International Journal of Engineering, Technology and Natural Sciences
E-ISSN : 2685-3191 | P-ISSN: 2775-7706
Vol 6 No 1 (2024)

Designing of a Shell and Tube Heat Exchanger for Methyl Chloride Production

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Abstract

This study focuses on the design and performance analysis of a shell-and-tube heat exchanger engineered explicitly for effectively handling methyl chloride in industrial applications. While the application of heat exchangers in various industrial processes is well-documented, methyl chloride's distinct chemical and physical properties necessitate a specialized design approach. This research begins with a thorough review of existing literature and prior designs to identify the key considerations and challenges in developing an optimized heat exchanger for methyl chloride. The design process adheres to the standards set forth by the Tubular Exchanger Manufacturers Association (TEMA), ensuring compliance with established dimensional specifications. Critical parameters related to the working fluid are meticulously defined and evaluated. Performance analysis is conducted through manual calculations, facilitated by Microsoft Excel, to assess the heat exchanger's operational efficiency. The results indicate that the designed heat exchanger meets and exceeds the required standards, featuring 85 tubes and an effectiveness value exceeding 75%. The high effectiveness value underscores the heat exchanger's robust operational performance. It is a reliable component for industrial processes involving methyl chloride.

Keywords: Effectiveness, Heat Exchanger Parameters, Methyl Chloride, Shell, and Tube.

I. INTRODUCTION

Heat exchangers are crucial for heat and mass exchange in various industries such as oil refining, chemical engineering, environmental protection, electric power generation, and more [1]. A heat exchanger is a device used to transfer heat from one medium to another without the two mediums coming into direct contact. It facilitates the exchange of thermal energy between two or more fluids at different temperatures. This transfer can involve heating or cooling one fluid by transferring heat to or from another fluid or substance. Shell-and-tube heat exchangers (STHXs) are one of the widely employed types across industries [2]. Over 35–40% of heat exchangers belong to the shell-and-tube category [3]. This prevalence is primarily attributed to the robust structural design, convenient maintenance, and potential for upgrades offered by STHXs. Their versatility extends to widespread applications as both evaporators and condensers.

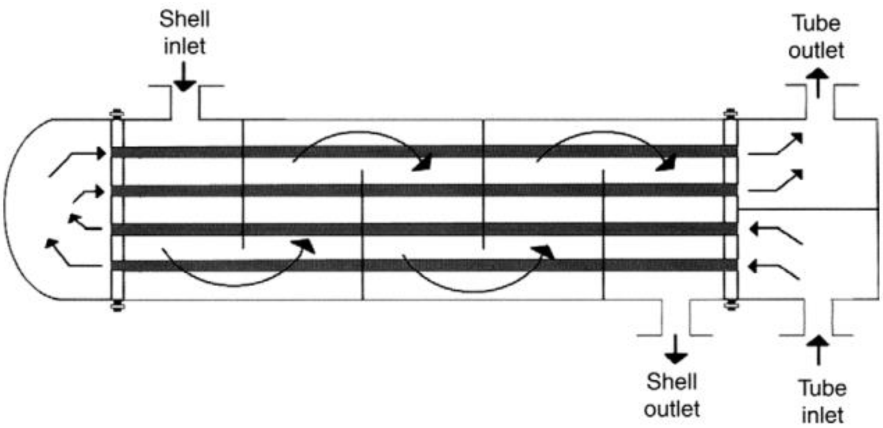

Figure 1 Schematic Illustration of a Shell-and-Tube Heat Exchanger [4]

In the production of methyl chloride, shell-and-Tube heat exchangers are integral to processes such as condensation and cooling, where maintaining precise temperature control and achieving efficient heat transfer are critical to the overall efficiency and effectiveness of the production process. These heat exchangers are designed to handle the specific thermal and pressure requirements inherent to methyl chloride production. It ensures that the heat transfer is optimized and the temperatures are regulated accurately throughout the various processing stages. Their design allows for effective thermal load management, crucial for processes requiring careful temperature management to ensure product quality and process efficiency.

Furthermore, shell-and-tube heat exchangers are well-suited for handling the high pressures and diverse temperature ranges typically encountered in synthesizing methyl chloride. Their robust construction and adaptability make them a practical choice for these demanding applications. By efficiently managing heat exchange in these critical stages, shell-and-tube heat exchangers contribute significantly to the stability and reliability of the production process, thereby enhancing the overall efficiency and safety of methyl chloride synthesis. Their ability to accommodate varying operational conditions ensures they meet the rigorous demands of the chemical production environment, ultimately supporting methyl chloride's successful and efficient production.

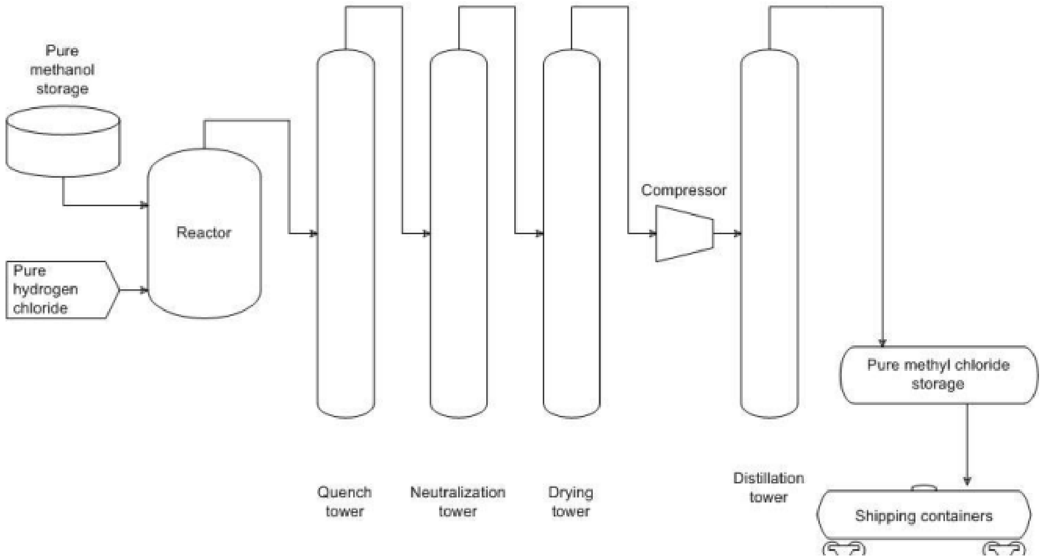

Figure 2 Scheme of The Methyl Chloride Production [5]

The evaluation of heat exchanger efficiency relies on determining the minimum heat transfer area and assessing the pressure drop occurring within the exchanger. The evaluation of heat exchanger efficiency relies on determining the minimum heat transfer area and assessing the pressure drop occurring within the exchanger [6]. Nandiyanto et al. designed a shell and tube heat exchanger (with a dual-pass configuration) intended for use within the titanium dioxide (TiO2) production sector. Their study revealed that the exchanger comprises 29 tubes with an effectiveness exceeding 65% [7]. Furthermore, Apriandi MS et al. developed a straightforward Shell and Tube heat exchanger (single-pass) to recover wasted heat from air conditioning systems within the hospitality industry. The designed heat exchanger successfully met effectiveness standards, boasting 152 tubes and achieving effectiveness exceeding 90% while maintaining an impurity factor of 0.014 [8].

Besides, Alm et al. designed and tested a complex ceramic micro heat exchanger. Using a combination of rapid prototyping methods—stereolithography and low-pressure injection molding—alumina micro-components were precisely manufactured in micrometer sizes. The heat exchanger, assembled from sintered components using glass solder, underwent performance testing at a system pressure of 8 bar after being developed based on its geometric design [9]. Meanwhile, Sadighi Dizaji et al. utilized corrugated shells and tubes instead of smooth ones within a shell and tube heat exchanger. However, introducing corrugations increased exergy loss and NTU (Number of Transfer Units). Specifically, when the tube and shell featured corrugations, the exergy loss and NTU escalated by approximately 17–81% and 34–60%, respectively. The most significant exergy loss was observed in heat exchangers constructed with convex corrugated tubes and concave corrugated shells [10].

This paper focuses on designing and analyzing a shell-and-tube heat exchanger meticulously engineered to handle methyl chloride efficiently. Heat exchangers are universally acknowledged for their critical role in industrial processes, yet the specific and demanding characteristics of methyl chloride require a tailored design approach to ensure optimal performance. Given the unique properties of methyl chloride—such as its chemical reactivity and thermal behavior—the design of the heat exchanger must address these specialized requirements effectively. To achieve this, the study includes a comprehensive review of existing literature and an in-depth exploration of previous designs, aiming to identify the critical factors and challenges inherent in developing an efficient heat exchanger for this application. This detailed analysis outlines the necessary design considerations and potential obstacles, providing a clear framework for developing a heat exchanger that meets the rigorous demands of handling methyl chloride. By integrating insights from prior research and practical design considerations, the study seeks to advance the understanding and application of heat exchangers in contexts requiring specialized handling of complex substances.

II. METHOD

The current heat exchanger, a shell-and-tube type, was designed by the Tubular Exchanger Manufacturers Association (TEMA) standard, which guides the dimensioning of such apparatus. Post dimensioning based on this standard, the initial performance assessment of the equipment involves calculating key heat exchanger parameters. This includes conducting a thermal analysis encompassing calculations for overall values like U (overall heat transfer coefficient), LMTD (log mean temperature difference), Q (heat transfer rate), and pressure drop. All these parameters are referenced from Ragadhita and manually computed utilizing basic Microsoft Office applications, following Equations 1-28 detailed in Table 1.

Table 1 Heat Exchanger Parameters Calculation

Section	Parameter	Equation	Eq.
Basic Parameters	The energy transferred (Q)	$Qc = Qhm_c \times Cp_c \times \Delta T_c \quad = \ m_h \ \times \ Cp_h \ \times \ \Delta T_h$ Where, Q = the energy transferred (Wt) *m* = the mass flow rate of the fluid (Kg/s) *Cp* = the specific heat ΔT = the fluid temperature difference (°C).	(1)
	Logarithmic mean temperature differenced (LMTD)	$LMTD = \frac{(T_{hi} - T_{ci}) - (T_{ho} - T_{co})}{ln \frac{(T_{hi} - T_{ci})}{(T_{ho} - T_{co})}}$ Where, T_{hi} = temperature of hot fluid inlet (°C) T_{ho} = temperature of the hot fluid outlet (°C) Tc_i = temperature of cold fluid inlet (°C) Tc_o= temperature of cold fluid outlet (°C)	(2)
	Correction factor	$P = \frac{T_{co} - T_{ci}}{T_{hi} - T_{ci}}$	(3)
		$R = \frac{T_{hi} - T_{ho}}{T_{co} - T_{ci}}$	(4)
		$F = \frac{\sqrt{R^2 + 1} \ln\left(\frac{1 - P}{1 - PR}\right)}{(R - 1) \ln\left(\frac{2 - P(R + 1 - \sqrt{R^2 + 1}}{2 - P(R + 1 + \sqrt{R^2 + 1}}\right)}$	(5)
		Thus, the value of the temperature change is $\Delta\mathrm{T} = \mathrm{F} \times \mathrm{LMTD}$ Where, T_{hi} = temperature of hot fluid inlet (°C) T_{ho} = temperature of the hot fluid outlet (°C) Tc_i = temperature of cold fluid inlet (°C) Tc_o= temperature of cold fluid outlet (°C) *P* = temperature efficiency of the heat exchanger *R* = ratio of the product of fluid flow in the shell with specific heat to fluid flow in the tube *F* = correction factor Δt = temperature change LMTD = Logarithmic mean temperature differenced (calculated using Eq. 2)	(6)
	Heat Transfer Field Area (A)	$A = \frac{Q}{U(LMTD \times F)}$ Where, Q = the energy transferred (W) U = the overall heat transfer coefficient *LMTD* = the logarithmic mean temperature difference.	(7)

Section	Parameter	Equation	Eq.
	Number of Tubes (Nt)	$Nt = \frac{A}{\pi \times D_o \times l}$	(8)
Tube	Surface Area of Total Heat Transfer in Tube (a_t; m^2)	$a_t = Nt\frac{a't}{n}$	(9)
		$a't = \frac{\pi}{4} \times \left(D_{i,t}\right)^2$	(10)
	Mass Flow Rate of Fluid in Tube (Gt)	$Gt = \frac{m_{th}}{a_t}$	(11)
	Reynold number (Re,t)	$Re_t = \frac{di_t \times Gt}{\mu}$	(12)
	Prandtl Number (Pr,t)	$Pr = \left(\frac{C_p \times \mu}{K}\right)^{\frac{1}{2}}$	(13)
	Nusselt number (Nu,t)	$Nu = 0.023 \times Re_t^{0.6} \times Pr^{0.33}$	(14)
	Inside coefficient (hi)	$hi = \frac{Nu \times K}{d_{i,t}}$	(15)
Shell	Shell flow area (A_s)	$A_s = \frac{d_s \times C \times B}{P_t}$	(16)
	Mass Flow Rate of Water in Shell (Gs)	$Gs = \frac{m_c}{A_s}$	(17)
	Equivalent diameter (de)	$d_e = \frac{4\left(\frac{Pt}{2} \times 0.087\, Pt - \frac{1}{2}\pi\frac{d_{o,t}^2}{4}\right)}{\frac{1}{2}\pi d_{o,t}}$	(18)
	Reynold number (Re,s)	$Re_s = \frac{d_e \times Gs}{\mu}$	(19)
	Prandtl Number (Pr,s)	$Pr = \left(\frac{C_p \times \mu}{K}\right)^{\frac{1}{2}}$	(20)
	Nusselt number (Nu,s)	$Nu_s = 0.023 \times Re_s^{0.6} \times Pr^{0.33}$	(21)
	Convection Heat Transfer Coefficient (hs)	$hs = \frac{Nu \times K}{d_e}$	(22)
Heat rate	Hot Fluid Rate (tube) (Ch)	$C_h = m_h \times Cp_h$	(23)
	Cold Fluid Rate (shell) (CC)	$C_c = m_c \times Cp_c$	(24)
Maximum Heat Transfer Rate (Qmax)		$Qmax = C_h(T_{hi,t} - T_{ci,s})$	(25)
Effectiveness	Heat Exchanger Effectiveness (ε)	$\varepsilon = \frac{Qact}{Qmax} \times 100\%$	(26)
	Number of Transfer Units (NTU)	$NTU = \frac{U \times A}{C_{min}}$	(27)
Tube Length	Tube Length (Lt)	$Lt = \frac{NTU \times C_{min}}{U \times \pi \times d_{o,t} \times Nt \times 2}$	(28)

III. RESULTS AND DISCUSSION

The heat exchanger industry relies on the TEMA (Tubular Exchanger Manufacturers Association) standard from America. TEMA comprehensively covers various aspects, including heat exchanger types, performance calculation methodologies, design strengths, component terminology, and fundamental guidelines for their industrial application. This standard serves as a critical reference point to mitigate potential adverse outcomes for users, minimizing risks such as damage, operational failure, security concerns, and estimated operational costs. Table 2 presents the dimensions of the heat exchanger apparatus following the specifications outlined by the TEMA standard.

Table 2 Information Regarding the Operation of a Heat Exchanger

Specification	Input Fluid
Tube Side (Hot Fluid)	
Mass flow rate (m_{th} (kg/s))	1.7
dynamic viscosity (μ (kg/m.s))	0.000633
Inlet Temperature in tube side (T_{hi} ©)	360
Inlet Temperature in tube side (T_{hi} (K))	633
Outlet Temperature in tube side (T_{ho} (C))	270
Outlet Temperature in tube side (T_{ho} (K))	543
Heat capacity (Cp (J/kg.K))	2161
Thermal conductivity of fluid material (K (W/m.K))	0.135
Shell Side (Cold Fluid)	
Mass flow rate (m_{sh} (kg/s))	2.1
Dynamic viscosity (μ (kg/m.s))	0.00223
Inlet Temperature in shell side (T_{ci} (C))	240
Inlet Temperature in shell side (T_{ci} (K))	513
Outlet Temperature in shell side (T_{co} (C))	260
Outlet Temperature in shell side (T_{co} (K))	533
Heat capacity (Cp (J/kg.K))	4186
Thermal conductivity of fluid material (K (W/m.K))	0.64

Using the information from Table 2 as a basis, Table 4 presents the outcomes of calculations aimed at assessing the performance of the designed heat exchanger. Results indicate a heat transfer rate of 330633 W (Table 2). Various parameters such as LMTD, surface area, number of tubes, overall heat transfer coefficient, and the effectiveness of the designed heat exchanger were computed as 58°C, 9.310 m^2, 85 pieces, and 75%, respectively (see Table 3). The high overall heat transfer coefficient suggests an efficient heat transfer from the hot to the cold fluid. The achieved effectiveness of the heat exchanger exceeds 60%, indicating higher heat transport with more considerable temperature differences between input and output [12].

Table 3 Performance Parameters Derived from Computed Designs of Heat Exchangers

Parameter	Result
Initial Heat Transfer Rate (Q)	330633 W
Logarithmic Mean Temperature Difference (LMTD)	58.141 ℃
Area of Heat Transfer (A)	9.310 m^2
Number of Tube (Nt)	85
Total Heat Transfer Surface Area in Tube (at)	0.005 m^2
Mass Flow Rate of Water Fluid in Tube (Gt)	373.396 kg/m^2.s
Reynold Number in Tube (Re,t)	9738.981
Prandtl Number in Tube (Pr,t)	10.133
Nusselt Number in Tube (Nu,t)	12.210
Convection Heat Transfer Coefficient in the Tube (hi)	99.842 W/m^2.K
Total Heat Transfer Surface Area in Shell (A_s)	0.039 m^2
Mass Flow Rate of Water Fluid in Shell (Gs)	54.236 kg/m^2.s
Equivalent Diameter (De)	0.014 m
Reynold Number in Shell (Re,s)	350.221

Parameter	Result
Prandtl Number in Shell (Pr,s)	3.819
Nusselt Number in Shell (Nu,s)	1.203
Convection Heat Transfer Coefficient in Shell (ho)	53.481 W/m^2.K
HE Effectiveness ($\boldsymbol{\varepsilon}$)	75%
Number of Transfer Units (NTU)	2.027
Tube Length	0.914 °C.m^2/W

Table 3 provides a comprehensive overview of the performance parameters for the heat exchangers derived from the computed designs. The initial heat transfer rate of the system is 330,633 W, indicating a substantial capacity for thermal energy transfer. The logarithmic mean temperature difference (LMTD) is measured at 58.141°C, which is crucial in determining heat transfer efficiency between the hot and cold fluids. The total area available for heat transfer in the system is 9.310 m², a critical factor in ensuring adequate thermal exchange. The heat exchanger is designed with 85 tubes, each providing a heat transfer surface area of 0.005 m². The mass flow rate of the water fluid circulating through the tubes is 373.396 kg/m².s, essential for maintaining effective heat transfer rates. The calculated Reynolds number for the tube side is 9,738.981, which suggests turbulent flow conditions that enhance heat transfer efficiency. The Prandtl number is 10.133, and the Nusselt number is 12.210, reflecting the convective heat transfer characteristics within the tubes. The convection heat transfer coefficient on the tube side is 99.842 W/m².K, indicating a solid capacity for heat transfer.

On the shell side of the heat exchanger, the total heat transfer surface area is 0.039 m², providing an additional area for thermal exchange. The mass flow rate of the water fluid in the shell is 54.236 kg/m².s. The equivalent diameter of the shell is 0.014 m. The Reynolds number for the shell side is 350.221, indicative of laminar flow conditions, typically resulting in lower heat transfer efficiency than turbulent flow. The Prandtl number on the shell side is 3.819, and the Nusselt number is 1.203, which, combined with a convection heat transfer coefficient of 53.481 W/m².K, suggests less effective heat transfer than the tube side. The heat exchanger's effectiveness ($\boldsymbol{\varepsilon}$) is calculated at 75%, demonstrating a high level of thermal performance. The number of transfer units (NTU) is 2.027, a parameter used to assess the efficiency of the heat exchanger. Additionally, the tube length is specified as 0.914 °C.m²/W, further detailing the design parameters that contribute to the overall efficiency and performance of the heat exchanger.

The analysis of the heat exchanger's performance, as detailed in Tables 2 and 3, provides valuable insights into its operational characteristics and efficiency. The operational data reveal significant details about the heat exchanger's function and its effectiveness in handling specific thermal processes. For instance, the hot fluid on the tube side has a mass flow rate of 1.7 kg/s and experiences a temperature drop from 360°C (633 K) to 270°C (543 K), demonstrating a substantial heat transfer process. This substantial temperature differential is crucial for effective heat exchange, and similar temperature gradients have been discussed in recent studies examining high-performance heat exchangers [13], [14]. On the shell side, the cold fluid's mass flow rate of 2.1 kg/s and its temperature rise from 240°C (513 K) to 260°C (533 K) suggest a different heat transfer dynamic than the hot fluid. The higher heat capacity of the cold fluid, which is 4186 J/kg·K, and its thermal conductivity of 0.64 W/m·K play a significant role in determining the overall heat transfer efficiency. Recent research has emphasized the impact of fluid properties on heat exchanger performance, noting how variations in heat capacity and thermal conductivity can affect heat exchange effectiveness [15], [16].

The computed performance parameters further illuminate the heat exchanger's capabilities. The initial heat transfer rate of 330,633 W and the logarithmic mean temperature difference (LMTD) of 58.141°C highlight the efficiency of the heat exchanger in managing thermal loads. The heat transfer area of 9.310 m² and the design of 85 tubes, each with a surface area of 0.005 m², are aligned with typical design specifications for high-efficiency heat exchangers. These results corroborate findings from recent studies that focus on optimizing heat transfer surfaces and configurations [17], [18]. The performance metrics, such as the Reynolds number of 9,738.981 on the tube side, indicate turbulent flow conditions, which are known to enhance heat transfer efficiency. The Prandtl number of 10.133 and Nusselt number of 12.210 support the effectiveness of the heat exchanger in this regard [19], [20]. Conversely, the shell side's Reynolds number of 350.221 suggests laminar flow conditions, which are less effective for heat transfer. These observations align with the literature on flow regimes and their impact on heat exchanger performance. Finally, the heat exchanger's effectiveness of 75% and the number of transfer units (NTU) of 2.027 are consistent with expectations from similar systems. Studies have shown that achieving high effectiveness and maintaining optimal NTU values are critical for efficient heat exchange [21], [22]. The data suggest that the heat exchanger performs well within established parameters, providing a reliable and efficient solution for managing thermal energy in complex industrial processes.

IV. Conclusion

The heat exchanger, meticulously designed by the TEMA standard, employs a shell-and-tube configuration featuring a two-pass process and integrates 85 tubes. Under these operational parameters, it achieves a substantial heat transfer rate of 330,633 W. The design allows for turbulent flow on the tube side, which enhances heat transfer efficiency, while the shell side maintains laminar flow. This combination results in an effectiveness exceeding 70%, underscoring the unit's commendable performance. Such high effectiveness indicates the heat exchanger's ability to perform well under the given specifications, demonstrating that it meets or surpasses the expected performance benchmarks. Adhering to TEMA standard guidelines is pivotal for ensuring optimal performance and meeting fundamental requirements in heat exchanger design. These standards encompass a comprehensive range of factors, including fluid temperature, flow rate, and material properties. Additionally, they provide detailed specifications for dimensions and geometries, such as tube length, shell and tube diameters, and the number of tubes and baffles. Compliance with these parameters is essential for achieving the desired efficiency and reliability. By following these rigorous standards, the heat exchanger can maintain its high level of performance and meet critical operational demands, thereby ensuring its effectiveness in various applications.

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