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Analysis Aspects of Pressure Tank: A Review

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Abstract

This review paper provides a comprehensive assessment of pressure vessels, emphasizing the use of finite element analysis (FEA) to evaluate their structural integrity and performance. Pressure vessels play a vital role in various industrial sectors, including power plants, petrochemical facilities, and chemical manufacturing units, where they are subjected to elevated pressure and temperature environments. Ensuring their safe operation requires a clear understanding of stress distribution, deformation behavior, and possible failure mechanisms. This study compiles existing research on thermal stresses and deformations that develop under various loading conditions and compares FEA results with analytical methods to validate the accuracy of computational approaches The design of the pressure vessel follows ASME Section VIII Division 2 standards, focusing on parameters such as shell thickness, head geometry, and overall structural stability. Static and thermal analyses are performed using ANSYS, incorporating multi-physics simulations to study combined thermal and mechanical effects. Modal analysis is also reviewed to determine natural frequencies, which help in predicting vibration responses and preventing resonance failures A key aspect of this review is the examination of different boundaries and support conditions, particularly the saddle support configurations. Two constraint conditions of the right-hand saddle are analyzed to understand their influence on stress distribution and deformation under constant internal design pressure and temperature. This comparative study provides valuable insights for optimizing support designs to improve the strength, safety, and service life of pressure vessels. Overall, this review highlights advancements in FEA-based pressure vessel analysis and supports the development of safer and more efficient designs.

Keywords: Reactors, finite element analysis (FEA), stress analysis, pressure vessels, finite element method (FEM)

INTRODUCTION

Pressure vessels are essential containment structures engineered to function under pressure levels that differ significantly from ambient conditions [1]. Due to the high internal pressures involved, their design and operation pose considerable safety concerns, as any failure can result in severe or even catastrophic outcomes [2]. The present study investigates pressurized oil storage tanks, focusing on identifying the key parameters that influence their structural integrity and operational performance under diverse service conditions. Contemporary pressure vessel design adheres to stringent standards, most notably the ASME Boiler and Pressure Vessel Code, Section VIII [3], which provides detailed engineering guidelines to ensure safety and reliability. These vessels are extensively utilized in various industries such as nuclear power generation, petroleum refining, and chemical manufacturing [4]. The growing demand for alternative fuels has further increased requirements for vessels capable of withstanding extreme pressures and temperatures [5]. Recent advancements in pressure vessel technology include:

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- Development of advanced materials and composites [6]
- Improved welding techniques [7, 8, 9]
- Enhanced computational analysis methods [10]
- Finite element analysis (FEA) has become indispensable for understanding complex phenomena such as fatigue behavior and creep deformation [11]. Multi-physics modeling enables comprehensive evaluation of combined mechanical and thermal loads [12], while transient dynamic analysis provides insights into time-dependent stress distributions [13]. These computational tools allow for accurate prediction of vessel performance under operational conditions, significantly improving design reliability.

LITERATURE REVIEW

Design Standards and Analysis Methods

The ASME standards establish a comprehensive framework for designing pressure vessels, helping to minimize development time while maintaining high safety standards. Finite Element Analysis (FEA) has become an essential technique for assessing different vessel configurations, especially those supported by saddles [14]. Previous research has highlighted the capability of FEA in optimizing parameters such as wall thickness and temperature distribution in boiler systems [15].

Nonlinear FEA techniques enable accurate simulation of large displacements and plastic deformation in pressure vessel components. These advanced methods provide valuable insights into limit load predictions and material behavior under extreme conditions [16].

Material Innovations

Significant progress has been made in material technology for pressure vessels:

- Cryogenic treatment of austenitic stainless steel can double allowable stresses, enabling 60-75% reduction in wall thickness [17]
- Fiber-reinforced polymer (FRP) composites offer 75% weight reduction compared to steel while eliminating corrosion concerns [18]
- Multilayered vessel designs demonstrate 26% material savings and more uniform stress distribution (12.5% variation vs 17.35% in monoblock designs) [19]

Welding and Joint Integrity

Recent research on welded joints reveals that increased heat input improves crack resistance during pressure cycling. The heat-affected zone (HAZ) of microalloyed steels shows particularly good performance under variable loading conditions [20]. Advanced welding techniques, including Plasma Transferred Arc Welding (PTAW), have proven effective for applying wear-resistant coatings.

Nozzle and Mixing Dynamics

Nozzle design significantly affects mixing efficiency:

- Larger nozzle diameters reduce mixing time while improving energy efficiency [21]
- Hartridge-Roughton mixers achieve complete homogenization in under 5 milliseconds [22]
- Optimal fuel oil-to-steam pressure ratios minimize Sauter Mean Diameter (SMD) in atomization processes [23]
- Computational fluid dynamics (CFD) simulations have become essential for analyzing mixing phenomena and validating nozzle designs [24].

Structural Analysis and Failure Prevention

Comprehensive studies have been investigated:

- Stress distribution in saddle-supported vessels [25]
- Burst pressure prediction using Ramberg-Osgood models [26]
- Nozzle-vessel interactions under wall thinning conditions [27]

Transient analysis of valve components [28], The WRC Bulletin 107/297 methods provide reliable stress analysis for nozzle reinforcements, with good correlation to FEA results [29]. Ellipsoidal and dished end configurations demonstrate superior stress distribution compared to flat or hemispherical designs [30]. The thresher blade press tool was designed and analyzed, revealing that the fixture ensures proper part orientation and positioning in the assembly [31]. This review synthesizes current knowledge across these critical areas, providing a foundation for improved pressure vessel design and analysis methodologies. The integration of advanced materials, optimized geometries, and sophisticated analysis techniques continues to push the boundaries of pressure vessel performance and reliability.

INFERENCES FROM LITERATURE SURVEY

From the review of existing literature, it is evident that the design and performance analysis of pressure vessels have been extensively studied. In the chemical industry, vessels are primarily used for the storage and transportation of various chemicals. However, the combined effects of internal pressure and temperature often cause deformation within the vessel walls, leading to the development of localized high-stress regions. A detailed stress analysis helps in understanding these stress concentrations, and the maximum stress values are crucial for predicting possible failure points in the vessel.

- *Burst pressure prediction*: Finite Element Analysis (FEA) is an effective approach for estimating the burst pressure at which cracks initiate in a pressure vessel. The propagation of such cracks can reduce the fatigue life of the vessel, but this can be mitigated through detailed FEA-based evaluation.
- *Structural response evaluation*: FEA is widely employed to determine how components behave under various boundary and loading conditions.
- *Nonlinear analysis accuracy*: Nonlinear finite element analysis provides more precise results when dealing with complex, non-routine problems compared to standard linear analyses.
- *Combined loading effects*: The interaction of static and thermal loading conditions in pressure vessels requires thorough investigation to ensure accurate prediction of stress behavior and to improve overall structural reliability [32].

METHODOLOGY

Finite Element Analysis (FEA) is a highly advanced and extensively used computational technique in modern engineering, employed to examine and predict the behavior of complex structures and components when subjected to different types of loading conditions. It serves as a vital computational tool integrated within Computer-Aided Design (CAD) software, allowing engineers to simulate and study the performance of systems before physical testing or manufacturing. FEA divides a structure into a finite number of small, interconnected elements of simple geometric shapes such as triangles, quadrilaterals, or rectangles. Each of these elements is linked through nodes that together form a network or mesh representing the overall geometry of the model [33].

In the present study, the analysis has been conducted using ANSYS, a widely used engineering simulation software that employs the FEA technique. Through ANSYS, a complete representation of the physical system is developed by defining the geometry of the part or assembly, material properties, and boundary conditions. FEA essentially converts a physical problem into a set of mathematical equations, which are solved to determine the structure's response under specific loads and environmental conditions. The process consists of three main stages: pre-processing, solution, and post-processing. These phases collectively represent model preparation, computation, and interpretation of results. FEA is particularly useful for complex geometries and loading conditions where theoretical or analytical methods are either too cumbersome or do not provide accurate results [34].

Accurate modeling techniques, proper selection of boundary conditions, and awareness of the limitations of the FEA procedure are crucial to achieving realistic results. Many engineering structures—such as pressure vessels, bridges, aircraft wings, automobiles, turbine blades, and high-rise buildings—are characterized by complex shapes and multiple load combinations. Traditional analytical methods often fail to evaluate such systems accurately due to their nonlinear and multidimensional behavior. However, the FEA technique enables detailed examination of these structures by dividing them into numerous finite elements. This discretization method forms the foundation of the finite element approach, allowing each small element to behave according to defined mathematical relations while collectively representing the behavior of the entire system [35].

Applications for Finite Element Analysis

Finite Element Analysis can be employed to determine various structural properties, including:

a. Static displacements and stresses.
b. Natural frequencies and vibration mode shapes.
c. Amplitudes and stresses due to harmonic or cyclic loading.
d. Time-dependent responses such as transient deformation and stress.
e. Random or unpredictable dynamic stresses caused by irregular loading patterns.

FEA allows engineers to examine how a structure responds to static and dynamic loading, enabling optimization for strength, stability, and material efficiency [36].

Steps in the Finite Element Method (FEM)

Step 1: Pre-processing

The pre-processing stage involves developing the mathematical model of the structure. It includes defining geometry, assigning material properties, and selecting appropriate element types such as solid, shell, or beam elements. Once the element type is selected, meshing is performed, where the structure is subdivided into finite elements. The fineness of the mesh greatly affects the accuracy of results, finer meshes produce more precise outcomes but require greater computational resources. Boundary conditions and loads, such as pressures, forces, or thermal gradients, are then applied to represent the physical scenario. At this stage, the model is fully defined, and the mesh represents the physical structure as a collection of nodes and elements, ready for analysis [37].

Step 2: Solution (Analysis Phase)

During the solution phase, the governing equations of equilibrium are established and solved. The element stiffness matrices are formulated and assembled to create the global stiffness matrix for the entire structure. The general equilibrium equation used in FEA is expressed as: $F = [K]u$Where, F= Vector of external forces, $[K]$= Global stiffness matrix, u= Displacement vector.

By solving this equation, nodal displacements are obtained, which represent how each point of the structure moves under applied loads. Using these displacement values, strains, stresses, and reaction forces are computed. The solution phase may also include nonlinear analyses, where large deformations, material plasticity, or contact between components are taken into account. The computed results are stored for further evaluation in the next phase.

Step 3: Post-processing

The post-processing stage involves interpreting and visualizing the numerical data obtained from the solution phase. Raw data, such as displacement and stress values at various nodes, are processed and converted into graphical formats for better understanding. Common visualization outputs include deformation shapes, contour plots of stress, strain distributions, temperature gradients, and reaction forces. In ANSYS and similar software, post-processing also enables animation of results, helping engineers clearly observe how a structure behaves under different loading conditions. This graphical interpretation is essential for validating the design, identifying high-stress regions, and making necessary modifications to improve performance and safety [38].

Types of Structural Analysis in FEA

1. *Static structural analysis*: This type of analysis is performed to evaluate displacements, stresses, and reaction forces in a structure under steady or constant loading conditions. It assumes that loads are applied slowly enough for inertia and damping effects to be neglected. However, nonlinear factors such as large deformations, material plasticity, or creep behavior can also be considered when necessary to achieve more accurate results.
2. *Modal analysis*: Modal analysis is carried out to determine the natural frequencies and corresponding vibration mode shapes of a structure. It plays a crucial role in studying dynamic behavior, helping engineers ensure that the operating frequencies of machinery or systems do not align with the natural frequencies of the structure, thereby preventing resonance and possible structural failure.
3. *Harmonic analysis:* Harmonic analysis is used to study the steady-state response of a structure when it is exposed to loads that vary sinusoidally over time. This method helps in understanding the relationship between the applied load and the resulting displacement or stress, particularly in terms of amplitude and phase differences, which are essential for analyzing vibration and fatigue behavior in mechanical systems.
4. *Transient dynamic analysis*: Used to analyze structures under time-dependent or shock loads. This method computes variations in displacement, velocity, and acceleration over a specific time period, making it essential for studying impact or crash scenarios.
5. *Spectrum analysis:* An extension of modal analysis, spectrum analysis evaluates structural responses to dynamic loads such as earthquakes or vibrations from rotating machinery, using predefined response spectra.
6. *Buckling analysis*: Determines the critical load at which a structure becomes unstable and begins to buckle. Both linear (eigenvalue-based) and nonlinear buckling analyses can be performed to predict failure and improve stability design.

In structural simulation, 3D FEA models are typically employed to investigate stresses, deflections, and safety factors under various load conditions. By performing static, modal, harmonic, transient, and buckling analyses, engineers can predict how a structure behaves in real-world scenarios. The insights obtained from FEA not only enhance the reliability and safety of designs but also help optimize material usage, reduce manufacturing costs, and extend the operational life of engineering systems. Thus, Finite Element Analysis stands as a cornerstone in modern engineering analysis, bridging the gap between theoretical design and practical performance validation [39].

CONCLUSIONS

The present study highlights the critical role of transient dynamic stress analysis and finite element analysis (FEA) in improving the fatigue life of mixing tanks used in chemical industries. Given the extreme operational conditions varying pressures, fluctuating temperatures, and time-dependent loading this pressure vessels experience significant stress concentrations that can lead to premature failure. Through FEA simulations in ANSYS, this research identifies key stress points, predicts fatigue behavior, and proposes design modifications to enhance structural resilience. Optimizing the nozzle angle for better mixing efficiency further contributes to improved performance and longevity. The findings underscore the importance of advanced materials, precise design adjustments, and computational analysis in developing robust pressure vessels, ensuring increased safety and reliability in industrial applications.

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