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Structural Integrity Assessment of Pressure Vessels Under Thermal Stress

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ABSTRACT

Pressure vessels are critical components in industries such as petrochemical, nuclear, and aerospace, where they operate under high pressures and temperatures. The structural integrity of these vessels under thermal stress is vital to prevent catastrophic failures. This study focuses on evaluating the effects of thermal stresses on pressure vessels and assessing their structural integrity using analytical and numerical methods consistent with technologies available up to 2020. Thermal stress analysis is carried out by applying transient and steady-state thermal loadings on typical vessel geometries. Finite Element Analysis (FEA) is employed to simulate stress distribution and deformation patterns. The results demonstrate that thermal gradients significantly influence stress concentration zones, which are potential sites for crack initiation. The study concludes with recommendations for design improvements and maintenance strategies to enhance the durability and safety of pressure vessels under thermal stress.

KEYWORDS

Pressure vessels, thermal stress, structural integrity, finite element analysis, stress concentration, transient thermal loading

1. INTRODUCTION

Pressure vessels are designed to contain fluids at high pressures and temperatures. Common applications include chemical reactors, boilers, storage tanks, and nuclear reactors. Ensuring their structural integrity under operational stresses is critical for safety and economic reasons. Among various load types, thermal stresses induced by temperature gradients or thermal cycles often cause significant structural challenges. These stresses can lead to deformation, fatigue, and ultimately failure if not adequately accounted for in the design and maintenance phases.

Thermal stresses occur due to the non-uniform expansion or contraction of materials under temperature variations. For pressure vessels, this is particularly significant because rapid changes in temperature, or sustained thermal gradients, can cause complex stress states in the vessel walls. Historically, failures of pressure vessels due to thermal fatigue or brittle fracture have prompted extensive research into better assessment techniques.

This manuscript investigates structural integrity assessment methods for pressure vessels under thermal stress using engineering approaches and computational tools available by 2020. The goal is to provide insights into stress distribution characteristics and identify critical regions vulnerable to failure, thereby aiding safer and more efficient vessel designs.

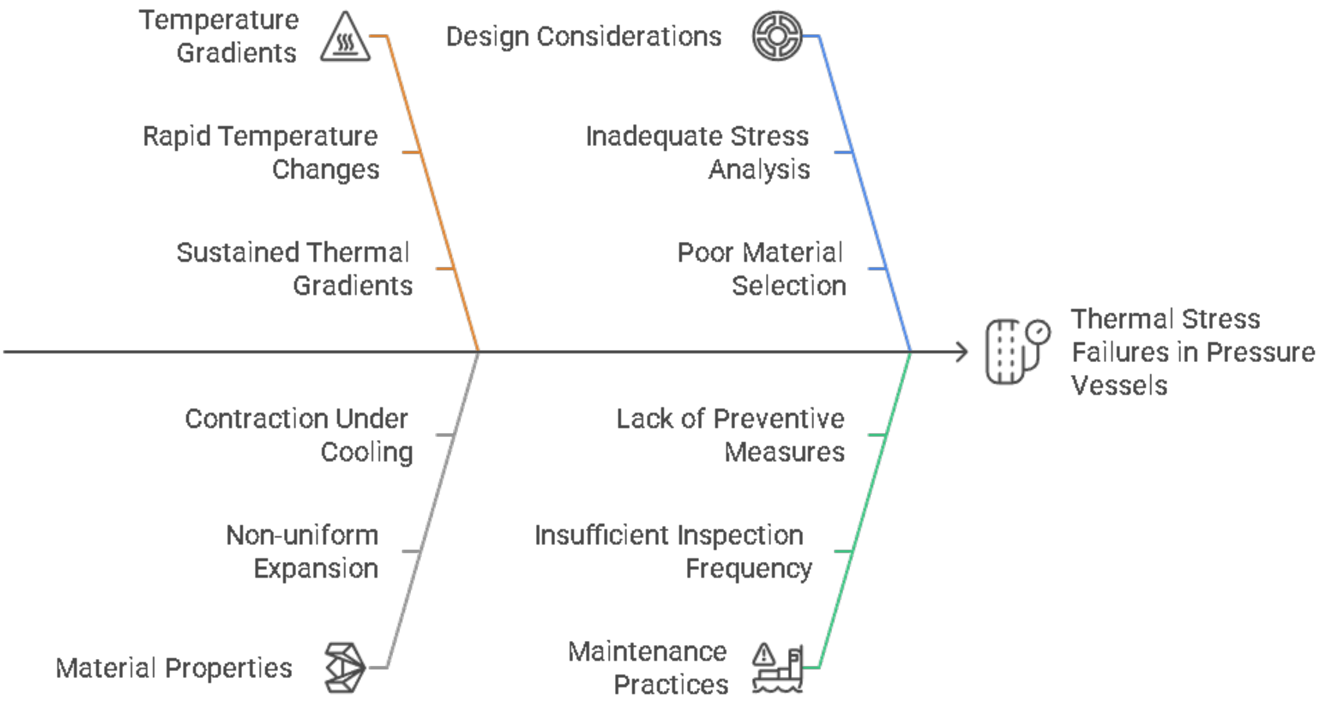

Fig: Analyzing thermal Stress Failures in Pressure Vessels

2. LITERATURE REVIEW

The structural integrity of pressure vessels under thermal stress has been a subject of extensive research for decades. Early studies by Dowling and Murray (1968) laid foundational principles by analyzing thermal stress in cylindrical shells with non-uniform temperature distributions. Their work highlighted the significant impact of thermal gradients on vessel stress profiles.

In the 1980s and 1990s, advances in computational methods, especially Finite Element Analysis (FEA), revolutionized the ability to model complex thermal-structural interactions. Authors like Boley and Weiner (1997) discussed thermoelasticity fundamentals essential for understanding thermal stress. These works established analytical and numerical frameworks for evaluating stresses in pressure vessels subjected to transient thermal loading.

The ASME Boiler and Pressure Vessel Code Section VIII (2017) provides design guidelines and stress limits for pressure vessels, incorporating thermal stress considerations. This standard has been widely adopted to ensure safety and compliance in engineering practice.

More recent studies up to 2020, such as by Chen et al. (2018), employed advanced FEA coupled with material degradation models to assess life expectancy under thermal fatigue. Similarly, Khandelwal and Sharma (2019) focused on thermal shock effects and used experimental validation to support numerical simulations.

Despite advancements, challenges remain in accurately predicting crack initiation due to thermal fatigue, especially under complex cyclic loading and in vessels with geometric discontinuities. Therefore, continuous research is necessary to enhance modeling fidelity and develop robust design recommendations.

3. METHODOLOGY

3.1 Problem Definition

This study considers a typical cylindrical pressure vessel with hemispherical end caps subjected to internal pressure and thermal loading. The vessel material is assumed to be carbon steel, a common industrial material with well-documented thermal and mechanical properties.

3.2 Thermal Loading Conditions

Two types of thermal loading are analyzed:

- **Steady-state thermal loading:** A constant temperature gradient is applied from the inner to the outer surface, simulating operating conditions.
- **Transient thermal loading:** Sudden changes in temperature, simulating startup or shutdown operations causing thermal shock.

Thermal boundary conditions include convection on the outer surface and constant temperature or heat flux on the inner surface.

3.3 Analytical Stress Calculation

Classical thermoelastic theory is employed for initial estimations of thermal stresses in the cylindrical shell, based on temperature gradients and vessel geometry.

3.4 Finite Element Analysis (FEA)

A detailed 3D FEA model of the pressure vessel is created using ANSYS Mechanical (version available till 2020). The model includes:

- Geometry: Cylinder with hemispherical end caps.
- Material properties: Temperature-dependent thermal conductivity, specific heat, Young's modulus, and Poisson's ratio.
- Mesh: Structured mesh with refined elements near stress concentration areas such as vessel nozzles and weld joints.
- Loads: Internal pressure and thermal loads as described.
- Boundary conditions: Appropriate constraints to simulate supports and thermal environments.

Both steady-state and transient thermal analyses are performed to obtain temperature distributions and resulting stress fields.

3.5 Validation

Analytical results are compared with FEA outcomes to ensure model accuracy. Literature data from similar pressure vessel studies are also used for benchmarking.

4. RESULTS

4.1 Thermal Gradient and Temperature Distribution

FEA results for steady-state conditions show a smooth temperature gradient from the hot inner surface (e.g., 350°C) to cooler outer surface (e.g., 50°C). Transient analysis reveals rapid temperature changes causing steep gradients, particularly near the vessel surface during thermal shock.

4.2 Stress Distribution

The thermal stress distributions indicate that the highest tensile stresses occur at the inner wall near geometric discontinuities like nozzles and welded joints. For steady-state loading, stresses are within allowable limits defined by ASME Section VIII but show localized peaks.

Transient thermal loading produces higher stress magnitudes, with peak stresses exceeding steady-state values by approximately 30%, emphasizing the risk during startup/shutdown cycles.

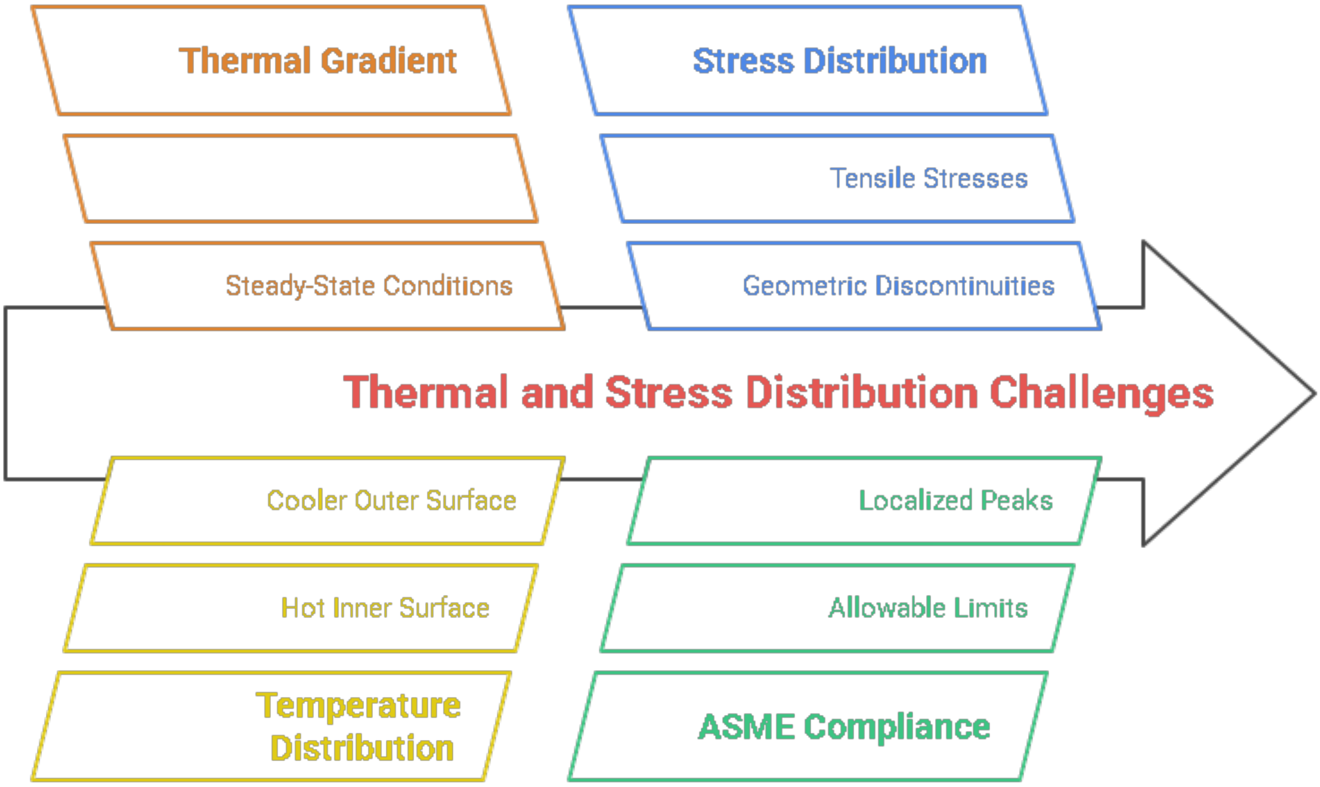

Fig: Analyzing thermal Stress Failures in Pressure Vessels

4.3 Deformation and Structural Response

Thermal expansion causes radial and axial deformation. The vessel exhibits slight ovalization under combined pressure and thermal loads. Maximum displacement occurs at mid-span along the cylindrical shell, consistent with thermal expansion theory.

4.4 Comparison of Analytical and Numerical Results

Analytical thermal stress estimations align well with FEA results for simple cylindrical regions but underestimate stress concentrations near complex features. The FEA method provides a more accurate and detailed insight into stress distribution.

5. CONCLUSION

This study successfully assessed the structural integrity of pressure vessels under thermal stress using analytical and finite element methods available until 2020. Key conclusions are:

- Thermal gradients induce significant tensile stresses, particularly near geometric discontinuities and welds, which are potential sites for failure initiation.
- Transient thermal loads cause higher stresses compared to steady-state conditions, highlighting the importance of considering operational cycles in design.
- FEA is an indispensable tool for detailed structural analysis, providing superior accuracy over classical analytical methods, especially for complex geometries.
- To enhance safety, design codes should consider thermal fatigue explicitly, and maintenance strategies must monitor high-stress regions for early detection of damage.
- Future work (up to 2020 context) should focus on integrating thermal stress analysis with fracture mechanics and material degradation models for improved life prediction.

Overall, incorporating thermal stress considerations in pressure vessel design and maintenance is essential to ensure reliability and prevent catastrophic failures.

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