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Design and Analysis of a Waste Heat Recovery System for Domestic Refrigerators

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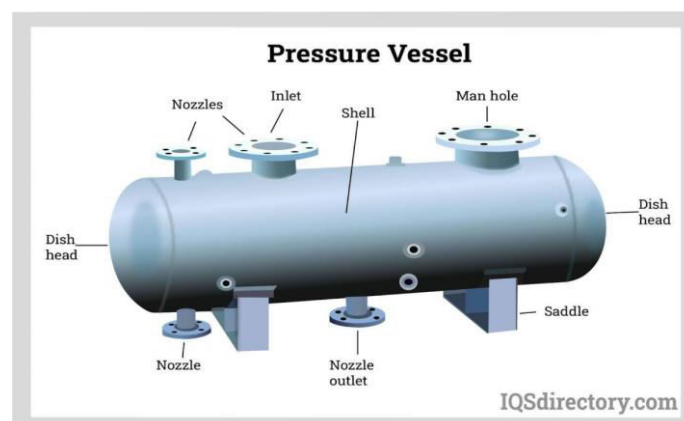
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ABSTRACT: Energy conservation has become a crucial concern in the face of rising fuel costs and growing environmental issues. A significant amount of energy is lost in residential settings, particularly through household appliances such as refrigerators and water heaters. Refrigerators, while essential, release a considerable amount of heat from their condensers directly into the surroundings, contributing to energy wastage and thermal pollution, often referred to as the "heat island effect." On the other hand, water heating systems consume large amounts of electricity or gas to produce hot water. This project explores a practical solution that combines these two systems by capturing the waste heat from a refrigerator's condenser and using it to heat water. By integrating a heat recovery system, this approach aims to utilize otherwise wasted energy for a useful domestic purpose without affecting the normal operation of the refrigerator. Through an extensive review of existing research and feasibility studies, the project demonstrates that such a setup is both technically possible and economically beneficial. This system holds the potential for wide adoption in households and small-scale industries, contributing to improved energy efficiency and reduced environmental impact.

KEYWORDS: Waste heat recovery, Refrigerator condenser heat recovery, Energy efficiency, Hot water heating

I. INTRODUCTION

Pressure vessels are essential components in various industries, designed to contain fluids or gases under high-pressure conditions. They serve diverse applications such as chemical reactors, steam generators, storage tanks, and heat exchangers. Constructed with materials like carbon steel and stainless steel, pressure vessels adhere to stringent engineering standards and codes, ensuring safety and reliability. Regular inspection and maintenance are crucial to prevent accidents and ensure continued operation.[1] Compliance with regulatory standards, such as the ASME Boiler and Pressure Vessel Code, is mandatory. Overall, pressure vessels play a vital role in industrial processes, providing a safe and efficient means of handling fluids and gases at elevated pressures.[3]



Typical Components

Fig 1-Typical component of Pressure vessel

A) Introduction to ASME Codes

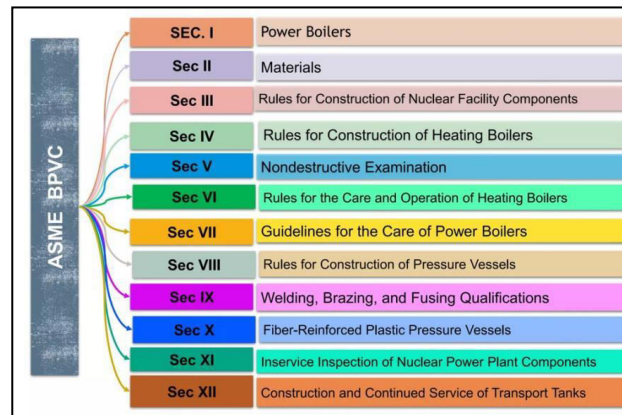


Fig 2- ASME Standard

The ASME Code refers to the set of standards and codes developed by the American Society of Mechanical Engineers (ASME). Specifically, the ASME Boiler and Pressure Vessel Code (BPVC) is one of the most widely used and recognized codes in the field of mechanical engineering, particularly in the design, construction, and inspection of pressure vessels and boilers. [2]

The ASME Code is not a single document but a collection of various sections, each addressing different aspects of pressure vessel and boiler design and fabrication. The key sections of the ASME BPVC include:

- Section I: Rules for Construction of Power Boilers: Provides requirements for the design, fabrication, and inspection of power boilers, including high-pressure boilers used in power generation.
- Section II: Materials: Specifies requirements for materials used in the construction of pressure vessels and boilers. It includes specifications for various materials, such as ferrous and non-ferrous alloys.
- Section III: Rules for Construction of Nuclear Facility Components: Focuses on the design and construction of nuclear power plant components
- Section IV: Rules for Construction of Heating Boilers: Addresses the design, construction, and inspection of boilers used for heating purposes, excluding power boilers.
- Section V: Nondestructive Examination: Outlines various nondestructive testing methods used to assess the integrity of materials and welds.
- Section VI: Rules for the care and operation of heating boilers
- Section VII: The Recommended Guidelines for the Care of Power Boilers, is a section of the ASME Boiler and Pressure Vessel Code that provides guidelines for the safe and reliable operation of power boilers. The section's purpose is to promote safety in the use of power boilers
- Section VIII: Rules for Construction of Pressure Vessels: This is a crucial section for pressure vessel design. It provides guidelines for the design, fabrication, and inspection of pressure vessels, including rules for determining allowable stresses, welding requirements, and vessel testing.
- Section IX: Welding and Brazing Qualifications: Specifies requirements for the qualification of welding and brazing procedures, welders, and braziers.
- Section X: Fiber-Reinforced Plastic Pressure Vessels: Covers the design and construction of fiber reinforced plastic pressure vessels.
- Section XI: Rules for In-service Inspection of Nuclear Power Plant Components: Focuses on the in-service inspection and testing of nuclear power plant components.
- Section XII: Rules for Construction and Continued Service of Transport Tanks: Addresses the design, construction, and ongoing service of transport tanks.[2]

B) Introduction to Crude Column

The refining industry plays a pivotal role in meeting global energy demands by converting crude oil into various valuable products. Within this intricate landscape of refining processes, the crude column stands as a critical component, facilitating the separation of crude oil into its constituent fractions. Crude oil distillation is the separation of hydrocarbons in crude oil into fractions based on their boiling points which lie within a specified range. The separation is done in a large tower that is operated at atmospheric pressure. Process used for separation of hydrocarbon called as Fractional distillation process.[3]

C) Fractional Distillation

Imagine a ladder extending through the heart of the column. Each rung represents a different level of temperature and molecular weight. Lighter, more volatile components climb the ladder first, vaporizing at lower temperatures and condensing higher up. Heavier molecules, clinging to their liquid form, take their time, descending the ladder to meet their designated exit points. This intricate dance of separation, known as fractional distillation, unlocks the hidden treasures within the crude.[3]

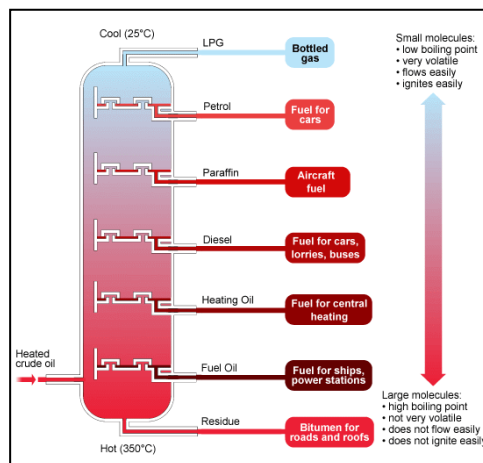


Fig 3 – Fractional distillation process

D) Background of the Project

The design and analysis of crude columns constitute a fundamental aspect of process engineering within the petroleum industry. As crude oil compositions vary significantly across different sources, the design of crude columns necessitates a meticulous understanding of thermodynamics, fluid dynamics, and material science. By effectively separating crude oil into its constituent fractions such as gasoline, diesel, and heavier hydrocarbons, crude columns serve as the cornerstone of downstream refining processes.[5]

E) Importance of Crude Columns in Industry

Crude columns are indispensable components within refining facilities, serving as the primary means of separating crude oil into its various hydrocarbon products. The efficiency and reliability of crude column operations directly impact the overall productivity and profitability of refining operations. Moreover, adherence to industry standards, such as those outlined in the American Society of Mechanical Engineers (ASME) Section VIII Division 1, ensures the structural integrity and safety of crude column installations.[4]

II. OBJECTIVES

The primary objective of this project is to undertake a comprehensive design and analysis of a crude column based on given operational parameters and industry standards. Specifically, the project aims to:

1. Employ ASME Section VIII Division 1 standards to design a crude column capable of efficiently separating crude oil into its constituent fractions.

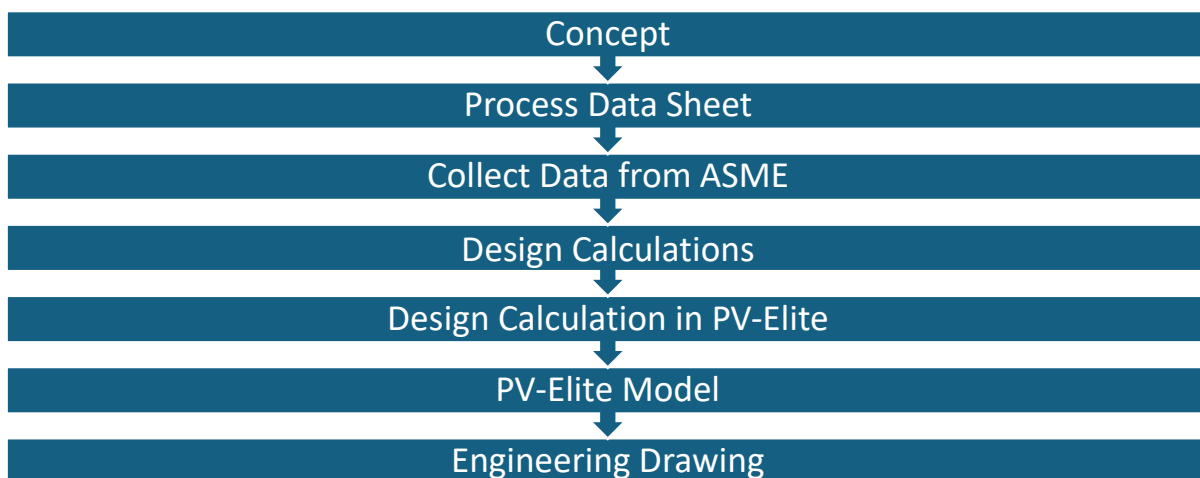
2. Perform manual calculations to determine key design parameters, including pressure, temperature, and material selection, ensuring compliance with regulatory requirements and operational needs.
3. Validate the design using advanced engineering software, such as PV Elite, to assess structural integrity, thermal performance, and operational safety.
4. Generate detailed assessment drawings of the crude column, incorporating design specifications and operational considerations to facilitate construction and installation processes.
5. Provide insights into the feasibility, efficacy, and practical implications of the designed crude column, thereby contributing to the body of knowledge within the field of refining engineering.

III. SCOPE

1. Understanding the purpose, operating conditions, and expected lifespan of the vessel.
2. Familiarity with applicable codes and standards (e.g., ASME BPVC) governing pressure vessel design.
3. Evaluating material properties based on factors like temperature, pressure, corrosion resistance, and compatibility with the process fluid.
4. Designing and implementing pressure relief systems to prevent overpressure events.
5. Developing welding procedures and specifications for vessel fabrication.

IV. METHODOLOGY

This entire project is a planning and design using ASME code and methodology followed in this is as follow:



V. LITERATURE REVIEW

Pioneering research laid the groundwork for modern distillation. McCabe-Thiele's groundbreaking work on tray efficiency illuminated the path, while Gilliland's rigorous modeling techniques solidified the foundation. Sorel's insights into mass transfer principles continue to guide vapor-liquid contact optimization within the column.[1]

Evolution marched on Computational tools like CFD simulations soared in popularity, visualizing flow patterns, predicting mass transfer rates, and pre-empting potential issues. Structured packing emerged, offering increased flexibility and efficiency compared to its traditional tray counterparts.[2]

Sustainability became the rallying cry. Heat recovery strategies, emission control technologies, and eco-friendly materials dominated research avenues. Adapting to diverse feedstock compositions and optimizing for dynamic operating conditions became pressing concerns.[3]

Unresolved mysteries lingered. Fouling behavior prediction and real-time optimization remained elusive. Artificial intelligence and machine learning beckoned on the horizon, promising revolutionary advances in process control. Novel separation technologies whispered of a future beyond traditional distillation.[4]

This literature equips us with the knowledge and inspiration to forge our own path in crude column design. Standing on the shoulders of giants, we embrace the challenges and opportunities that lie ahead, striving for a future where efficiency and sustainability dance hand-in-hand.[5]

VI. DETAILS OF PROJECT

6	MECHANICAL DATA			Re
7	Design Code		ASME Section VIII Div.1 2019 Edition	
8	Content		Hydrocarbons , Liquid / Vapor	
9	Design Pressure (Internal/External)	bar (g)	4.5 / FV	
10	Design Temperature	°C	400	
11			TOP BOTTOM	
12	Operating Pressure	bar (a)	0.35 1	
13	Operating Temperature	°C	150 350	
14	Hydrotest Pressure	bar (g)	As per Code	
15	Density (Vapour/Liquid)	kg /m ³	4.21 / 705.00	
16	Capacity	m ³	6.6	
17	Corrosion Allowance	mm	0	
18	MDMT	°C	-23	
19	Joint Efficiency (Shell / Head)		1.0 / 1.0	
20	Radiography (Shell / Head)		Full	
21	PWHT		As per code	
22	Insulation (Top / Bottom)		100 / 140	
23	Fireproofing		No	
24	Painting		Yes	
25	Pickling & Passivation		Yes (For SS Internals only)	
26	Inspection By		Purchaser/TPI	
27	Code stamp		No	
28	Wind Data		As per note 15	
29	Seismic Data		As per note 16	
30	Empty Weight	kgs	To be provided	
31	Operating Weight	kgs	To be provided	
32	Hydrotest Weight (Shop)	kgs	To be provided	
33				
34	MATERIAL SPECIFICATION			
35	Shell	SA 240 GR. 316L /SB 127 (for top 3m)	Internal Attachments	SS 316L
36	Dished Ends		External Attachments	SA 516 GR 70
37	Nozzle Necks (Fab.)	SA 240 GR. 316L	Internal Bolting / Nuts	SA 193 GR. B8M / SA 194 GR. 8M
38	RF Pad	SA 240 GR. 316L	Nozzle Bolting / Nuts	SA 193 GR. B7 / SA 194 GR. 2HM
39	Nozzle Pipes	SA 312 TP 316L	Gaskets	SS 316 Spiral wound with graphite filler with SS inner and outer ring
40	Nozzle Flanges	SA 182 F 316L		
41	Pipe Fittings	SS 316L		
42	Support	SA 516 Gr. 70		
43	Name Plate	SS316		
44	Earthing Boss	SS316		
45	Anchor Bolt	SA 307 Gr B		
46				
47				
48				

Table No 6.1: Process Data Sheet

NOZZLES SCHEDULE										
NOZ ZLE	SIZE (NPS)	QTY.	SCH/ THK	FLANG E RATING	FLANG E TYPE / FACING	PROJECTI ON (NOTE 3)	PAD W X T	SERVICE	Remarks	Rev
N1	4"	1			WNRF			Inlet		
N2	3"	1			WNRF			Bottom Liquid Outlet	With vortex breaker	
N3	10"	1			WNRF			Top Vapour Outlet		
N4	2"	1			WNRF			Reflux from Naphtha Pump		
N5	2"	1			WNRF			Utility Connection		
N6	2"	1			WNRF			Diesel to Diesel Stripper		
N7	2"	1			WNRF			Diesel Vapours from Diesel Stripper		
N8	2"	1			WNRF			MCF		
N9	3"	1			WNRF			Spare		
K1	2"	1			WNRF			Temperature Transmitter		
K2	2"	1			WNRF			Temperature Transmitter		
K3A/B	2"	2			WNRF			Level transmitter		
K4A/B	2"	2			WNRF			Level transmitter		
K5	2"	1			WNRF			Level Switch		
K6	2"	1			WNRF			Temperature Transmitter		
K7A/B	2"	2			WNRF			Pressure Differential Indicator		
H1	8"	1			WNRF			Hand Hole		

Table No 6.2: Process Data Sheet for Nozzle

VII. DESIGN CALCULATION (SOFTWARE)

A) INPUT DATA

From	To	X (Horiz.) mm	Y (Vert.) mm	DX (Horiz.) mm	DY (Vert.) mm
Skrit	5000	...	5000
Elliptical 1	5050	...	50
Shell 1	6950	...	1900
Shell 2	13450	...	6500
flange 1	13500	...	50
flange 2	13559.5	...	50
Shell 3	18459.5	...	4900
Shell 4	21459.5	...	3000
Flange 3	21509.5	...	50

Table No. 3 Input Data

INPUT DATA DESCRIPTION

INPUT DATA

Design Internal Pressure (for Hydro test)	0.6895 MPa
Design Internal Temperature	93.3 °C
Type of Hydro test	UG-99(b)
Hydro test Position	Horizontal
Projection of Nozzle from Vessel Top	0 mm
Projection of Nozzle from Vessel Bottom	0 mm
Minimum Design Metal Temperature	-28.9 °C
Type of Construction	Welded
Special Service	None
Degree of Radiography	RT-1

B) Shell Calculation

Internal Pressure Calculation

Element Thickness, Pressure, Diameter and Allowable Stress:

From	To	Int. Press + Liq. Hd MPa	Nominal Thickness mm	Total Corr Allowance mm	Element Diameter mm	Allowable Stress(SE) MPa
Shell	1	0.45	8	...	710	90.934
Shell	2	0.45	8	...	710	90.934
Shell	3	0.45	8	...	710	90.934
Shell	4	0.45	8	...	710	99.9

Table 5: Element Thickness, Pressure, Diameter and Allowable Stress

Element Required Thickness and MAWP:

From	To	Design Pressure MPa	M.A.W.P. Corroded MPa	M.A.P. New & Cold MPa	Minimum Thickness mm	Required Thickness mm
Shell	1	0.45	3.50323	4.43602	8	1.5
Shell	2	0.45	3.01271	3.8149	8	1.76201
Shell	3	0.45	2.02187	2.56023	8	1.76201
Shell	4	0.45	2.22123	2.86604	8	1.60343

Table 6: Element Required Thickness and MAWP

Required Thickness due to Internal Pressure [tr]:

$$= (P \cdot R) / (S \cdot E - 0.6 \cdot P) \text{ per UG-27 (c) (1)}$$

$$= (0.035 \cdot 355.0) / (90.93 \cdot 1.0 - 0.6 \cdot 0.035)$$

$$= 1.7367 + 0.0000$$

$$= 1.7367 \text{ mm}$$

Max. Allowable Working Pressure at given Thickness, corroded [MAWP]:

$$= (S \cdot E \cdot t) / (R + 0.6 \cdot t) \text{ per UG-27 (c)(1)}$$

$$= (90.93 \cdot 1.0 \cdot 14.0) / (355.0 + 0.6 \cdot 14.0)$$

$$= 3.503 \text{ MPa}$$

Maximum Allowable Pressure, New and Cold [MAPNC]:

$$= (S \cdot E \cdot t) / (R + 0.6 \cdot t) \text{ per UG-27 (c)(1)}$$

$$= (115.15 \cdot 1.0 \cdot 14.0) / (355.0 + 0.6 \cdot 14.0)$$

$$= 4.436 \text{ MPa}$$

Actual stress at given pressure and thickness, corroded:

$$= (P \cdot (R + 0.6 \cdot t)) / (E \cdot t)$$

$$= (0.035 \cdot (355.0 + 0.6 \cdot 14.0)) / (1.0 \cdot 14.0)$$

Results for Maximum Stiffened Length (Slen):

Tca	OD	SLEN	D/t	L/D	Factor A	B
14.000	738.00	404263.34	52.71	50.0000	0.0003998	27.20
					0.688 MPa	

$$\text{EMAP} = (4 \cdot B) / (3 \cdot (D/t)) = (4 \cdot 27.2004) / (3 \cdot 52.7143) =$$

COMPARISON BETWEEN MANUAL & SOFTWARE CALCULATION FOR SHELL:

	Manual Result	Software Result
Required Thicknesses	1.7	1.76
Design Thicknesses	2	2
Nominal Thicknesses	2	2
External calculation	Failed	Failed
New Required Thickness	8	8
New Design & Nominal Thickness	8	8

Table 7: Comparison between Manual & Software Results

C) Dished Calculation

Element Thickness, Pressure, Diameter and Allowable Stress :

From	To	Int. Press + Liq. Hd MPa	Nominal Thickness mm	Total Corr Allowance mm	Element Diameter mm	Allowable Stress(SE) MPa
Elliptical	1	0.45	14	...	710	90.934

Table 8: Element Thickness, Pressure, Diameter and Allowable Stress

INTERNAL PRESSURE CALCULATION RESULTS:

ASME Code, Section VIII Division 1, 2017
Elliptical Head From 20 To 30 SA-240 316L at 400 °C

Required Thickness due to Internal Pressure [tr]:

$$= (P \cdot D \cdot K_{cor}) / (2 \cdot S \cdot E - 0.2 \cdot P)$$
 Appendix 1-4(c)

$$= (0.45 \cdot 710.0 \cdot 1.0) / (2 \cdot 90.93 \cdot 1.0 - 0.2 \cdot 0.45)$$

$$= 1.7576 + 0.0000 = 1.7576 \text{ mm}$$

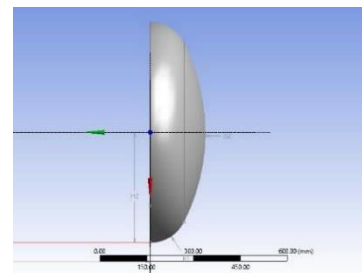
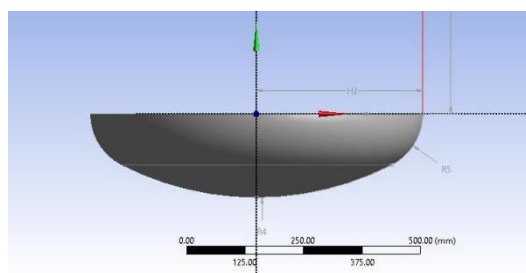


Fig 15: Dish End 3D Model

External Pressure Calculation Results:

From	To	Int. Press + Liq. Hd MPa	Nominal Thickness mm	Total Corr Allowance mm	Element Diameter mm	Allowable Stress(SE) MPa
Elliptical	1	0.45	14	...	710	90.934

Table 10: External Pressure Calculation Results

Element Required Thickness and MAWP:

ASME Code, Section VIII Division 1, 2017
Elliptical Head From 20 to 30 Ext. Chart: HA-4 at 400 °C
Elastic Modulus from Chart: HA-4 at 400 °C : 0.162E+06 MPa
Results for Maximum Allowable External Pressure (MAEP):

Tca	OD	D/t	Factor AB	
14.0	738.00	52.71	0.0026347	39.32

VIII. RESULTS AND DISCUSSION

The results obtained from the design and analysis of the crude column are presented in this section, along with a discussion of their significance and implications.

Design Parameters:

Based on the given data including pressure, temperature, and material properties, the design parameters such as shell thickness, head thickness, and nozzle sizes were calculated manually. These calculations were then validated using PV Elite software, ensuring compliance with ASME SEC 8 DIV 1 standards. The results indicate that the design meets the required safety factors and structural integrity criteria.

General Assessment Drawing:

A comprehensive general assessment drawing of the crude column was prepared based on the calculated parameters. This drawing provides a detailed overview of the column's layout, including dimensions, component

locations, and nozzle orientations. It serves as a visual reference for fabrication and installation purposes, ensuring accurate implementation of the design.[3]

IX. CONCLUSION

In summary, this project has successfully executed the design and analysis of a crude column in accordance with ASME SEC 8 DIV 1 standards. By combining manual calculations with validation through PV Elite software, we ensured the column's structural integrity and safety under varying operational conditions. Comprehensive 3D and GA drawings facilitated a clear understanding of the column's layout and components. Emphasizing safety, efficiency, and sustainability, the project adhered to industry best practices, contributing to enhanced standards within the field. While objectives were achieved and the project scope addressed, the iterative nature of engineering design implies ongoing refinement and improvement.

This endeavor provides valuable insights into practical engineering applications, particularly in pressure vessel design, offering a foundation for future research and development. By fostering collaboration and innovation, we can continue advancing industrial safety and efficiency. This conclusion encapsulates the project's achievements, methodologies, and implications, serving as a significant resource for engineers and researchers engaged in process equipment design.

In conclusion, the successful completion of this project underscores the importance of meticulous design, rigorous analysis, and adherence to standards in ensuring the safety and efficiency of industrial equipment.

ACKNOWLEDGEMENT

The successful design and analysis of the crude column demonstrate the efficacy of the methodologies employed in this project. By integrating manual calculations with software validation, we have developed a robust design that meets industry standards and operational requirements. The general assessment drawing further enhances the clarity and understanding of the column's design, facilitating seamless fabrication and installation processes.

Moreover, the adherence to ASME SEC 8 DIV 1 standards underscores our commitment to safety and quality in engineering practice. The results obtained from this project not only validate the design approach but also contribute to the body of knowledge in pressure vessel design and analysis.

Overall, the outcomes of this project highlight the importance of rigorous design procedures, collaborative efforts, and adherence to standards in ensuring the reliability and safety of industrial equipment. Moving forward, the insights gained from this project can inform future research and development initiatives in process equipment design and optimization.

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