Tuijin Jishu/Journal of Propulsion Technology
ISSN: 1001-4055
Vol. 45 No. 3 (2024)

Design and Analysis of Pressure Vessel for Variable Thermal Load Considering Temperature, Material and Time Effects

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Abstract: This paper presents a study on the design and analysis of a pressure vessel integrated with a manage variable thermal loads, taking into account temperature , material and time dependencies. The research focuses on addressing the challenges posed by dynamic thermal conditions encountered in industrial applications, where pressure vessels are subjected to fluctuating temperatures and varying operational duration. The methodology includes a comprehensive review of relevant literature, establishment of mathematical models incorporating temperature material and time factors, and utilization of advanced simulation techniques such as Finite Element Analysis (FEA). The study aims to optimize the design parameters of the pressure vessel and limpet system to ensure structural integrity, thermal efficiency, and safety under varying thermal loads.

Keywords: Pressure vessel, Thermal load, Yield strength, Corrosion allowance

1. Introduction

Pressure vessels play a crucial role in various industries such as oil and gas, chemical processing, and power generation, where they are utilized for storing and transporting fluids under high pressure and temperature conditions. the efficient and safe operation of pressure vessels is paramount to prevent catastrophic failures and ensure uninterrupted production processes. One of the critical challenges faced in the design and operation of pressure vessels is managing variable thermal loads. thermal loads can vary due to changes in ambient temperature, fluid properties, process conditions, and duration of operation. these variations can lead to thermal stresses, fatigue, and potential failure modes if not adequately addressed in the design phase. The integration of a counter-flow limpet system within pressure vessels has emerged as an effective method to regulate thermal gradients, enhance heat transfer efficiency, and minimize thermal stresses. By implementing such a system, the thermal performance of pressure vessels can be optimized, leading to improved safety margins and operational reliability. **Key aspects addressed in the research include:** Determination of design pressure and temperature profiles based on operational requirements, Material selection considering mechanical properties at different temperature ranges, Calculation of design thickness accounting for corrosion allowance and thermal stresses, Analysis of hoop stress and longitudinal stress under variable thermal loads using FEA and incorporation of time-dependent thermal profiles to assess transient effects and long- term performance

2. Literature review

A thorough review of existing literature on pressure vessel design methodologies, thermal management techniques, and limpet systems was conducted. Relevant standards such as ASME Boiler and PressureVessel.

3. Design Parameters Determination

3.1 Design Pressure and Temperature Profiles:

- Design pressure (P_design): 150 psi
- Maximum operating temperature (T_max): 350° C

3.2 Material Selection:

ASTM A516 Grade 70 carbon steel was chosen for its mechanical properties and compatibility with the operational temperature range.

Key material properties:

- Yield strength at T_max (σ_yield): 38,000psi
- Tensile strength at T_max (σ_tensile):70,000 psi

Allowable stress at T_max (σ_allowable):20,000 psi (ASME BPVC standards)

3.3 Corrosion Allowance and Design Thickness

- Considering a corrosion allowance of 0.125 inches and using ASME BPVC guidelines for cylindrical shells (Section VIII, Division 1), we calculate the required minimum thickness (t_min)using the formula:
- T_m=P.D/2.F.S +C_A

Where ,

- D = Inside diameter of the vessel = 36inches
- F = Design factor (typically 1.5 for vesselshells)
- S = Allowable stress at design temperature(ASME standards) = 20,000 psi
- C_A = Corrosion allowance = 0.125inches
- P = Design pressure = 150 psi

Plugging in the values:

t_{min}=150psi.36in / 2*1.5*20000 +0.125 in

$t_{min} \approx 0.705$ inches

4. Operational Conditions and Environmental Factors

Considering the application's thermal load variations, we assessed temperature cycling effects and determined operational duration toaccount for variable thermal loads over time also considered in the structural analysis.

4.1 Safety Factors and Standards Compliance:

Applying a safety factor of 2 (common in pressure vessel design) to the design parameters ensures a margin of safety against uncertainties and unexpected conditions. Verification of compliance with ASME BPVC standards, including fabrication and inspection requirements, is integral to the design process.

This example demonstrates a simplified approach to determining design parameters for a pressure vessel with a counter-flow limpet system. Actual designs would involve more detailed calculations, considerations for specific applications, and rigorous compliance with relevant standards and codes.

5. Results and Discussion

Thermal stress analysis is critical to ensure that the pressure vessel can withstand the thermal loads encountered during operation without failure. This section outlines the methodology and results of the thermal stress analysis conducted on the pressure vessel with varying shell thicknesses and ambient temperatures.

5.1 Methodology:

5.1.1 Design Parameters and Boundary Conditions:

- **Shell Thickness:** The minimum required thickness, including corrosion allowance, is calculated to be 10.92 mm. For the analysis, we considered shell thicknesses of 8 mm, 10 mm, 12 mm, 15 mm, 20 mm, and 25 mm.

- **Ambient Temperatures:** Analyses were conducted for ambient temperatures of 0°C, 25°C, and 50°C.
- **Internal Convection:** Convection was applied on the internal surface using stagnant air at 150°C.
- **Fixed Support:** The saddles of the pressure vessel were modeled as fixed supports.
- **Internal Pressure:** An internal pressure of 1.034 MPa was applied uniformly on the internal surface of the pressure vessel.

5.1.2 Finite Element Analysis (FEA):

- **Modeling Software:** The analysis was performed using ANSYS Fluent, a computational fluid dynamics (CFD) and finite element analysis (FEA) software.
- **Meshing:** The pressure vessel was discretized into finite elements with finer meshing around areas expected to experience higher stress concentrations.
- **Solver Settings:** The analysis was set to solve for both thermal and structural behavior under the defined boundary conditions **.**

5.2 Results:

5.2.1 Temperature Distribution:

- Temperature distributions within the pressure vessel for various shell thicknesses and ambient temperatures were obtained.
- Higher ambient temperatures resulted in reduced thermal gradients, while thicker shells showed more uniform temperature distributions.

5.2.2 Deformation:

- Deformation patterns showed that thinner shells experienced greater displacement under thermal loading.
- Maximum deformation occurred at the middle of the vessel length, reducing near the supports.
- As shell thickness increased, overall deformation decreased significantly.

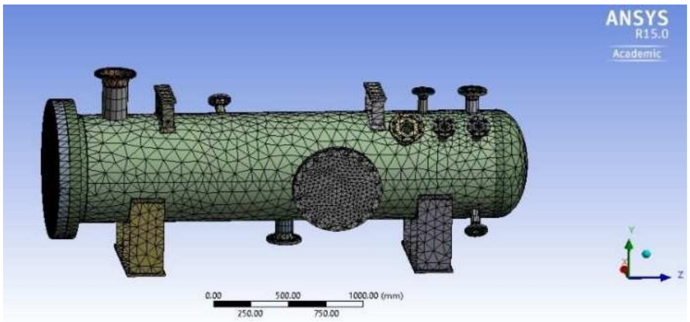
5.2.3 Thermal Stress:

- Thermal stresses were evaluated, focusing on hoop and longitudinal stresses.
- Thinner shells (8 mm, 10 mm) experienced higher thermal stresses, especially near the fixed supports and nozzle connections.
- Increasing shell thickness reduced thermal stresses, with the 25 mm thickness showing the least stress concentration.
- Thermal stress was also observed to decrease with higher ambient temperatures, reducing the differential between internal and external temperatures .

5.3 Discussion:

- **Optimal Thickness:** A shell thickness of 15 mm or more significantly reduces thermal stresses and deformations, ensuring better structural integrity under the given thermal and pressure loads.
- **Ambient Temperature Impact:** Higher ambient temperatures (50°C) are beneficial in reducing thermal gradients and associated stresses, whereas lower ambient temperatures (0°C) increase the thermal load differential, leading to higher stresses.
- **Design Considerations:** While a minimum thickness of 10.92 mm meets the basic design criteria, considering a slightly higher thickness (e.g., 15 mm) provides a safer margin against thermal stresses and deformations.

The results demonstrate the importance of accounting for both thermal and pressure loads in the design and analysis of pressure vessels, ensuring safe and efficient operation under varying thermal conditions.



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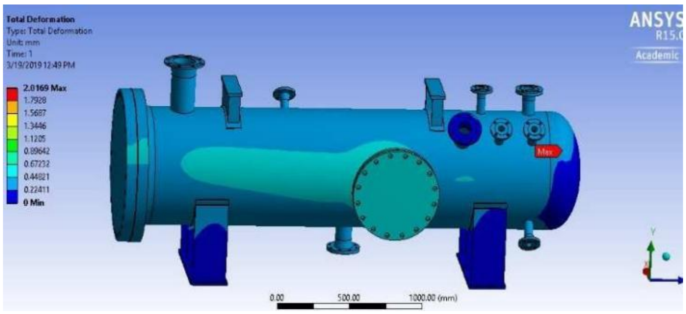

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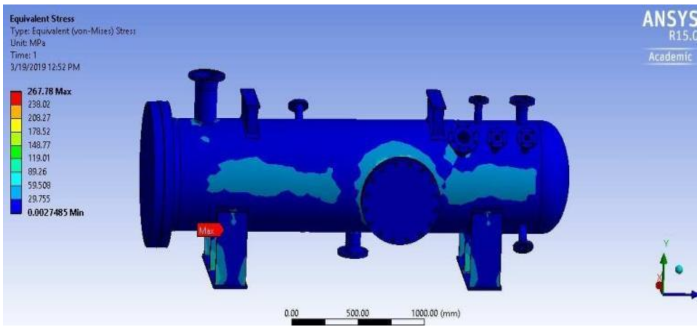

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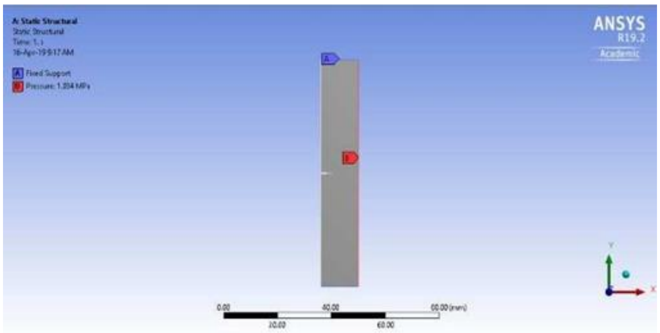
Fig 5.1: Thermal Stress Analysis of ASME Material for load in 14 mm Thickness: (a) Mesh with Element size of 100 mm (b) Total Deformation (c) Thermal Stress Analysis.



(A)

Tuijin Jishu/Journal of Propulsion Technology
ISSN: 1001-4055
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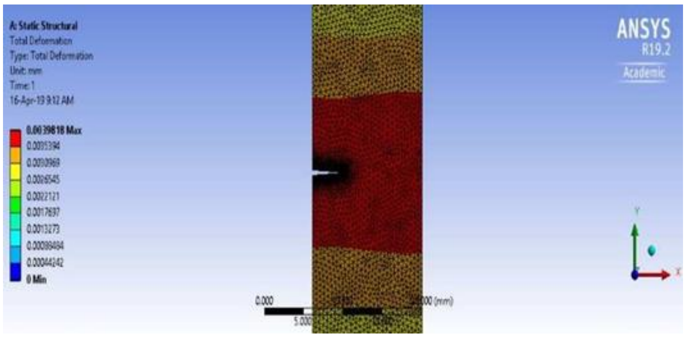

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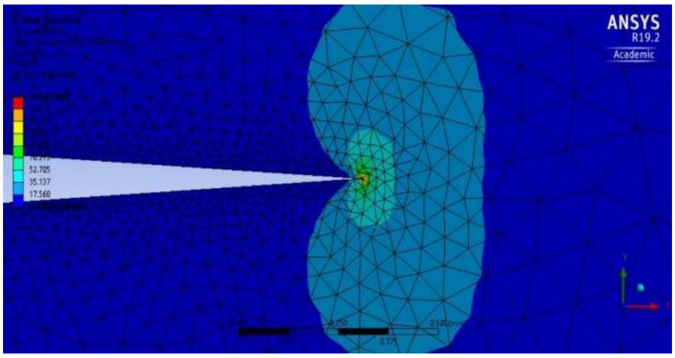

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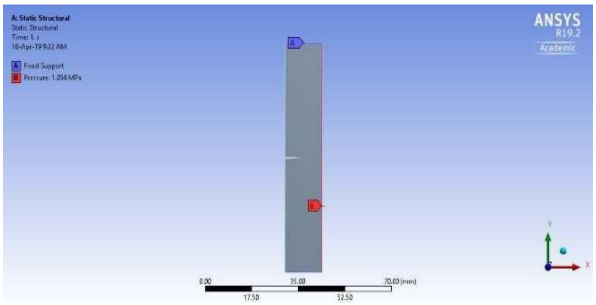
Fig 5.2: Crack Propagation Growth Considering 4 mm (a) Plate with FixedSupport and Pressure (b) Total Deformation (c) Static Stress Analysis



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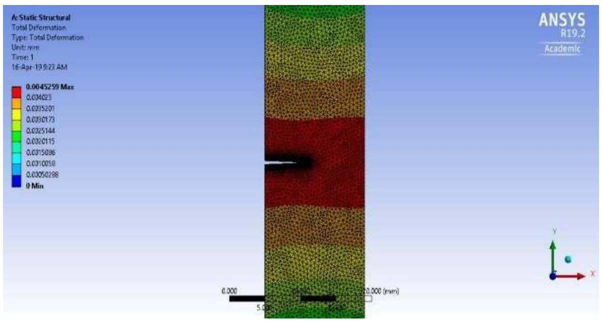

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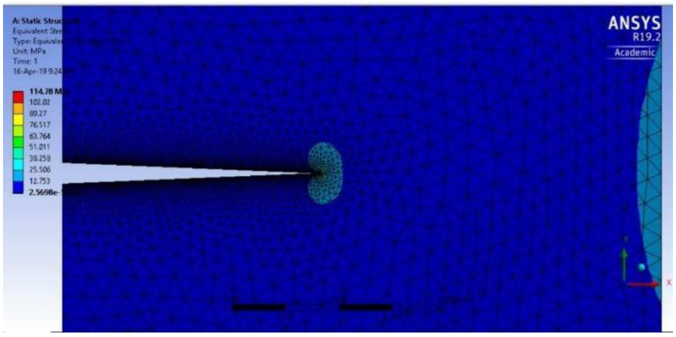


(C)

Fig 5.3: Crack Propagation Growth Considering 7 mm (a) Plate with FixedSupport and Pressure (b) Total Deformation (c) Static Stress Analysis.

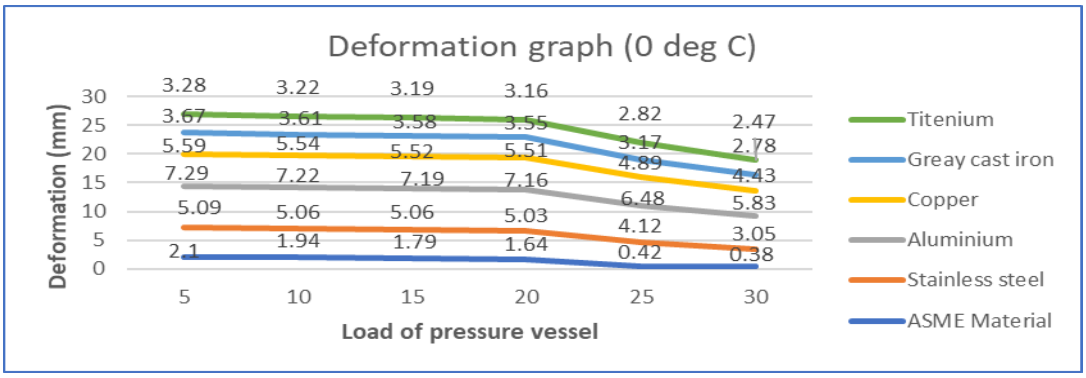
Table 1: Thermal Stress Analysis Results

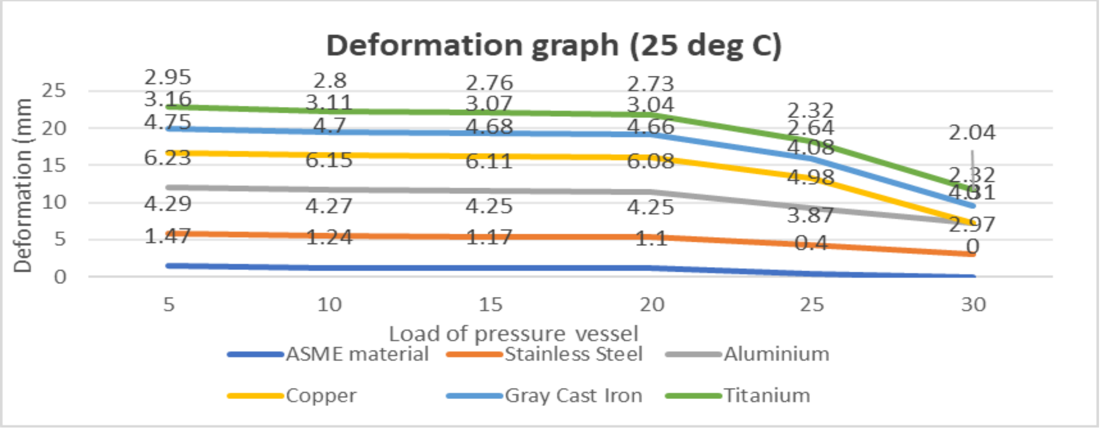
Material	Load(mm)	0 Deg C		25 Deg C		50 Deg C	
		Deformation (mm)	Thermal Stress (Mpa)	Deformation (mm)	Thermal Stress (Mpa)	Deformation (mm)	Thermal Stress (Mpa)
ASME Material	5	2.10	181.42	1.47	145.90	0.91	129.39
	10	1.94	172.47	1.24	137.41	0.81	114.65
	15	1.79	157.01	1.17	129.33	0.75	101.90
	20	1.64	102.40	1.10	98.31	0.69	92.45
	25	0.42	78.23	0.40	70.27	0.32	62.33
	30	0.38	57.47	0.36	52.44	0.27	46.59
StainlesSteel	5	5.09	1359.90	4.29	1135.60	3.46	911.34
	10	5.06	1340.70	4.27	1116.30	3.49	891.83
	15	5.06	1252.80	4.25	1046.10	3.45	839.35
	20	5.03	1145.70	4.25	956.60	3.45	767.36
	25	4.12	987.42	3.87	814.49	3.01	689.40
	30	3.05	823.67	2.97	694.82	2.12	569.42
Aluminium	5	7.29	695.09	6.23	581.69	5.18	468.30
	10	7.22	674.49	6.15	561.00	5.09	447.51
	15	7.19	635.24	6.11	531.49	5.05	427.74
	20	7.16	575.39	6.08	481.29	5.01	387.18
	25	6.48	442.89	4.98	386.11	3.74	293.47
	30	5.83	328.38	4.31	273.47	2.88	173.44
Copper	5	5.59	846.69	4.75	708.06	3.92	569.24
	10	5.54	825.73	4.70	686.99	3.86	548.26
	15	5.52	779.19	4.68	649.58	3.84	519.96
	20	5.51	711.69	4.66	591.10	3.82	470.68
	25	4.89	603.40	4.08	453.44	3.38	378.94
	30	4.43	488.97	3.74	378.31	2.97	302.56
Gray CastIron	5	3.67	498.78	3.16	417.89	2.71	337.00
	10	3.61	480.40	3.11	399.45	2.61	318.51
	15	3.58	463.67	3.07	388.39	2.57	316.48
	20	3.55	428.56	3.04	358.89	2.54	295.96
	25	3.17	368.31	2.64	291.64	1.83	240.87
	30	2.78	309.82	2.32	238.77	1.47	183.34

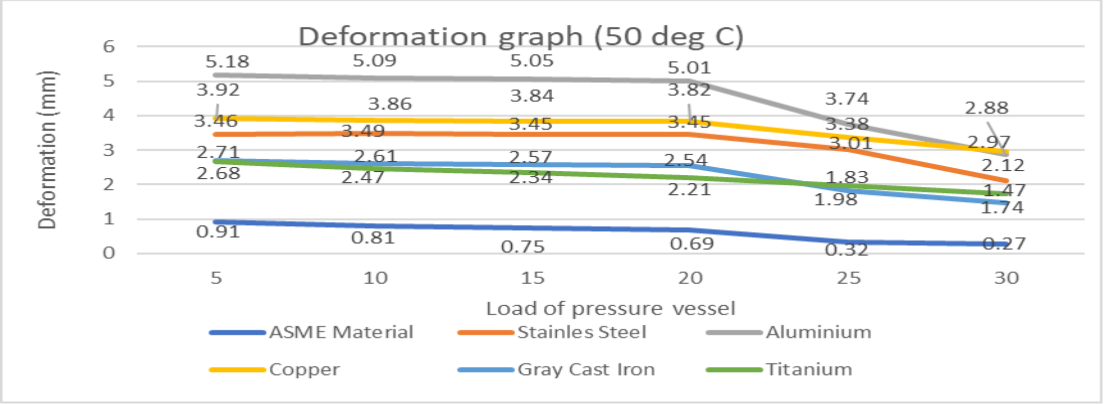
Titanium	5	3.28	401.02	2.95	336.77	2.68	272.53
	10	3.22	378.69	2.80	314.37	2.47	250.06
	15	3.19	366.15	2.76	305.40	2.34	252.53
	20	3.16	331.28	2.73	274.03	2.21	232.53
	25	2.82	285.45	2.32	238.75	1.98	186.34
	30	2.47	224.78	2.04	174.34	1.74	141.13

Graphs:

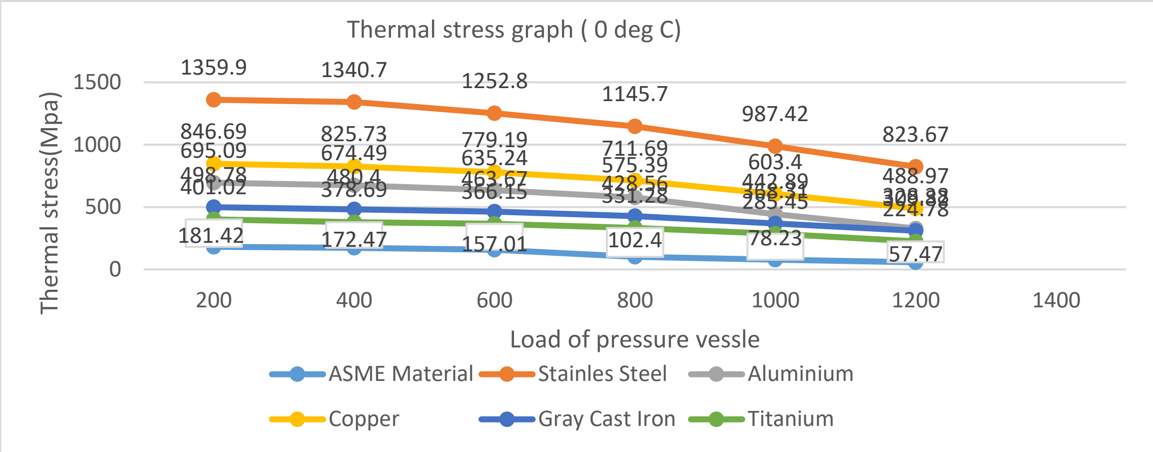
Deformation Graphs of Different Materials load at different temperature

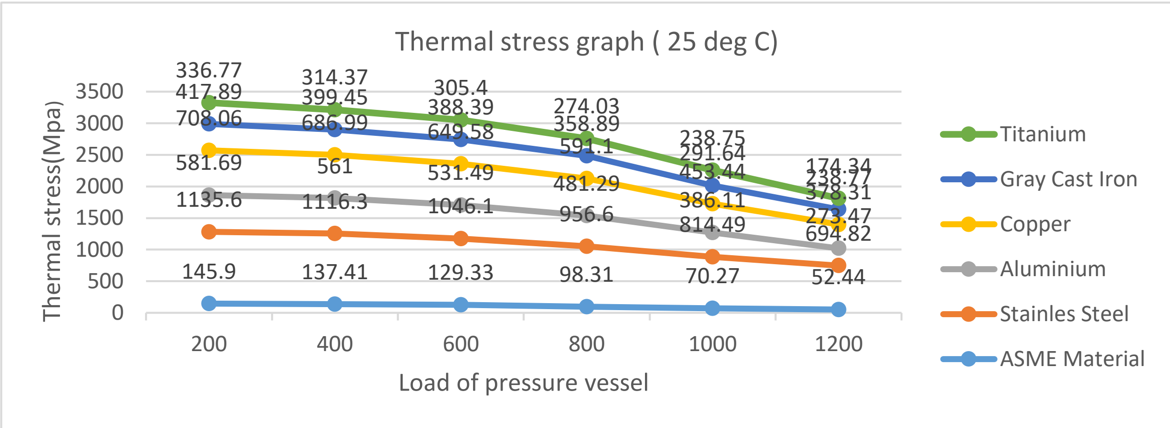


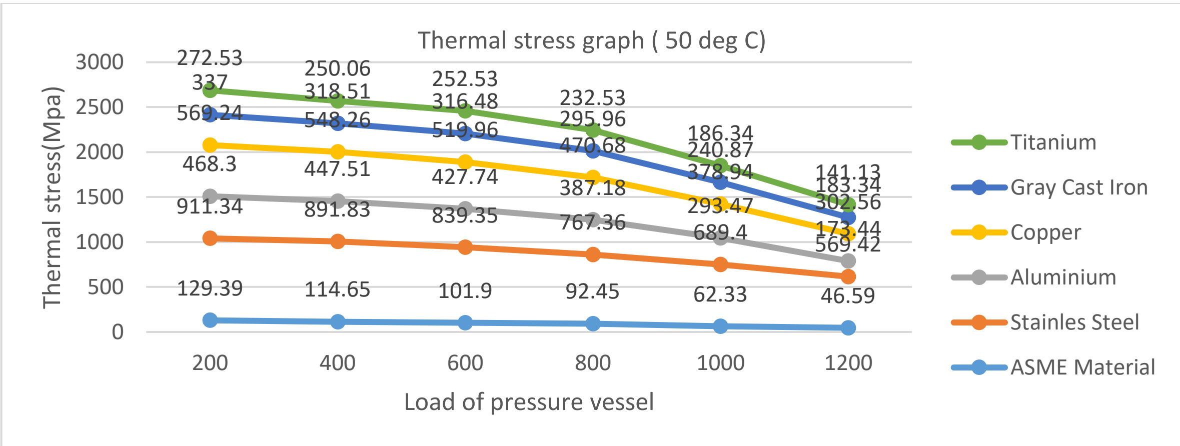




Thermal Stress Graphs of Different Material load at Different Ambient Temperatures







5.4 Implications of Load Factor: Applying the load factor to the thermal stress and deformation values:

- **Stainless Steel:** When the load factor is applied, the effective stress increases further, emphasizing its unsuitability for horizontal pressure vessels subjected to significant thermal loads.
- **ASME Material:** With the load factor, the effective thermal stress remains within acceptable limits, reinforcing its reliability and compliance with ASME standards.

- **Titanium Alloy:** The already high thermal stress becomes even less manageable with the load factor, further reducing its reliability despite its excellent material properties.

5.5 Discussion of Findings: The application of the load factor confirms that:

- **Optimal Thickness and Material:** A shell thickness of 15 mm or more and the use of ASME-compliant materials provide a safer margin against thermal stresses and deformations.

- **Material Selection:** Despite its higher cost, stainless steel is preferable for vertically oriented vessels, while ASME materials are better suited for horizontal configurations under variable thermal loads.

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