Finite Element-Based Transient Stress and Vibration Analysis of Mixing Chambers

Satish Endole[1], Nitin A. Kharche[2], Santosh R. Shekokar[3], Yugesh A. Kharche[4], Sachin Chaudhari[5], Sachin Bhole[6]

[1]*P.G. student, Department of Mechanical Engineering, Padm. Dr. V. B. Kolte College of Engineering, Malkapur, Maharashtra, India*

[2,3,4,5,6]*Department of Mechanical Engineering, Padm. Dr. V. B. Kolte College of Engineering, Malkapur, Maharashtra, India*

Abstract

Pressure vessels, integral components in industries such as oil, gas, chemical processing, and power generation, are designed to handle highly toxic and compressible fluids under extreme pressure. With the increasing demand for alternative fuels, the need for high-pressure and high-temperature vessels has escalated, particularly in petroleum refineries and chemical plants. Recent advancements in pressure vessel technology have focused on new-grade materials, composite materials, and welding techniques, with finite element analysis (FEA) playing a pivotal role in understanding fatigue and creep behaviour. Mixing chambers, a type of pressure vessel used in chemical industries, experience significant deformation and distortion due to varying pressure and temperature conditions. For instance, additives are introduced at different time intervals, with pressures cycling from 0 to 0.16 MPa and fluid temperatures ranging from 0 to 200°C. This fluctuating environment generates high local stresses that reduce the fatigue life of the mixing chamber, often leading to premature failure. The present study aims to perform transient dynamic stress analysis to identify stresses within the mixing chamber under general time-dependent loads. Additionally, finite element analysis is employed to predict and enhance fatigue life by determining time-varying displacements, strains, and forces acting on the pressure vessel. The study also seeks to modify the existing design provided by the manufacturer, optimize the nozzle angle for improved mixing, and validate the findings through simulation using ANSYS. By addressing these objectives, the research contributes to the development of more resilient mixing chambers, enhancing their longevity and performance under variable operational conditions. These insights are crucial for industries reliant on high-performance pressure vessels, ensuring safety, efficiency, and reliability in their processes.

Keywords: Mixing chambers, Finite element analysis (FEA), Stress analysis

Introduction

Pressure vessels are containers used to handle fluids which are highly toxic, compressible and works at high pressures. These vessels are applied in numerous industries such as oil, gas, petroleum, beverage, chemical, power generation, food and fertilizer, etc. Pressure vessels are used for various purposes such as nuclear reactor vessels, pneumatic reservoirs and storage vessels of liquefied gases (Lee et al., 2017). From last few decades due to increased demand of alternative fuels generates the need of high pressure and temperature vessels for petroleum refineries and chemical plants. Currently there is much advancement in the pressure vessel field like in case of investigating new grade material, composite materials, welding techniques, etc. The applications of finite element analysis is important for understanding of fatigue and creep process (Raffiee et al., 2018). In some chemical industry mixing of liquid or gaseous chemical take place in enclosed chamber such as pressure vessel hence it is called as mixing chamber. For deeper understanding of stress can be archived by transient dynamic analysis. The transient dynamic analysis is used to determine to determine of structure under the action of any general time dependent loads. It is used to determine the time varying displacements, strains and force of a component by Patil et al. (2016).

In mixing chamber during the operation chemicals comes through the nozzle with different pressure and temperature which varies with respect to time. The change in pressure and temperature results deformation and distortion with high local stresses in mixing chamber which in turns reduces the fatigue life of mixing chamber. The transient dynamic analysis is used to find stress and deformation in the pressure vessels. Hence in present investigations an attempt is made to carry out transient dynamic stress analysis to determine the stresses in structure under the action of any general time dependent loads. Also, the fatigue life is predicted and enhanced by finite element analysis to determine the time varying displacements, strains and force acting on pressure vessels. The various types of pressure vessel are discussed in next section; the Fig. 1 shows the generalized diagram of pressure vessel.

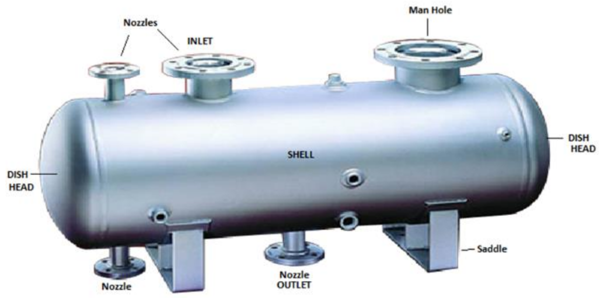


Fig. 1 Mixing chamber

Literature Review

As per the stated problem the work focused on this area is reviewed with the help of standard journal papers. After studying the literature, it can be observed that some work has been done in the field of mixing chamber as pressure vessel.

A computational method was carried out by Kong et al., (2014) to simulate the starting transient flow of a vacuum ejector system. The vacuum ejector-diffuser system has been widely used in many applications such as refrigeration systems. The starting transient flows of supersonic vacuum ejector-diffuser system, and its performance characteristics were simulated and analyzed by numerical methods. Primary numerical analysis results show that the chevrons get a positive effect on the vacuum ejector performance: less starting time and secondary chamber equilibrium pressure are found in chevron transient flow, compared with the convergent nozzle. A CFD method based on transient scheme has been applied to simulate the equilibrium flows and flow dynamics behaviour of the secondary chamber.

Alam et al. (2020) focus on the design of filament-wound composite overwrapped pressure vessels, emphasizing their strength-to-weight advantages. Their tests show that these composite vessels withstand pressures up to 300 MPa with minimal deformation, offering a 25% weight reduction compared to traditional metal vessels. The authors find that composite materials provide increased resilience under dynamic loading conditions, with failure strains reduced by 15-20% in optimized composite layers. These results support the use of composites in aerospace and marine applications where weight efficiency is paramount.

Arumugam et al. (2020) analyze corroded pipelines with single defects under internal pressure, using FEA to quantify the impact of corrosion on structural integrity. They find that pipelines with defects of 5 mm depth experience a 30% reduction in burst pressure. For example, pipelines with this level of corrosion failed at around 150 MPa, whereas intact pipelines withstood pressures up to 220 MPa. These results underscore the importance of regular inspections and timely repair in extending pipeline service life.

Azeem et al. (2024) examine the effects of varying winding angles on hoop stress in composite pressure vessels through FEA, aiming to enhance vessel design. They find that adjusting winding angles significantly reduces hoop stress, with optimal configurations decreasing stress by up to 20%. For instance, a winding angle of 55° showed the lowest stress concentrations, whereas non-optimal angles led to increases in stress by 10-15%. The study highlights that adjusting winding angles not only enhances strength but also improves overall vessel stability under high-pressure conditions. These findings support the use of customized winding configurations to maximize performance in composite pressure vessels, particularly in aerospace and chemical applications where pressure tolerance is critical.

Baadal et al. (2023) investigates crack-induced pressure intensity factors within cylindrical vessels using FEA, discovering that crack position plays a significant role. They find that cracks positioned closer to the vessel's midsection (within 10 cm) resulted in pressure reductions of 20-30%, compared to cracks located near the edges. For example, a vessel with a midsection crack failed at 180 MPa, while one with an edge crack maintained structural integrity up to 250 MPa. This study provides valuable insights for optimizing vessel inspection and maintenance routines, with a focus on midsection crack management.

Gabor et al. (2023) investigate the influence of semi-elliptical cracks on pressure vessel failure, focusing on stress intensity and fracture patterns. Using FEA, they find that crack depth and shape greatly impact failure risk, with vessels featuring deeper cracks (over 2 mm) experiencing stress intensities that increase by nearly 30% compared to shallower cracks. For example, a semi-elliptical crack with an aspect ratio of 0.6 resulted in a 25% reduction in pressure tolerance. Their results suggest that even minor deviations in crack geometry can lead to a marked increase in the likelihood of vessel rupture. These findings underscore the need for strict monitoring of crack morphology in pressure vessels to maintain structural safety.

Johnson et al. (2023) conducts a parametric study on the burst strength of thin and thick-walled pressure vessels, identifying wall thickness as a crucial factor. Their FEA results indicate that increasing wall thickness from 10 mm to 15 mm raises burst strength by approximately 40%, while reducing thickness by 5 mm can lower burst resistance by up to 25%. For thin-walled vessels, burst strength averaged around 200 MPa, while thick-walled vessels withstood up to 350 MPa. These findings help guide vessel design across industries, supporting the need for tailored thickness requirements based on operational pressures.

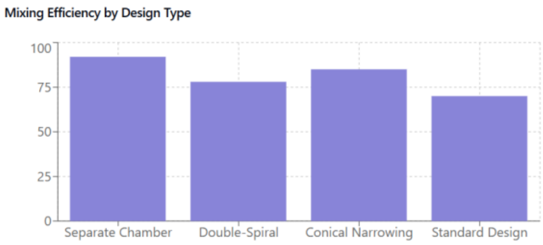


Fig. 2 Mixing efficiency by design type

Material Selection:

Material selection is another vital aspect. For example, using high-grade carbon steel such as ASTM A516 Grade 70 provides superior notch toughness and tensile strength, necessary for the dynamic operational environment. Design standards such as ASME Section VIII guide the minimum required shell thickness and allowable stress. Pressure vessel is major part of equipment used in chemical industry. Selection of material for pressure vessel is depending upon different condition such as pressure, temperature and corrosion effect due to acid and alkalis. The material selection is done based on application point of view, for pressure vessel SA516-Grade 70, (ASME –Sec. 8 Div. 2-Part D) is mostly used as, A516 Grade 70 is an excellent choice for service in lower than ambient temperature application. It has excellent notch toughness and is used in both pressure vessels and industrial boilers. It offers a greater Yield and Tensile strength when compared to ASTM A516 Grade 65 and can operate in lower temperatures. It's ideally suited for high standard set by the oil, gas and petrochemical industry. The mechanical properties of the material are as follows whereas the chemical composition of material is shown in Table 1 and Table 2.

Table 1 Typical chemical composition of material

Grade	C	Mn	Si	Al	P	S
70	0.20	1.05	0.32	0.04	0.015	0.008

Table 2. Mechanical Properties for carbon steel material

Properties	**Values**	**Units**
Elastic modulus	180000	MPa
Poisons ratio	0.23	
Tensile strength	630	MPa
Yield strength	262	MPa
Density	7850	Kg/mm^3

Design of Chamber

Finite Element Analysis

The mixing chamber was modelled in ANSYS Workbench 17.0. The geometry focused on the shell, head, nozzles, flanges, and supports, with particular attention to nozzle orientation (optimized to a 30° inclination for improved performance). The meshing utilized a quadrilateral dominant method with Shell93 elements due to thin-walled geometry.

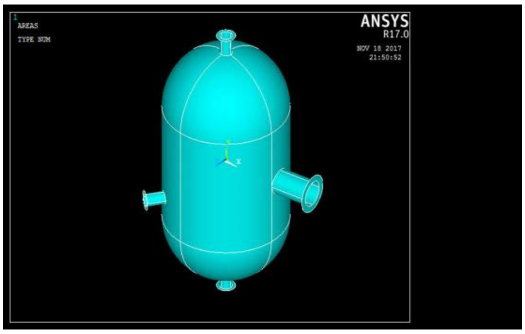


Fig 3. Modelling of Mixing Chamber

Structural Analysis of optimize mixing chamber

It is most common application of finite element method. Static structural analysis is used to determine stress and displacement. Mixing chamber displacement and stresses shown in the Fig. 4 and Fig. 5 respectively.

- Maximum total deformation = 0.47857 mm
- Minimum total deformation = 0.0563 mm
- Maximum total displacement is near nozzle.
- Maximum Von Mises stress on the Mixing chamber is 81.18MPa.
- Minimum Von Mises stress on the Mixing chamber is 0.0056138 MPa
- As stress acting on the mixing chamber within the allowable stress hence design is safe.

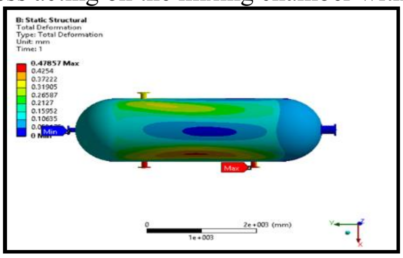


Fig 4. Displacement of mixing chamber

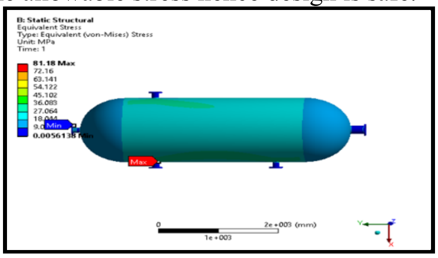


Fig. 5 Stress Results for pressure analysis

Gravity + self-weight analysis

Gravity analysis is also called self-weight analysis. Model with Young's modulus of 180 Gpa, Poisons ratio 0.23 and density 7850kg/ mm^3Mixing chamber model is subjected to standard earth gravity. Fig. 6 and Fig. 7 shows the displacement results for self-weight analysis and stress results for self-weight analysis respectively.

- Maximum total deformation = 0.092474 mm
- Minimum total deformation = 0.010275 mm
- Maximum total displacement is near nozzle
- Maximum Von Mises stress on the Mixing chamber is 17.267MPa.
- Minimum Von Mises stress on the Mixing chamber is 0.00064551 MPa
- Maximum stresses occur at nozzle area.

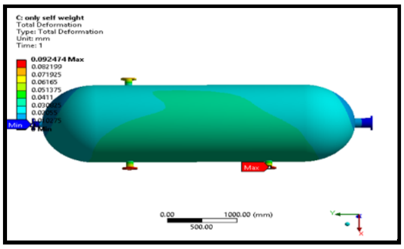


Fig 6. Displacement Results for Self-weight analysis

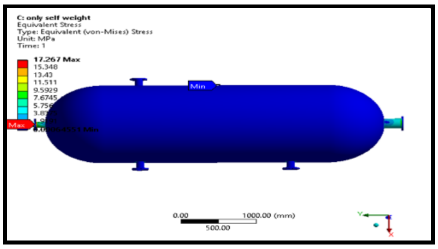


Fig. 7 Stress Results for Self-weight Analysis

Structural Analysis of Incline nozzle of mixing chamber

Consider the geometry given below. Two input nozzle are incline at 30 deg with horizontal axis. Structural analysis is done to check stress concentration at incline nozzle area as shown in the Fig. 8

Tuijin Jishu/Journal of Propulsion Technology
ISSN: 1001-4055
Vol. 46 No. 4 (2025)

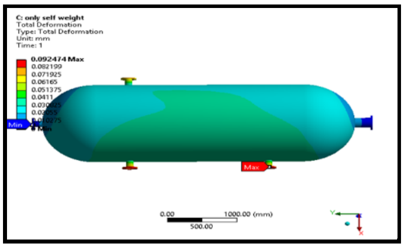


Fig 8. Displacement Results for Incline Nozzle Analysis

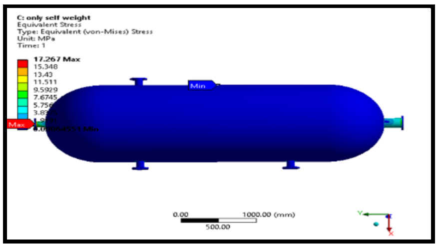


Fig. 9 Stress Results for Incline Nozzle Analysis

- Maximum total deformation = 0.099819 mm
- Minimum total deformation = 0.011091mm
- Maximum total displacement has occurred near incline nozzle area.

Fig. 9 shows the stress results for incline nozzle analysis.

- Maximum Von Mises stress on the Mixing chamber is 51.851 MPa.
- Minimum Von Mises stress on the Mixing chamber is 0.0022663 MPa
- Maximum stresses occur near incline nozzle area. As stress acting on incline nozzle is within allowable limit. Hence design is safe.

Thermal Analysis

Boundary conditions and load applied in this analysis are

1) Fix support – two nozzle flange fix at both ends
2) Temperature- 200^0c temperature is applied at inner face of shell

A steady state thermal analysis calculates the effect of temperature on the component. Model having thermal coefficient of expansion 1.3e-5/c, Temperature, T = 200 deg c.

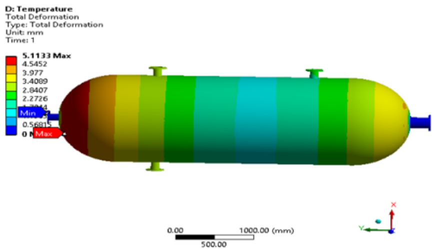


Fig 10. Displacement Results for Thermal Analysis

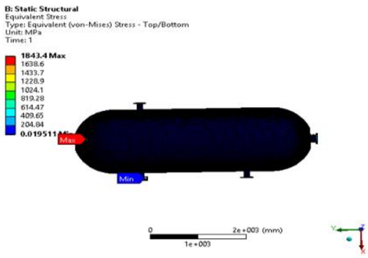


Fig. 11 Stress Results for Thermal Analysis

Fig. 10 shows the displacement results for thermal analysis.

- Maximum total deformation = 5.113 mm
- Minimum total deformation = 0.00013mm
- Maximum total displacement is near head

Fig. 11 shows the stress results for thermal analysis.

- Maximum Von Mises stress on the Mixing chamber is 1843.4MPa.
- Minimum Von Mises stress on the Mixing chamber is 0.019511 MPa

Maximum stress occurs is above the allowable stress hence design is not safe. Stress generated is very high is which about 1843.4 Mpa. Hence there is no space for thermal expansion. So that instead of fixing nozzle flange provide the saddle support for mixing chamber.

Saddle design

Stress due to thermal analysis is very high. As there is no space for thermal expansion horizontal cylinder is supported by saddle. The selection of type of support depends upon diameter and height of the vessel, available space, location, operating temperature and material. These attachments of support of vessel welded by fillet welds it should transfer load from vessel to support. Also per the requirement of input nozzle is inclined at 30 degree so two input nozzle making incline with horizontal for further analysis and validation. Fig. 12 shows the mixing chamber with saddle support and incline nozzle.

Tuijin Jishu/Journal of Propulsion Technology
ISSN: 1001-4055
Vol. 46 No. 4 (2025)

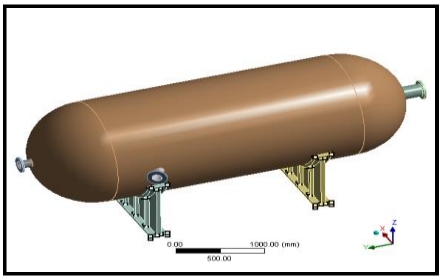


Fig. 12 Mixing Chamber with Saddle Support and Incline Nozzle

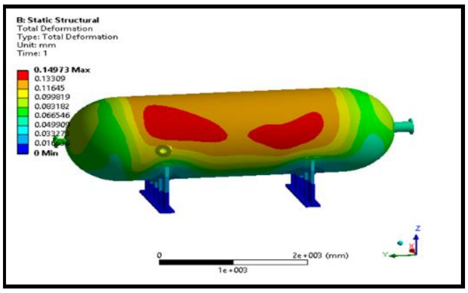


Fig 13. Displacement Results for Analysis of Mixing Chamber with Saddle

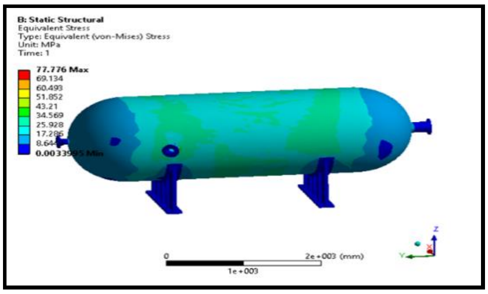


Fig. 14 Stress Results for Analysis of Mixing chamber with saddle

Fig 13 shows Displacement Results for Analysis of Mixing Chamber with Saddle

- Maximum total deformation = 0.14973mm
- Minimum total deformation = 0.016636mm

Fig. 14 shows the stress results for analysis of mixing chamber with saddle.
Maximum Von Mises stress on the Mixing chamber is 77.776MPa.
Minimum Von Mises stress on the Mixing chamber is 0.0033995 MPa.
As the stress generated in mixing chamber is within the allowable limit hence design is safe.

Transient Dynamic Analysis – Pressure Condition

This pressure condition transient dynamic analysis vibration + pressure effect is considered. Load steps, end time, time step size, damping, etc. are defined in the Analysis settings. Transient dynamic analysis there are two cycles of pressure changes with respect to time. In operating cycle pressure changes from 0 to 0.14MPa and in cleaning cycle pressure changes from 0 to 0.16MPa. Effect of vibration is considered with pressure condition. In transient dynamic analysis of mixing chamber with pressure condition is having operating and cleaning cycle. As pressure load is vary with respect to time in this cycle. The time for operating cycle is 0 to 1500 sec. and time for cleaning cycle is 1800 to 2300 sec. Fig. 15 shows the following result of mixing chamber deformation as varying pressure with respect to time.

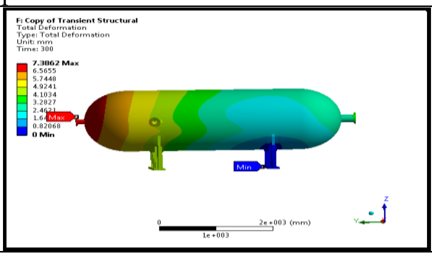


Fig. 15 Deformation Results of mixing chamber for time (0 to 300 sec)

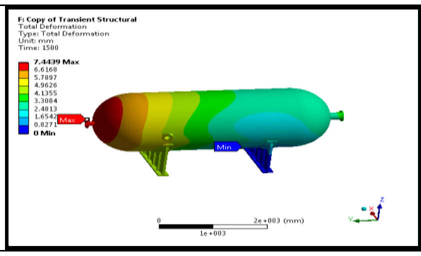
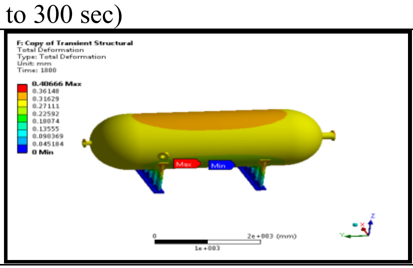


Fig. 16 Deformation Results of mixing chamber for time (300 to 1500 sec)



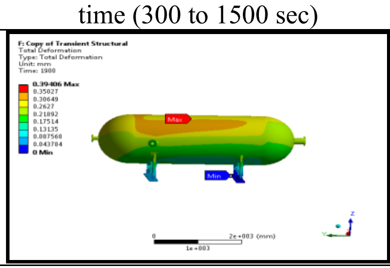


Fig. 17. Deformation Results of mixing chamber for time (1500 to 1800 sec)	Fig. 18. Deformation Results of mixing chamber for time (1800 to 1900 sec)

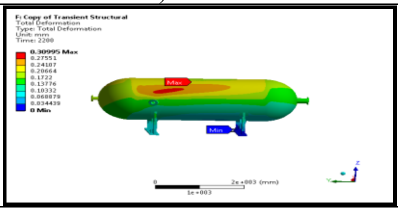
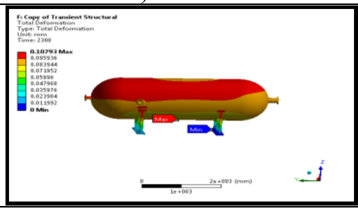

	

Fig. 19. Deformation Results of mixing chamber for time (1900 to 2200 sec)	Fig. 20 Deformation Results of mixing chamber for time (2200 to 2300)

Result & Discussion

The results of von-mises stresses after analysis with help of ANSYS 17.0 which are verified results by mathematical method. After comparing results, it is concluded design is safe which is seen from Table 3.

Table 3 Static Structure Analysis of Mixing chamber

Analysis	Displacement (Mm)	Von Mises Stress (Mpa)	Stress Limits (Mpa)
1. Structural	0.14973	77.776	131
2.Self -weight analysis	0.092474	17.267	131
3.Transient dynamic (pressure condition)	0.5662	39.289	131

Experimental Validation

Experiment is conducted by actual testing of mixing chamber with strain gauge. A strain gauge is a sensor whose resistance varies with applied force. It converts force, pressure, tension, weight, etc. into change in the electrical resistance which can be measured. When external forces applied to a stationary object strain can be obtained. Strain is defined as the displacement and deformation. The mixing chamber was checked for maximum deformation under the fluid pressure of 0.14Mpa to 0.16 Mpa and the working temperature is 200℃. Strain gauge of (LC1X) HBM type was located at moving saddle at shell junction. The following Table 3 shows the valve for deformation obtained analytically and experimentally.

Table 4. Comparison Experimental vs. analytical results

Sr. No.	Hydro Test (Mpa)	Maximum deformation by finite element analysis (mm)	Maximum deformation by experimental (mm)
1.	0.1409	4.9241	5.0909
2.	0.1409	4.9626	5.0909
3.	0.005	4.3137	0.7781
4.	0.1598	0.2627	0.6332
5.	0.1598	0.10332	0.5243
6.	0.0041	0.10793	0.5243

As maximum deformation in the simulation and experimental process is same, in experimental process it is varied between 0.5243% - 5.0909% and in simulation process is varied between 0.10793% - 4.9241%. It can be show that finite element result is good with experimental result (± 5).

Conclusion

Nozzle position is optimized by varying nozzle angle with finite element analysis. The optimization results show minimum stress and deformation position of nozzle. Thermal analysis shows change the support system to give space for thermal expansion Self-weight analysis of mixing chamber show that support can be used to avoid failure by deflection. Self-weight analysis and thermal analysis of mixing chamber shows that two saddles are sufficient to avoid failure by deflection. The combined analysis proves that the optimized thickness of mixing chamber is safe as per ASME sec VIII div II Part 5D, design by analysis to avoid plastic collapse. Fatigue life improvement is many times of initial fatigue life of mixing chamber.

Future Directions

Mixing chamber can be analyzed with different pressure and temperature cycle condition w.r.t time by transient dynamic analysis. Design new mixing chamber by design by analysis Computational fluid dynamic of mixing chamber can be done to study behaviour of fluid.

References

1) Alam, S., Yandek, G. R., Lee, R. C., & Mabry, J. M. (2020). Design and development of a filament wound composite overwrapped pressure vessel. Composites Part C: Open Access, 2, 100045.
2) Arumugam, T., Karuppanan, S., & Ovinis, M. (2020). Finite element analyses of corroded pipeline with single defect subjected to internal pressure and axial compressive stress. Marine Structures, 72, 102746.
3) ASME. (1998). ASME Boiler & Pressure Vessel Code Section VIII Division 1. American Society of Mechanical Engineers.
4) ASME. (1998). Section II Part D. American Society of Mechanical Engineers. (Cited in Zengliang Gao et al., 2005).
5) Azeem, M., Hamdan, H. Y., Alam, M. A., Kumar, M., Sajid, Z., Gohari, S., ... & Khan, S. H. (2024). Influence of winding angles on hoop stress in composite pressure vessels: Finite element analysis. Results in Engineering, 21, 101667.
6) Baadal, A., Eachan, C., Gabor, G., Jabali, I., & Zacarias, Y. (2023). Pressure intensity factor interface in cylindrical vessel through crack using finite element approaches. World Engineering and Applied Sciences Journal, 14(4), 389-393.
7) Boresi, A. P. (2003). Advanced Mechanics of Materials. John Wiley & Sons.
8) Di Patrizio, N., Bagnaro, M., Gaunand, A., Hochepied, J., Horbez, D., & Pitiot, P. (2016). Hydrodynamics and mixing performance of Hartridge Roughton mixers: Influence of the mixing chamber design. Chemical Engineering Journal, 283, 375-387.
9) Gabor, G., Jabali, I., Naagarjun, L., Paal, O., & Baadal, A. (2023). Investigating the effect of semi-elliptical crack on the failure of pressure vessels using finite element analysis. Asian Journal of Basic and Applied Sciences, 10(6), 300-303.
10) Imran, M., Shi, D., Tong, L., & Waqas, H. M. (2019). Design optimization of composite submerged cylindrical pressure hull using genetic algorithm and finite element analysis. Ocean Engineering, 190, 106443.
11) Johnson, W. R., Zhu, X. K., Sindelar, R., & Wiersma, B. (2023). A parametric finite element study for determining burst strength of thin and thick-walled pressure vessels. International Journal of Pressure Vessels and Piping, 204, 104968.
12) Khan, S. (2010). Stress distributions in a horizontal pressure vessel and the saddle supports. International Journal of Pressure Vessels and Piping, 87(5), 239-244.
13) Kong, & Kim, D. (2014). Starting transient simulation of a vacuum ejector-diffuser system under chevron effects. International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics, 955-959.
14) Marques, E. S., Silva, F. J., & Pereira, A. B. (2020). Comparison of finite element methods in fusion welding processes—A review. Metals, 10(1), 75.
15) Okodi, A., Lin, M., Yoosef-Ghodsi, N., Kainat, M., Hassanien, S., & Adeeb, S. (2020). Crack propagation and burst pressure of longitudinally cracked pipelines using extended finite element method. International Journal of Pressure Vessels and Piping, 184, 104115.
16) Paal, O., Udichi, S., Waen, W., Zacarias, Y., & Baadal, A. (2023). Exploring the consequence of stress concentration elements on the breakdown of pressure vessels. International Journal of Technology and Scientific Research, 13(6), 4401-4406.
17) Pande, S., Darade, P., & Gogate, G. (2014). Transient analysis and fatigue life prediction of tubesheet. International Journal of Research in Engineering and Technology, 3(9), 464-471.
18) Patil, K., & Patil, V. (2016). Analysis of balance stiffness valve by using transient analysis method. International Journal on Recent and Innovation Trends in Computing and Communication, 4(7), 145-151.
19) Qadir, M., & Redekop, D. (2009). SCF analysis of a pressurized vessel–nozzle intersection with wall thinning damage. International Journal of Pressure Vessels and Piping, 86(8), 541-549.
20) Rafiee, R., & Torabi, M. (2018). Stochastic prediction of burst pressure in composite pressure vessels. Composite Structures, 185, 573-583.
21) Sanal, Z. (2000). Nonlinear analysis of pressure vessels: some examples. International Journal of Pressure Vessels and Piping, 77(12), 705-709.

22) Siva Kumar, B., Prasanna, P., Sushma, J., & Srikanth, K. (2018). Stress analysis and design optimization of a pressure vessel using Ansys package. Materials Today: Proceedings, 5(2), 4551-4562.
23) Udichi, S., Waen, W., Zacarias, Y., Eachan, C., & Baadal, A. (2023). Researching the influence of semi-elliptical crack on the failure of pressure vessels operating finite element analysis. European Journal of Scientific and Applied Sciences, 10(6), 1099-1104.
24) Wasewar, K., & Sarathi, J. (2008). CFD modelling and simulation of jet mixed tanks. Engineering Applications of Computational Fluid Mechanics, 2(2), 155-171.