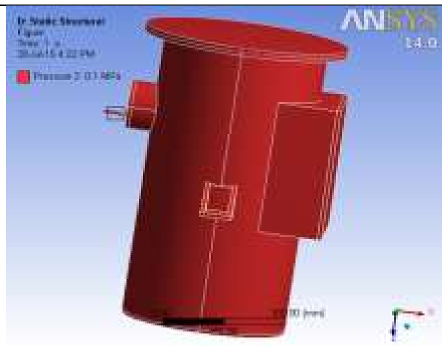
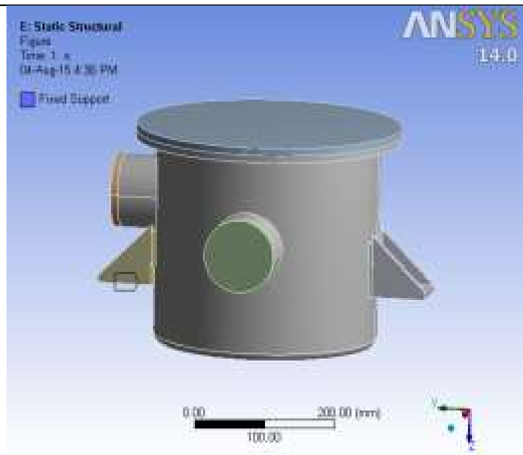
| | |
|---|---|
| Density | 8.e-006 kg mm^-3 |
| Thermal Conductivity | 1.62e-002 W mm^-1 C^-1 |

**stainless steel > Isotropic Elasticity**

| Temperature C | Young's Modulus MPa | Poisson's Ratio | Bulk Modulus MPa | Shear Modulus MPa |
|---|---|---|---|---|
| | 1.93e+005 | 0.28 | 1.4621e+005 | 75391 |

**stainless steel > Tensile Yield Strength**

| Tensile Yield Strength MPa |
|---|
| 205 |

| | |
|---|---|
| **iv. Defining Boundary conditions**<br><br>Inside temperature 80°C<br>Outside temperature 30°C | <br><br>Inside tempararue 80C |
| Inside – Pressure (full vacuum) 5 | <br><br>Inside operating pressure 5kpa |
| Outside – Pressure 101kPa (NTP) | <br><br>Outside pressure NTP |
| Fixed support -<br>by Pedestal to skid of equipment | <br><br>Model was mounted SS Skid by bolting |

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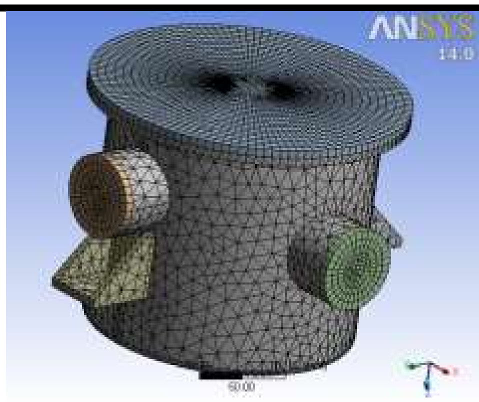
| | |
|---|---|
| **v. Mesh Generation**<br>Meshing was done using tetrahedron mesh. In this tetrahedron meshing method the component was divided into small triangles which give number of nodes and elements of the component to be analyzed. The meshing was done by varying mesh sixe from 20,18,16,14, and 12mm. Due to change in density of the meshing it resulted in variation of number of nodes and element of meshed component<br>Type: Hexahedron mesh<br>Element size -12 mm<br>No. of nodes - 81157<br>No. of Elements -30513 | <br>Tetrahedron Hyper meshing |
| **vi. Run Finite Element Analysis to determine** | a. Von Mises stress – Kpa<br>b. Deformation- mm<br>c. Factor of safety |
| **vii. Review Results** | Compare with yield stress of Stainless steel (205MPa) |
| **viii. Rerun stress analysis**, if yield stress of material is less then Von-Mises steel | Changes the wall thickness and meshing |

**2.4. Validation of Shell thickness**

To validate wall thickness determined by ANSYS-14, shell thickness of VIU was calculated by ASME design equation 1 (ASME 2011). ASME approved design soft ware performed the design procedures and calculations.

The shell thickness calculation was to determine the wall thickness of the cylinder under vacuum without holes, nozzles etc. This calculation does not take into account the extra stress around holes for nozzles and is therefore a basic strength calculation. Calculation codes are as per ASME (ASME 2010) norms.

Wall thickness is calculated by using

$$t=\frac{P*R}{2SE-0.6P} \qquad \text{Eq. 1}$$

where,

t is the cylinder wall thickness in corroded condition (m),

P is the design pressure (MPa),

R is the cylinder inside radius in corroded conditioning (m),

S is the maximum allowable stress at design temperature (MPa) and

E is the joint efficiency in fraction.

**3.4.1 Procedure to run software programme for calculation of shell thickness (ASME 2011)**

The calculation also requires the user to enter dimensions of model, pressure, operating temperature, yield stress value and density of stainless steel etc. using data (Table 1-3 and Fig 2)

*Table.5: Data input for thickness calculation*

| | | | |
|---|---|---|---|
| Type of shell | | Cylinder ▾ | |
| Design pressure | P | 0.2 | $N/mm^2$ ( = 1 MPa = 10 Bar ) |
| Design temperature | T | 80 | $^0C$ |
| Material description | - | AISI-316 | |
| Select yield stress and specific gravity from material database | | | |
| Yield stress, design temp. | S | 205 | $N/mm^2$ |
| Specific gravity | ρ | 8006 | $kg/m^3$ |
| Outside diameter | $D_o$ | 408 | mm |
| Length tangent to tangent | L | 750 | mm (If not a sphere) |
| Nominal wall thickness | t | 4 | mm |
| Corrosion allowance | Ca | 1 | mm |
| Tolerance | tol | 1.03 | mm |
| Joint efficiency | E | 0.25 | - |
| Semi angle at apex cone | α | 0 | degree (For cone only) |
| Design Code | - | ASME ▾ | (ASME, Dutch R., PED) |
| | | Calculate | |

## III. RESULTS AND DISCUSSION

Results of the FEA analysis for the optimization of wall thickness of VIU are shown in Fig 4. The results of the stress analysis are presented in terms of Von Mises (equivalent) stress and, deformation and factor of safety below (Figs. 4-6).

### 3.1 Stress analysis of the Vacuum impregnation unit

The general view of the stress analysis is given in Fig. 4. It depicts a magnified picture of the highest and lowest peak stress regions. The red circle and two yellow color circles at the bottom show the regions where the highest (peak) compressive stresses are generated which are much less than yield stress of SS-316 (Fig 4 & 5). The peak stresses were seen only at bottom of the chamber (red & yellow color).

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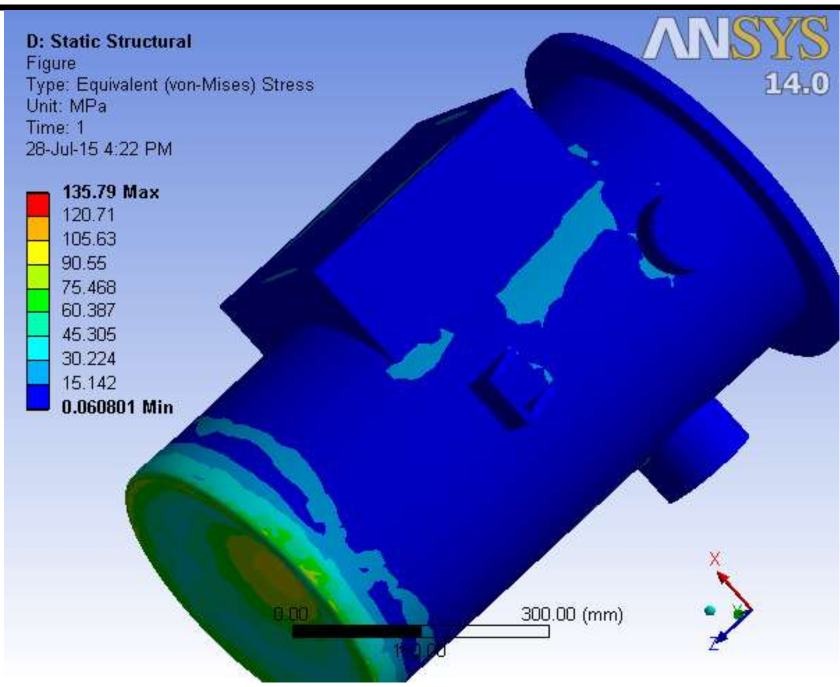


*Fig.4: Max Van Mises Stress is 135.79 MPa*

**3.2 Deformations from the stress analysis**

To complete the analysis, deformation generated from the stress analysis is presented in Fig. 5. The maximum total displacement was found to be 1.55 mm, noticed at the bottom of VIU.

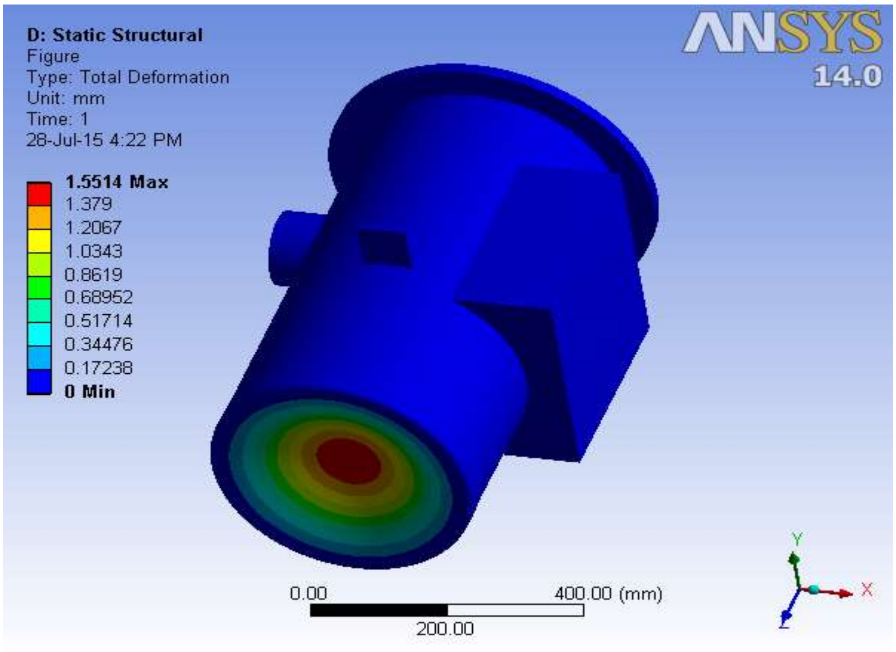


*Fig.5: View of the total max. Deformation (1.55mm)*

**3.3 Factor of Safety**

It is evident from the result of stress analysis (Fig 6) the minimum factor of safety obtained was 1.51 which is indicated in yellow color at the bottom of chamber. The highest factor of safety value (15) is shown in blue color. The vessel had experienced maximum stress at its bottom only.

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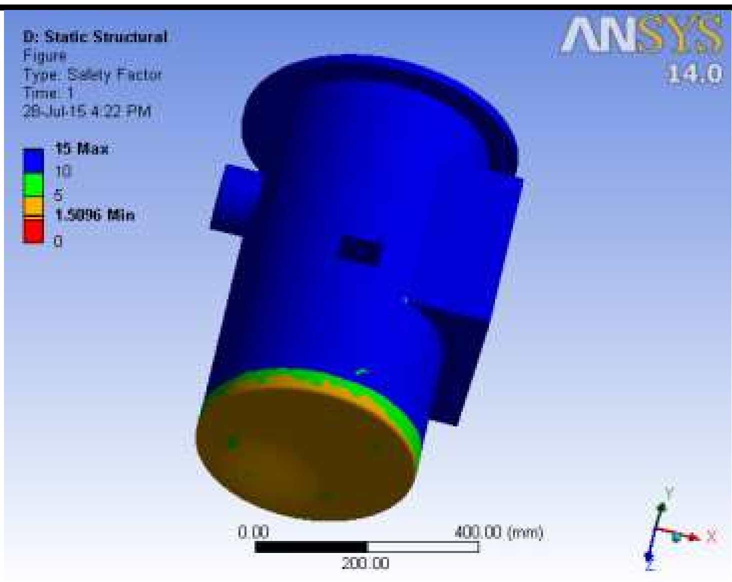


Fig 6 Min Factor of safety is 1.5

Further, to validate the FEA results, wall thickness of VIU was determined by using ASME approved design software program as described below.

**3.4 Determination of shell wall thickness by using ASME approved design equation software**.

Calculations were performed to support the design and structural analysis by FEA.To validate wall thickness of the shell, design data were fed to ASME design equation based soft ware. The results of thickness analysis results shown Table 5. The wall thickness obtained from the ASME calculation was 2.82 mm.

*Table.5: Result of Analysis of shell thickness*

**Wall thickness calculation of Cylinder**
according ASME

| | | | |
|---|---|---|---|
| Allowable stress | S = | 205 = | 205.00 $N/mm^2$ |
| Corroded thickness | $t_c = t - Ca - tol =$ | 4 - 1 - 1.03 = | 1.97 mm |
| **Cylinder:** | | | |
| Corroded inside radius | $R = \frac{D_o}{2} - t_c =$ | $\frac{408}{2} - 1.97 =$ | 202.03 mm |
| Required wall thickness | $t_r = \frac{P * R}{S*E - 0.6*P} =$ | $\frac{0.2 * 202.03}{205*0.25 - 0.6*0.2} =$ | 0.79 mm |
| Nominal required thickness | $t_m = t_r + Ca + tol =$ | 0.790 + 1 + 1.03 = | 2.82 mm |
| Max. Allowable Working Press. | $MAWP = \frac{S * E * t_c}{R + 0.6 * t_c} =$ | $\frac{205 * 0.25 * 1.97}{202.03 + 0.6 * 1.97} =$ | 0.50 $N/mm^2$ |
| Thickness analysis, t > $t_m$ ? | t = 4 mm is OK | | |
| Weight | | | 30.48 kg |
| Enclosed volume | | | 0.094 $m^3$ |

Above calculation does not take into account the extra stress around holes for nozzles. VIU consists of loading door, sight glass, flanges etc. They create abrupt changes in cross section and lead to stress concentration and reduce the strength of material. To overcome this 4 mm wall thickness was considered for fabrication.

**Discussion**

The Von Mises criterion states that failure occurs when the energy of distortion reaches yield stress (implosion in vacuum vessels). The maximum Von Mises stress obtained from stress analysis was 135.79 Mpa (Table 5), which was highest stress generated at the bottom of vacuum chamber (red color). The VIU was fabricated using 4.0 mm thick AISI-316 SS material. The peak stresses in the model was 135.79 MPa which was much below the yield strength (205 MPa) for SS-316. The Stresses generated due to high vacuum (5 kPa) are within the acceptable limits. The maximum deformation 1.55 mm which was generated at the bottom as indicated in red color circle which is very small (Fig. 4.2). Factor of safety obtained was 1.51 (Fig 4.3). It implies that the vacuum vessel can with stand compressive load up to 205 MPa. The analysis clearly showed that the stress were generated only at the bottom. The structural strength could be greatly increased by providing cross flat stiffeners. Inclusion of stiffeners would further reduce Van Mises stresses by limiting the deformation and increasing factor of safety.

The results of this analysis and simulation confirmed the correctness of the procedures and also in confirmation with ASME design procedures.

The working drawings of VIU were developed and actual fabrication was carried out adopting the prescribed sanitary standards. The unit was subjected to various safety tests and it successfully passed out all of them. Satisfactory production of *Gulabjamoon* was carried out in the newly designed and developed equipment resulting in a product of excellent quality confirming validity of the successful design.

## IV. SUMMARY AND CONCLUSION

- Designed and fabricated t a VIU from 4 mm thick AISI-316 to operate at 80° C under 5kPa Vacuum based on FEA, simulation and ASME procedures.
- The VIU unit was safe from implosion as the generated stress (135MPa) was lesser than yield stess of AISI-316 SS (205MPa).
- The shell wall thickness of 4 mm assured a safe design considering Von Mises creterian.
- Maximum Van misess stess was concetrated only at the bottom of the VIU.
- Von Moises stresses developed at the critical section of the VIU could be reduced by providing a reinforcement in the form of a stiffener made of SS flat at the bottom of the vessel by staggered welding. It is suggested a stiffener made of 25x6 mm flat would suffice to enhance the strength of the unit and explore an opportunity to use a 3 mm thick material instead of 4.0 mm thick which would greatly reduce material cost.

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