



Report of Cooperative Education

Design a Heat Exchanger for Cooling Down
the Temperature of Unreacted Residue from Cleavage Reactor
in Silane Monomers Production Process

Mr. Pornpiput Semjorn

A Report Submitted in Partial Fulfillment of the Requirements
for the Degree of Bachelor of Engineering (Petrochemical Engineering),
Department of Chemical Engineering, Faculty of Engineering,
King Mongkut's Institute of Technology Ladkrabang
Academic Year 2018



รายงานสหกิจศึกษาฉบับสมบูรณ์

การออกแบบเครื่องแลกเปลี่ยนความร้อนเพื่อลดอุณหภูมิให้กับส่วนที่เหลือ
ที่ไม่ทำปฏิกิริยาแล้วจากคลีเวจรีแอกเตอร์ในกระบวนการผลิตไซเลนโมโนเมอร์

นาย พรพิพัฒน์ เสมจร

รายงานนี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรวิศวกรรมศาสตรบัณฑิต
หลักสูตรวิศวกรรมปิโตรเคมี ภาควิชาวิศวกรรมเคมี คณะวิศวกรรมศาสตร์

สถาบันเทคโนโลยีพระจอมเกล้าเจ้าคุณทหารลาดกระบัง

ปีการศึกษา 2561

Cooperative Title: Design a Heat Exchanger for Cooling Down the Temperature of Unreacted Residue from Cleavage Reactor in Silane Production Process

By: Mr. Pornpiput Semjorn

Field of Study: Petrochemical Engineering

Advisor: Assist.Prof.Dr. Yaneeporn Patcharavorachot

Mentor (Position): Mr. Karoon Pleeram (Process Engineer)

Company: Asia Silicones Monomer Limited

Abstract

In this project, the installation of a heat exchanger at the bottom of Cleavage reactor was proposed to reduce the cooling time of unreacted residue (UR) before supplying to the residue drum. Shell and tube heat exchanger was selected to apply in the Silane monomers production process. As the physical layout of the exchanger cannot be determined whereas the area is known, a trial-and-error procedure was performed to obtain the optimal design of heat exchanger. The standard of Tubular Exchanger Manufacturers Association (TEMA) as a tool is useful for the users, engineers and designers who specify, design and install shell and tube heat exchanger. This project considers not only a heat exchanger design but also pipe sizing, valve selection and economic analysis. From the literature survey, a fixed tubesheet exchanger with AEL type following TEMA was chosen for this process. When a heat exchanger is included in the process, the calculation revealed that the cooling time can be reduced from 4 hours to 1 hour. Considering an economic analysis, it was found that the increased annual production after improvement is 0.36 batch/year as equal to about 1,236,000 THB/year with the payback period of 3.5 years. As results, the installation of a heat exchanger at the bottom of Cleavage reactor is also a debottlenecking project of Silane monomers production that makes the capacity of the main products to increase.

Keywords: Heat exchanger design, Shell and tube heat exchanger, TEMA, Piping system design, Valve selection, Cost estimation, Breakeven point, Payback period

Acknowledgments

I would like to thank Asia Silicones Monomer (ASM) Limited company for giving me the opportunity to learned and obtained a lot of good experience from the Co-operative Education program. In addition, I would like to thank my mentor, Mr. Karoon Pleeram, and all people in Project Engineer Reliability (PER) division for supervising, information, knowledge, and suggestion until completing the work.

I am also grateful to my advisor, Assist.Prof.Dr. Yaneeporn Patcharavorachot, who supported and guided me throughout helping me to solve any problems about this project.

Most importantly, I would like to express appreciation to my family for their encouragement and everything.

Finally, if there are any mistakes in this project, I apologize.

Mr. Pornpiput Semjorn



TABLE OF CONTENTS

	Page
Abstract.....	I
Acknowledgements.....	II
Table of Contents.....	III
List of Figures.....	V
List of Tables.....	VII
Chapter I. Introduction	
1.1 Background.....	1
1.2 Objective.....	4
1.3 Scopes of work.....	4
1.4 Expected outputs	4
Chapter II. Theory and Literature Review	
2.1 Principle of heat exchangers.....	5
2.2 Piping system.....	21
2.3 Economic study.....	24
Chapter III. Methodology	
3.1 Shell and tube heat exchanger design.....	31
3.2 Piping system construction.....	35
3.3 Economic analysis.....	35
Chapter IV. Results and Discussion	
4.1 Heat exchanger design.....	37
4.2 Piping system results.....	44
4.3 Economic summary.....	46
Chapter V. Conclusions	
5.1 Conclusions.....	50
5.2 Suggestion.....	50

TABLE OF CONTENTS (Cont.)

	Page
References.....	51
Appendix A. Data for heat exchanger design.....	52
Appendix B. Data for piping system construction.....	55
Appendix C. Data for economic analysis.....	57
Appendix D. Data of unreacted residue.....	60
Biography.....	62



LIST OF FIGURES

Figure	Page
1.1 A simple diagram of silicone production.....	1
1.2 Silane monomers production process overview.....	2
1.3 MCS reaction and four main products.....	2
1.4 Cleavage unit in silane production process.....	3
1.5 Cleavage reaction.....	3
1.6 Position for installation of a heat exchanger.....	4
2.1 Forced draft air-cooled heat exchanger.....	6
2.2 Gasketed plate heat exchanger.....	6
2.3 Cut section of a shell and tube heat exchanger.....	7
2.4 Nomenclature for heat exchanger components.....	10
2.5 Tube pattern arrangements.....	14
2.6 (a) Segmental baffle and (b) Flow pattern through the shell-side.....	15
2.7 Shell-bundle clearance.....	16
2.8 Baffle cage assembly.....	17
2.9 Tube-side friction factors.....	20
2.10 Shell-side friction factors, segmental baffles.....	20
2.11 Typical inherent flow characteristics.....	21
2.12 (a) Gate valve, (b) Ball valve and (c) Plug valve.....	22
2.13 (a) Globe valve, (b) Butterfly valve and (c) Diaphragm valve.....	23
2.14 Breakeven point.....	29
3.1 The overall procedure in this project.....	31
3.2 Design procedure for shell and tube heat exchanger.....	32
3.3 Tube-side heat transfer factor.....	34
3.4 Shell-side heat transfer factor, segmental baffles.....	34
3.5 Steps for piping system construction.....	35
4.1 Heat exchanger type as TEMA designation: fixed tubesheet exchanger with removable channel and cover, single pass shell.....	39
4.2 Schematic diagram for basic design of a cooler.....	40
4.3 (a) Temperature profile and (b) tube layout.....	43

LIST OF FIGURES (Cont.)

Figure	Page
4.4 Schematic piping system.....	44
4.5 Pipeline of unreacted residue: (a) UR in and (b) UR out.....	44
4.6 Pipeline of cooling water: (a) CWS and (b) CWR.....	45
4.7 Constructive piping system summary.....	46
4.8 Breakeven chart.....	49
B.1 Cleavage unit plot plan.....	56



LIST OF TABLES

Table	Page
2.1 The Constants for using in Equation 2.9, of Triangular and Square Patterns.....	16
2.2 Typical allowable pressure drops for liquids according to viscosity.....	19
2.3 Two Broad Classes of Valves According to Their Primary Function.....	22
2.4 Typical Pipe Velocities and Allowable ΔP for Pipe Sizing Consideration.....	23
2.5 Probable Accuracy Relative to the Cost of an Estimate.....	24
2.6 Installation Factors for Estimation of Project Fixed Capital Cost.....	27
4.1 Comparison of Performance Features for each Heat Exchanger Type.....	37
4.2 Three Principal Types of Shell and Tube Heat Exchangers.....	38
4.3 Physical Properties of each Fluid Stream.....	41
4.4 The Factors to Consider for Fluid Allocation.....	41
4.5 Performance and Construction Detail Summary of a Designed Heat Exchanger.....	42
4.6 Comparison of a Trial Value and the Calculated Value of U_o	43
4.7 Pipe Size Selection Summary.....	45
4.8 Fixed Capital Costs Estimation.....	47
4.9 Annual Operating Costs Estimation.....	47
4.10 Variable Costs Estimation.....	48
4.11 Revenue Estimation.....	48
4.12 Annual Production Before and After Improvement.....	49
A.1 Typical Overall Heat Transfer Coefficients for Trial Estimation.....	52
A.2 Typical Values of Fouling Factors (Coefficients).....	53
A.3 Conductivity of Metals.....	53
B.1 Carbon Steel Pipe Size.....	55
C.1 Purchased Equipment Cost for Common Plant Equipment.....	57
C.2 Location Factors.....	58
D.1 Physical Properties by Aspen EDR V10 in Aspen Plus V10 Program.....	60

CHAPTER I

INTRODUCTION

1.1 Background

1.1.1 About silicone

In daily life, silicones are variously used in many fields including electronics, automobiles, chemicals, textiles, foods, cosmetics, medicals and construction. Many forms of silicones are grouped into the fluid, rubbers, liquid rubbers, resins, and silanes. The principal raw material of silicone is silicon (Si). In nature, Si does not occur as a single element, it is normally found in the form of silica (SiO_2). Figure 1.1 shows A simple schematic diagram of silicone production.

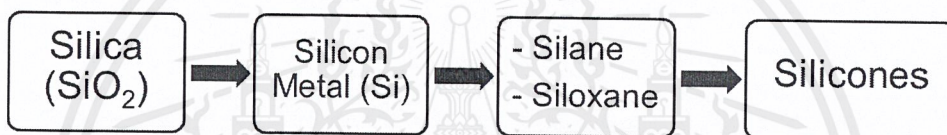


Figure 1.1 A simple diagram of silicone production.

Silicone, also known as polysiloxane, belongs to a classification of polymeric organosilicon compounds which are polymerized from siloxane monomers.[1] Siloxanes are produced by hydrolysis of chlorosilane compounds with water.

1.1.2 About company

Asia Silicones Monomer Ltd. (ASM) is an operated company with the manufacture of silicones monomer, which produces and dispenses silane monomers (methyl chlorosilane) and siloxane monomers (methyl siloxane) for the customers. The major customers are Shin-Etsu Chemical Co., Ltd., Momentive Performance Materials Inc., and Evonik Thai Aerosil Co. Ltd. ASM was established in 2001 and the plant was started up in 2004 where located in Asia Industrial Estate, Ban-Chang, Rayong. In the present, ASM is subsidiary of Shin-Etsu Chemical Co., Ltd. (SEC) that is the Japanese company. SEC has many businesses such as Electronics & Functional Material, PVC, Semiconductor Silicon, Specialty Chemicals and Silicones.[2]

At ASM, the production process is divided into two parts, including silane and siloxane monomers production. The raw material of silicones monomer is silicon (Si). In silane monomers production process as shown in Figure 1.2, silane monomers can be produced from

the reaction of silicon powder and methyl chloride (MeCl). After the methyl chlorosilane (MCS) reaction (Figure 1.3) finishes, the crude silane which includes the main of methyl chlorosilane and other by-products are formed and separated through the distillation column. Then, Silane monomers can be supplied to the customer or further used for siloxane monomers production.

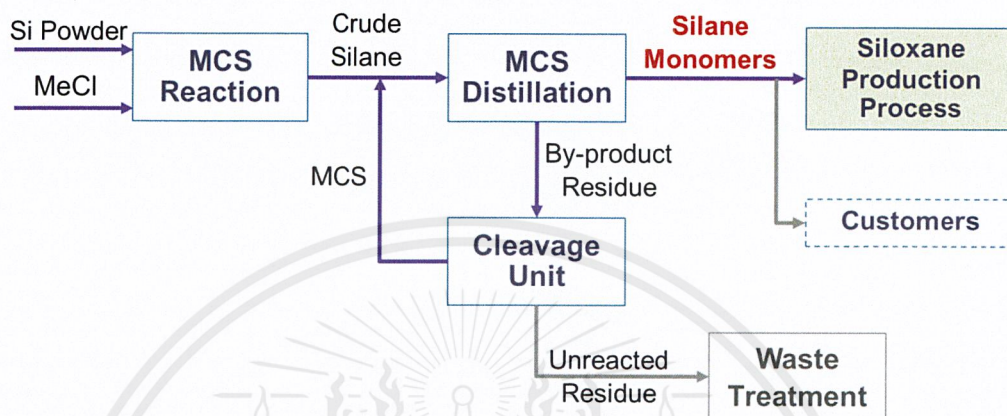


Figure 1.2 Silane monomers production process overview.

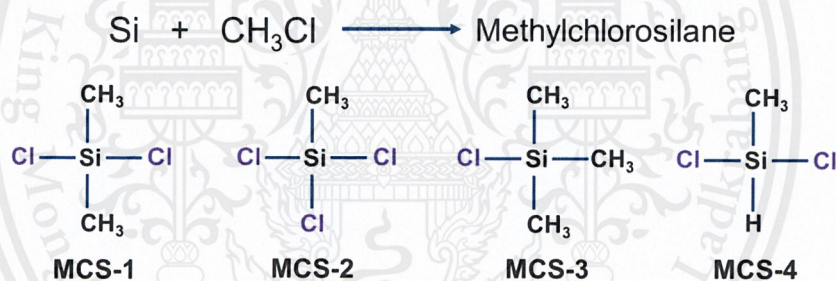


Figure 1.3 MCS reaction and four main products.

1.1.3 Cleavage Unit

As seen in Figure 1.2, the by-product residues that are separated from MCS through MCS distillation are fed into Cleavage Unit. Figure 1.4 presents the schematic of Cleavage Unit in silane production process. The use of Cleavage Unit is to cleave the silicon-silicon bond of a disilane molecule by reacting with HCl to produce Dimethyldichlorosilane (MCS-1), Methyltrichlorosilane (MCS-2) and Methylhydrogendichlorosilane (MCS-4). The Cleavage Reaction is demonstrated as shown in Figure 1.5. Cleavage reaction is performed to increase the overall yield of monomer products. Cleavage Reactor in Cleavage Unit uses steam for controlling the endothermic reaction temperature. The reactor is heated to suitable temperature under the agitation and HCl is fed to start the reaction. When the reaction

accomplishes, the MCS products are sent to next section whereas Unreacted Residue (UR) or non-cleavable disilane from the bottom of cleavage reactor is transferred to the waste treatment process to make non-hazardous waste.

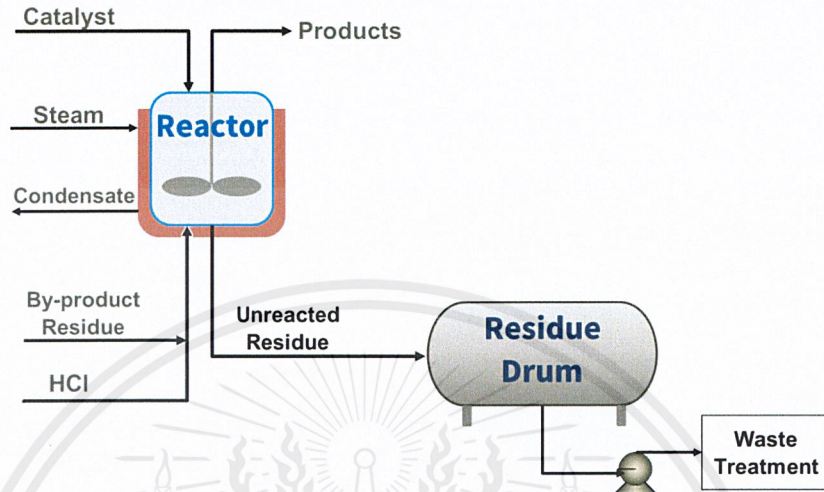


Figure 1.4 Cleavage unit in silane production process.

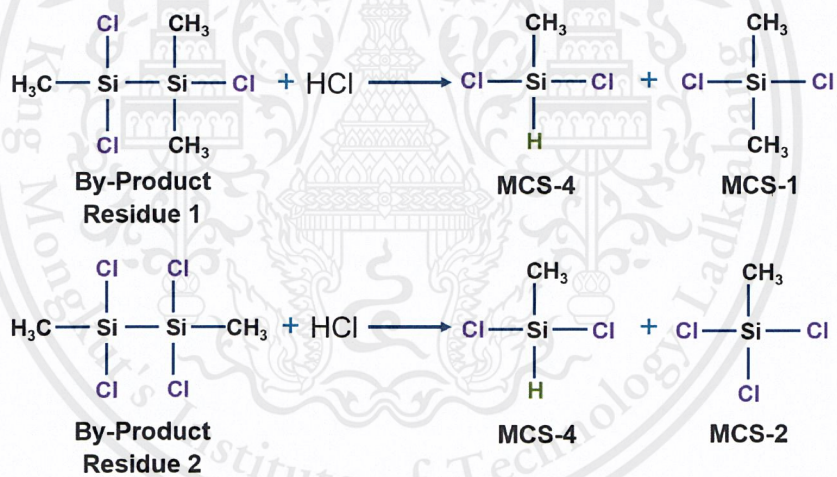


Figure 1.5 Cleavage reaction.

1.1.4 Discharge of Unreacted Residue

The cleavage reaction section is the batch process. When UR accumulates in reactor or reaction finishes, this section needs to be shutdown to discharge the accumulated UR every 25 to 30 days interval before starting next batch. The cooling down of UR and its discharge takes time around 4 hours. In the present, the more production capacities increase; this means that there are higher by-product residues for feeding into Cleavage Unit. Therefore, the reaction section must be more frequent shutdown which is changed from 25-30 days to 11 days interval.

From the consideration, it has been seen that 4 hours is too long to wait for cooling down the temperature of accumulated UR. This is motivated this project by the installation of a heat exchanger at the bottom of Cleavage reactor (Figure 1.6) to reduce the cooling time.

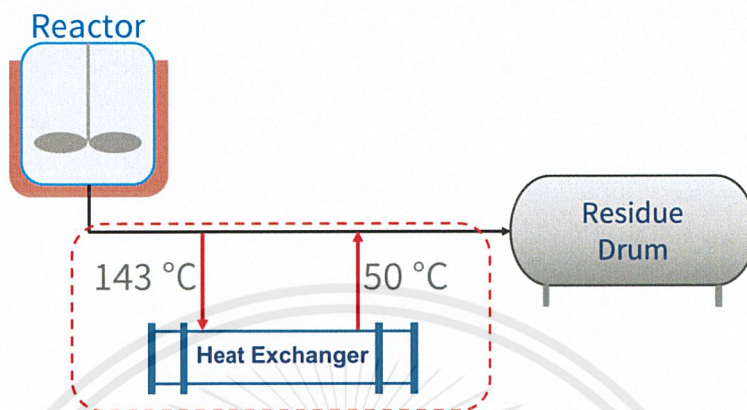


Figure 1.6 Position for installation of a heat exchanger.

1.2 Objective

To study the installation of a heat exchanger for the cooling time reduction of unreacted residue discharged from Cleavage reactor

1.3 Scopes of Work

1.3.1 Consider suitable type of heat exchanger and materials used for the process

1.3.2 Design heat exchanger by using trial-and-error procedure

1.3.3 Design piping system by considering pipe sizing and valve selection

1.3.4 Perform cost estimation and analyze breakeven point and payback period to determine the feasibility of this project

1.4 Expected Outputs

1.4.1 This project provides the design concept and design procedure of heat exchangers.

1.4.2 The design of heat exchanger and piping system that is suitable for cooling down the temperature of material stream can be obtained.

1.4.3 The obtained design of heat exchanger and piping can be guideline for applying in the real process.

1.4.4 The experiences and knowledge from this study can be applied in the future.

CHAPTER II

THEORY AND LITERATURE REVIEW

2.1 The principle of heat exchangers

2.1.1 Introduction of heat exchangers

Heat exchangers are the heat transfer equipment that provides the transfer of thermal energy between two or more fluids at different temperatures. They are used in various fields such as process, power, petroleum, transportation, air-conditioning, refrigeration, cryogenic, heat-recovery, and other industries for cooling, heating, evaporation, condensation, etc. Heat exchangers have to fulfill the following requirement [3]:

- Pressure drop as low as possible
- Reliability and life expectancy
- High-quality product and safe operation
- Material compatibility with process fluids
- Convenient size, easy for installation
- Easy for maintenance and servicing
- Light in weight but strong in construction to withstand the operational pressures and vibrations
- Simplicity of manufacture
- The possibility of effecting a repair to maintenance problems
- Low cost

The example of the principal types of heat exchanger used in the process industries are listed below [4]:

Air cooled heat exchangers

In an air-cooled heat exchanger, or air cooler, heat is transferred from the cooling air stream to the process fluid by extended surfaces or finned tubes. The use of an air-cooled or dry-cooling system in industry or in power plants is often justified where cooling water is not available or is very expensive.[5] A fan located below the tube bundle forces air up through the bundle or a fan above draws the air through the tube bundle.[3]

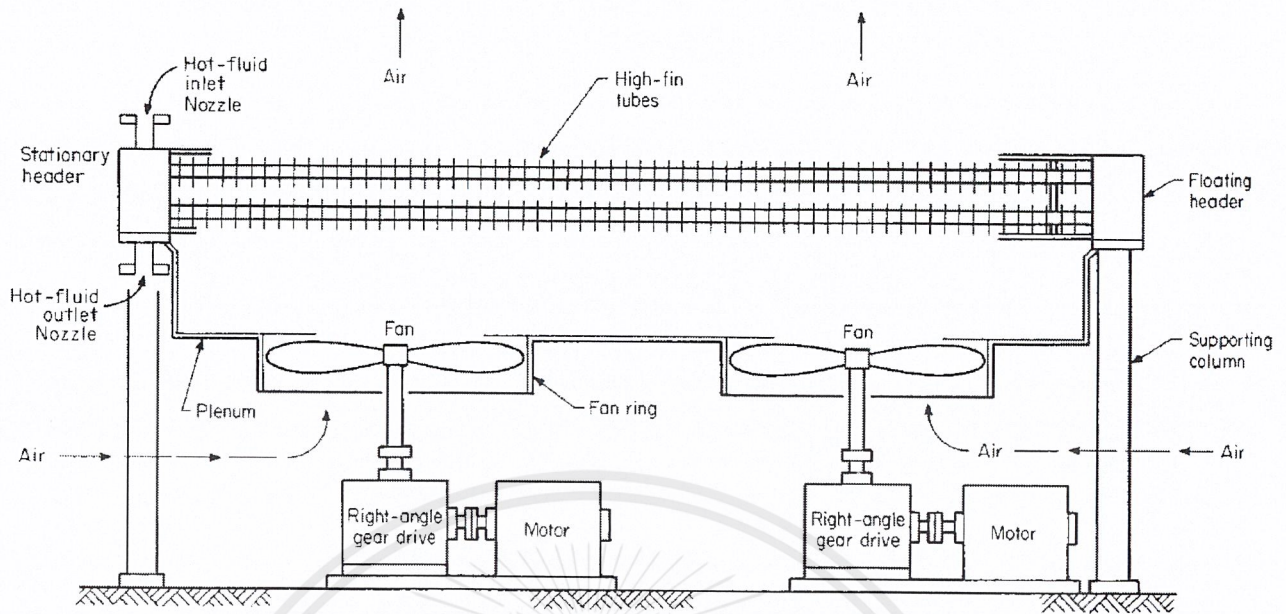


Figure 2.1 Forced draft air-cooled heat exchanger.[6]

Gasketed Plate Heat Exchangers

A gasketed plate heat exchanger, or plate and frame heat exchanger, consists a number of thin rectangular metal plates sealed around the edges by gaskets and held together in a frame.[7] Corner ports in the plates direct the flow from plate to plate. The plates are embossed with a pattern of ridges, which increase the rigidity of the plate and improve the heat-transfer performance. The layout and arrangement are shown in Figure 2.2.

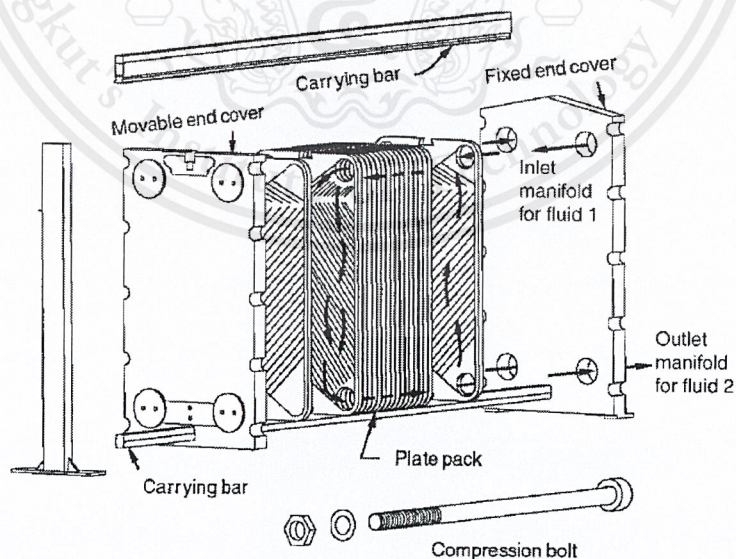


Figure 2.2 Gasketed plate heat exchanger.[7]

Shell and tube heat exchangers

The shell and tube heat exchanger is the most common type of heat transfer equipment used in the process industries. Shell and tube heat exchanger is generally built of a bundle of round tubes attached in a cylindrical shell with the tube axis parallel to the shell. One fluid flows inside the tubes, the other flows across and along the tube bundle. The major components of this exchanger are tubes (or tube bundle), shell, frontend head, rear-end head, baffles, and tubesheets.[7]

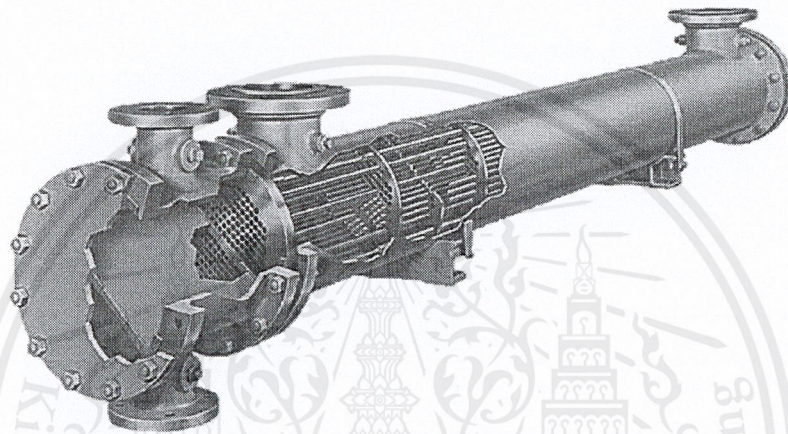


Figure 2.3 Cut section of a shell and tube heat exchanger.[3]

2.1.2 Basic design

The basic equation used for analysis are the energy balance or thermal equilibrium equation[8]

$$\dot{Q} = \dot{m}_h c_{p,h} \Delta T = \dot{m}_c c_{p,c} \Delta t \quad (2.1)$$

and heat transfer rate equations

$$\dot{Q} = UA\Delta T_m \quad (2.2)$$

where \dot{Q} = heat transferred per unit time, W

\dot{m}_h = mass flow rate of hot stream per unit time, kg/s

\dot{m}_c = mass flow rate of cold stream per unit time, kg/s

$c_{p,h}$ = specific heat capacity of hot fluid, J/kg°C

$C_{p,c}$ = specific heat capacity of cold fluid, J/kg°C

ΔT_m = the true mean temperature difference (MTD)

U = the overall heat transfer coefficient, W/m² °C

A = heat transfer area, m²

The prime objective in the design of a heat exchanger is to determine the surface area required for the specified duty (rate of heat transfer) using the temperature differences available. An estimate of the true mean temperature difference can be calculated from the difference in the fluid temperatures at the inlet and outlet of the exchanger, known as logarithmic mean temperature difference, and multiply by the temperature correction factor.

$$\Delta T_m = F_t \Delta T_{lm} \quad (2.3)$$

$$\Delta T_{lm} = \frac{(T_1 - t_2) - (T_2 - t_1)}{\ln \frac{(T_1 - t_2)}{(T_2 - t_1)}} \quad (2.4)$$

where F_t = the temperature correction factor

ΔT_{lm} = log mean temperature difference (LMTD)

T_1 = hot fluid temperature, inlet

T_2 = hot fluid temperature, outlet

t_1 = cold fluid temperature, inlet

t_2 = cold fluid temperature, outlet

The correction factor is a function of the shell and tube fluid temperatures, and the number of shell and tube passes as a function of two dimensionless temperature ratios as:

$$R = \frac{(T_1 - T_2)}{(t_2 - t_1)} \quad (2.5)$$

$$S = \frac{(t_2 - t_1)}{(T_1 - t_1)} \quad (2.6)$$

$$F_t = \frac{\sqrt{(R^2+1)} \ln \left[\frac{(1-S)}{(1-RS)} \right]}{(R-1) \ln \left[\frac{2-S[R+1-\sqrt{(R^2+1)}]}{2-S[R+1+\sqrt{(R^2+1)}]} \right]} \quad (2.7)$$

The overall coefficient is the reciprocal of the overall resistance to heat transfer, which is the sum of individual resistances.

$$U_o = \frac{1}{\frac{1}{h_o} + R_{f,o} + \frac{d_o \ln(d_o/d_i)}{k_{wall}} + \frac{d_o}{d_i} \left(\frac{1}{h_i} + R_{f,i} \right)} \quad (2.8)$$

where U_o = the overall coefficient based on the outside area of the tube, W/m²°C

h_o = outside fluid film coefficient, W/m²°C

h_i = inside fluid film coefficient, W/m²°C

$R_{f,o}$ = fouling factor of outside fluid, m²°C/W

$R_{f,i}$ = fouling factor of inside fluid, m²°C/W

d_o = tube outside diameter, m

d_i = tube inside diameter, m

k_{wall} = thermal conductivity of the tube wall material, W/m°C

2.1.3 Classification of Shell and Tube Heat Exchangers

The mechanical design features, fabrication, materials of construction, and testing of shell and tube heat exchangers are covered by TEMA (Tubular Exchanger Manufacturers Association) standards. TEMA helps the users, engineers and designers who specify, design and install shell and tube heat exchanger. The TEMA standards identify heat exchanger type by a three-letter code. The first letter denotes the front end. The second letter identifies the shell type and the third letter defines the rear end. Figure 2.4 illustrates the TEMA nomenclature.

Classification of shell and tube heat exchangers is divided into three types according to mechanical arrangement. There are fixed tubesheet exchangers, U-tube exchangers, and floating head exchangers.

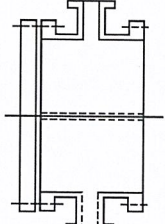
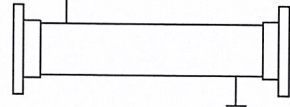
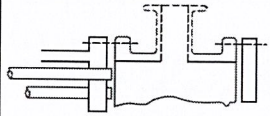
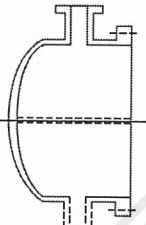
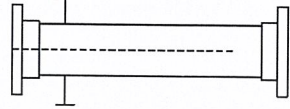
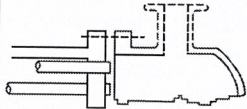
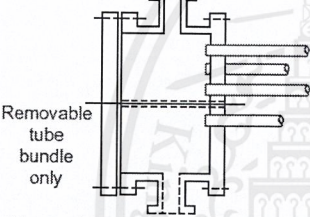
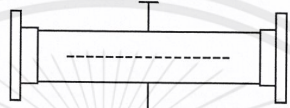
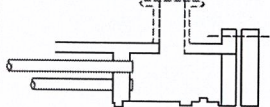
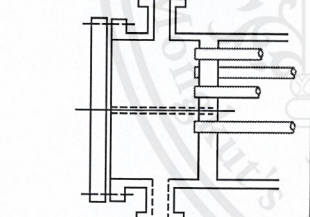
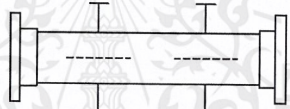
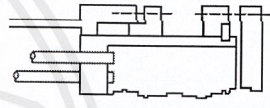
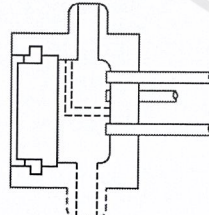

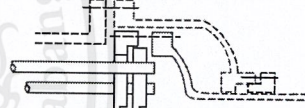
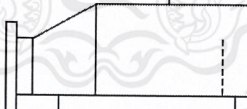

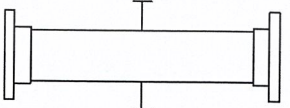
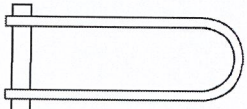
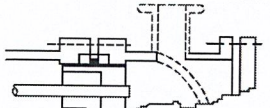
Front end stationary head types		Shell types		Rear end head types	
A	 Channel and removable cover	E	 One pass shell	L	 Fixed tubesheet like "A" stationary head
B	 Bonnet (integral cover)	F	 Two pass shell with longitudinal baffle	M	 Fixed tubesheet like "B" stationary head
C	 Removable tube bundle only Channel integral with tubesheet and removable cover	G	 Split flow	N	 Fixed tubesheet like "N" stationary head
N	 Channel integral with tubesheet and removable cover	H	 Double split flow	P	 Outside packed floating head
D	 Special high pressure closure	J	 Divided flow	S	 Floating head with backing device
		K	 Kettle type reboiler	T	 Pull through floating head
		X	 Cross flow	U	 U-tube bundle
				W	 Externally sealed floating tubesheet

Figure 2.4 Nomenclature for heat exchanger components (Standards of Tubular Exchanger Manufacturers Association).

- Fixed tubesheet exchangers

This type is the simplest and cheapest type of shell and tube heat exchanger. These types are constructed with the tubesheets integral with the shell. The fixed tubesheet exchanger uses straight tubes secured at both ends into tubesheets, which are tightly welded to the shell. Hence, gasketed joints are minimized in this type or the tube bundle cannot be removed for cleaning, and therefore least maintenance is required. They may be used with A-, B-, or N-type front head and L-, M-, or N-type rear head. However, fixed tubesheet exchangers can be designed with removable channel covers, “bonnet”-type channels, integral tubesheets on both sides, and tubesheets extended as shell flanges. For fixed tubesheet exchangers, when the difference between shell and tube mean metal temperatures becomes large (greater than approximately 50°C for carbon steel), the tubesheet thickness and tube end loads become excessive. When a thermal expansion problem exists, an expansion joint is incorporated in the shell.

- U-tube exchangers

This type requires only one tubesheet and is cheaper than the floating head types. The tube bundle can be removed from the heat-exchanger shell. A tube-side header (stationary head) and a shell with integral shell cover, which is welded to the shell, are provided. Each tube is free to expand or contract without any limitation being placed upon it by the other tubes. The U-tube bundle has the advantage of providing minimum clearance between the outer tube limit and the inside of the shell for any of the removable-tube-bundle constructions. Clearances are of the same magnitude as for fixed-tube-sheet heat exchangers. U-tube exchangers may be used with A-, B-, C-, N-, or D-type front head. As the tube bundle can be withdrawn, the outside of the tubes may be cleaned by mechanical means, but chemical cleaning is usually necessary for the inside of the tubes. The U-tube type is therefore limited to applications where the tube-side fluid is non-fouling. Erosion damage of U-bends is also seen at high tube-side velocity.

- Floating head exchangers [3]

The floating head exchanger consists of a stationary tubesheet and one floating tubesheet that is free to accommodate the thermal expansion of the tube bundle. They are suitable for high temperature differentials. They may be used with A-, B-, or C-type front head. There are four basic types of floating head exchangers.

Floating head, outside packed floating head: The floating head (P head), outside packed stuffing box heat exchanger uses the outer skirt of the floating tubesheet as part of the floating head. The packed stuffing box seals the shell-side fluid while allowing the floating head to move. The tube bundle is removable. Maintenance is also very easy since all bolting is from outside only. With this floating head, any leak (from either the shell-side or the tube-side) at the gaskets is to the outside, and there is no possibility of contamination of fluids. Since the bundle-to-shell clearance is large, sealing strips are usually required. The earlier types are recommended for LP, low-temperature, nonhazardous fluids.

Floating head, externally sealed floating tubesheet: In the floating head (W head), externally sealed floating tubesheet, or outside packed lantern ring heat exchanger uses a lantern ring around the floating tubesheet to seal the two fluids as the floating tubesheet moves back and forth. The lantern ring is packed on both sides and is provided with vent or weep holes so that leakage through either should be to the outside. Number of tube passes is limited to one or two. The tube bundle is removable. This is the lowest cost of the floating head design and can be used with type A, B, or C front head. This type is recommended for LP, low-temperature, and nonhazardous fluids.

Floating head, pull-through head: In the floating head (T head), pull-through head exchanger, a separate head or cover is bolted to the floating tubesheet within the shell. In this design, the tube bundle can be removed without dismantling the joints at the floating end. However, the clearance between the outermost tubes in the bundle and the shell must be made greater than in the fixed and U-tube designs to accommodate the floating-head flange, allowing the fluid to bypass the tubes. To overcome the reduction in thermal performance, sealing devices are normally required, and the shell diameter is somewhat increased to accommodate a required amount of surface area. An ideal application for the T head design is as the kettle reboiler, in which there is ample space on the shell-side and the flow bypass stream is of no concern.

Floating head with backing device: In the floating head (S head) with backing device, the floating head cover (instead of being bolted directly to the floating tubesheet as in the pull-through type) is bolted to a split backing ring. The shell cover over the floating head has a diameter larger than the shell. As a result, the bundle to shell clearance is reasonable, and sealing strips are generally not required. The tube bundle is not removable. Both ends of the

heat exchanger must be disassembled for cleaning and maintenance. This type is recommended for HP, nonhazardous process fluids.

2.1.4 Construction details of shell and tube heat exchangers

A shell and tube heat exchanger consists of a bundle of tubes enclosed in a cylindrical shell. The ends of the tubes are fitted into tubesheets, which separate the shell-side and tube-side fluid streams. Baffles are provided in the shell to direct the fluid flow and support the tubes.

2.1.4.1 Tube-side construction

- *Tubes:* The TEMA design allows tube diameters between 0.25 in. (6.4 mm) and 2 in. (50 mm). The most commonly used tubes in chemical plants and petroleum refineries are 0.75 in. (19.05 mm) and 1 in. (25.4 mm) outside diameter (d_o). These sizes give the best all-around performance and are most economical in most applications. The small diameters are preferred for most heat duties, more compact, and cheaper exchanger. For mechanical cleaning, the smallest practical size is 0.75 in. (19.05 mm). Larger tubes are easier to clean by mechanical method and are selected for heavy fouling fluids. As a guide, 0.75 in (19.05 mm) is a good trial diameter to start design calculation.
- *Thickness of the tube:* The tube thickness is generally identified and measured by the Birmingham wire gauge (BWG unit). It is selected to withstand the internal and external pressure and give the proper corrosion allowance. (The common tube diameters and gages for bare tube of copper, steel and alloy are listed in section 5, table RCB-2.21 of TEMA)
- *Tube length:* For a given surface area, the most economical exchanger is possible with a small shell diameter and long tubes. This will generally result in a lower-cost exchanger but will lead to an increase in pressure drop and pump work. The optimum tube length (L) to shell diameter ratio will usually fall within the range of 5 to 10. Standard lengths from TEMA standard, RCB-2.1, are 8, 10, 12, 16 and 20 ft. Other lengths may be used.
- *Number of tubes:* To design a shell and tube heat exchanger, the total number of tubes that can fit into the shell of a given inside diameter must be known. This is known as tube count. The number of tubes (N_t) also depends upon the fluid flow rate and the available pressure drop.
- *Tube-side passes:* Most exchangers have an even number of tube-side passes (N_p); 1, 2, 4, 6 and 8 tube passes are commonly used. When the number of tube passes is greater than

one, the shell and tube heat exchangers with any of the TEMA shell types (except for the F shell) represent a multipass exchanger to increase the length of flow path for given the required tube-side design velocity. The number of tube passes depends upon the available pressure drop, since higher velocity in the tube results in higher heat transfer coefficient, at the cost of increased pressure drop.

2.1.4.2 Shell-side construction

- *Shell types:* The principle shell arrangements are shown in Figure 2.4. The E shell is the most common due to its cheapness, simplicity, and ease of manufacture. It has one shell pass, with the shell-side fluid entry and exit nozzles attached at the two opposite ends of the shell. The tube-side may have a single pass or multiple passes.
- *Tube arrangements:* The tubes in an exchanger are usually arranged in (1) triangular, or (2) square pattern; see Figure 2.5 The triangular pattern gives higher heat transfer rates, higher pressure drops than square pattern. A square pattern is used for heavily fouling fluids where it is necessary to mechanically clean the outside of the tubes or on shell-side. Where a square pattern is used for ease of cleaning, the recommended minimum clearance between the tubes is 0.25 in. (6.4 mm). The minimum ratio of tube pitch (p_t) to tube outside diameter (pitch ratio) is 1.25. The minimum value is restricted to 1.25 because the ligament (a ligament is the portion of material between two neighboring tube holes) may become too weak for proper rolling of the tubes into the tubesheet.

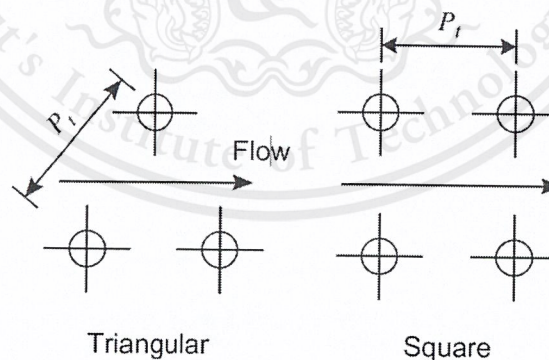


Figure 2.5 Tube pattern arrangements.

- *Baffles:* Baffles must generally be applied on the shell-side to support the tubes, to maintain the tube spacing, and to divert the flow across the tube bundle to obtain higher heat transfer coefficient. The most commonly used type of baffle is the single segmental baffle

shown in Figure 2.6 (a). The “baffle cut” is used to specify the dimensions of a segmental baffle. The baffle cut is the height of the segment removed to form the baffle, expressed as a percentage of the baffle disc diameter. Baffle cuts from 15% to 45% are used. Generally, a baffle cut of 20% to 25% will be the optimum, giving good heat-transfer rates, without excessive pressure drop. The practical range of single segmental baffle spacing (l_B) is 0.2–1 times of shell-inside diameter. A close baffle spacing will give higher heat-transfer coefficients, but at the expense of higher pressure drop. The optimum spacing will usually be between 0.3 to 0.5 times the shell diameter. TEMA Table RCB-4.52 provides maximum baffle spacing for various tube outer diameters, tube materials, and the corresponding maximum allowable temperature limit. The flow pattern through the shell-side and baffle arrangement are illustrated in Figure 2.6 (b).

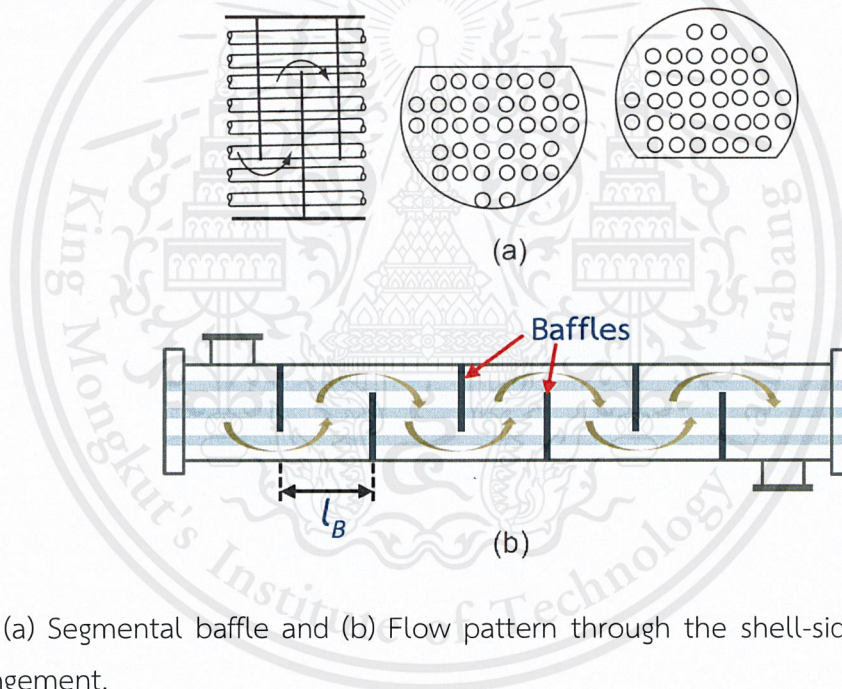


Figure 2.6 (a) Segmental baffle and (b) Flow pattern through the shell-side and segmental baffle arrangement.

- *Shell-inside diameter*: The shell-inside diameter (D_s) must be selected to give as close a fit to the tube bundle as is practical, to reduce bypassing around the outside of the bundle. The clearance required between the outermost tubes in the bundle and the shell inside diameter will depend on the type of exchanger. Therefore, the shell-inside diameter can be determined by calculating the bundle diameter (D_b) from equation 2.9. and estimating the shell-bundle clearance from Figure 2.7. The bundle diameter depends not only on the number tubes and the number of tube passes but also on the tube arrangement. Table 2.1 give the constants for using in following equation.

$$D_b = d_o \left(\frac{N_t}{K_1} \right)^{1/n_1} \quad (2.9)$$

where N_t = number of tubes

D_b = bundle diameter, mm

d_o = tube outside diameter, mm

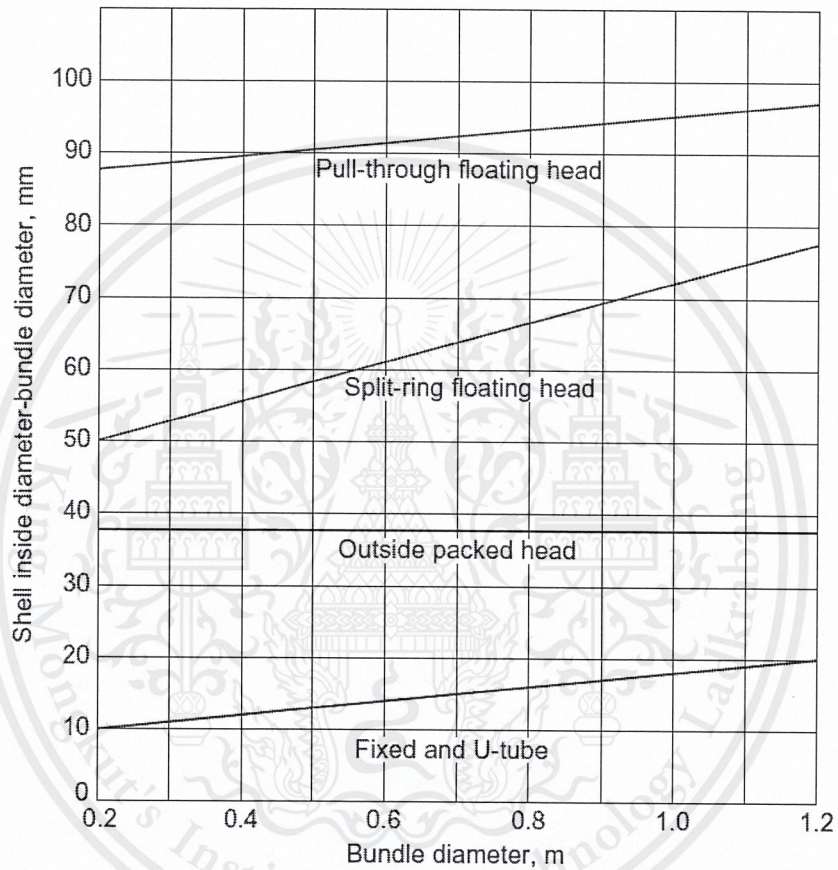


Figure 2.7 Shell-bundle clearance.

Table 2.1: The Constants for using in Equation 2.9, of Triangular and Square Patterns

No. passes	Triangular Pitch, $p_t = 1.25d_o$		Square Pitch, $p_t = 1.25d_o$	
	K_1	n_1	K_1	n_1
1	0.319	2.142	0.215	2.207
2	0.249	2.207	0.156	2.291
4	0.175	2.285	0.158	2.263
6	0.0743	2.499	0.0402	2.617
8	0.0365	2.675	0.0331	2.643

Other parts of shell and tube heat exchanger construction are such as tubesheets, spacers, tie-rods, and Shell and Header Nozzles. The baffles and tube bundle are held together with tie rods and spacers. Tie-rods and spacers may also be used as a sealing device to block bypass paths due to pass partition lanes or the clearance between the shell and the tube bundle. A baffle cage assembly showing the tie-rods and spacers is shown schematically in Figure 2.8 The tubesheet forms the barrier between the shell and tube fluids, and where it is essential for safety to prevent any possibility of intermixing due to leakage risk at the tubesheet joint. To allow sufficient thickness to seal the tubes, the tubesheet thickness should not be less than the tube outside diameter, up to about 25 mm diameter. Recommended minimum plate thicknesses are given in the standards. The thickness of the tube sheet will reduce the effective length of the tube slightly, and this should be allowed for when calculating the area available for heat transfer. As a first approximation, the length of the tubes can be reduced by 25 mm for each tubesheet.

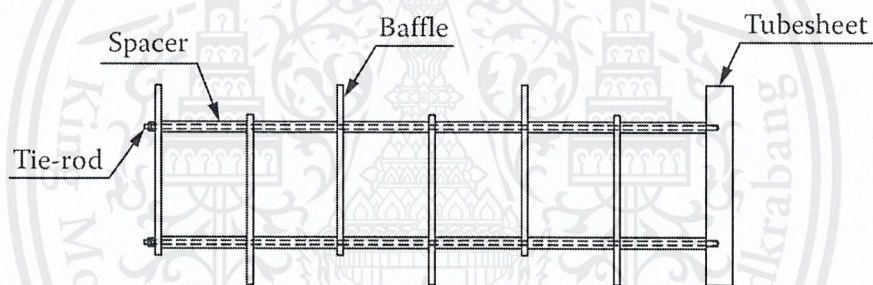


Figure 2.8 Baffle cage assembly.

2.1.5 General design considerations

2.1.5.1 Fluid allocation:

The consideration for placing the fluids that should be provided in the tube-side or shell-side where no phase change occurs can be determined the following factors.

- *Corrosion*: The more corrosive fluid should be allocated to the tube-side. This will reduce the cost of expensive alloy or clad component.
- *Fouling*: The fouling can be minimized by placing the fouling fluid in the tubes to allow better velocity control; increased velocities tend to reduce fouling. Also, the tubes will be easier to clean

- *Fluid temperatures:* High temperature services require expensive alloy materials, fewer alloy components are needed when the high temperature fluid stream is placed on the tube-side.
- *Operating pressures:* Placing a high-pressure fluid in the tubes will require fewer costly high-pressure components and the shell thickness will be less. High-pressure tube will be cheaper than a high-pressure shell.
- *Viscosity:* Higher heat transfer rates are generally obtained by placing the more viscous fluid on the shell-side, providing the flow is turbulent. The critical Reynolds number for turbulent flow in the shell-side is in the region of 200. However, if the flow is still laminar when in the shell, it is better to place the viscous fluid only on the tube-side because the tube-side heat transfer coefficient and flow distribution can be easier predicted with more certainty.
- *Stream flow rates:* Placing the fluid with the lower flow rate on the shell-side will give the economical design and safe from flow-induced vibration. Turbulent flow distribution exists on the shell-side at much lower velocities than on the tube-side.

2.1.5.2 Shell and tube fluid velocities:

High velocities will give higher heat transfer coefficients but also a high pressure drop. The velocity must be high enough to prevent any suspended solid settling, but very high velocity leads to erosion. High velocities will reduce the fouling. The typical design velocities for liquids are given:

- *Tube-side, process fluids:* 1 - 2 m/s, maximum 4 m/s if required to reduce fouling; water: 1.5 - 2.5 m/s
- *Shell-side:* 0.3 - 1 m/s

2.1.5.3 Pressure drops

The pressure drops available to drive the fluids through the exchanger will set by the process conditions. Fluid pressure drop is controlled by a wide variety of design variables and the process fluid flow parameters. The consideration of allowable pressure drop in a heat exchanger is essential for the optimum in design. The basic criterion that a designed heat exchanger should perform the given heat duty within the allowable pressure drop. The values

suggested below can be used as a general guide, and will give designs that are near the optimum.

- The typical value for liquids from Sinnott, R. and Towler, G.[4]:

Table 2.2: Typical allowable pressure drops for liquids according to viscosity

Viscosity	Allowable Pressure Drop
< 1 cP	0.35 bar
1 - 10 cP	0.5 - 0.7 bar

- The Rule of thumb of Coker, A. K.[9]: Pressure drops are 0.1 bar (1.5 psi) for boiling and 0.2 - 0.62 bar (3 - 9 psi) for other services.
- Assumption from Schlunder, E. U.[10]: Allowable pressure drops on each side are assumed to be about 0.5 - 0.1 bar except for low-pressure gas, two-phase flows, and very viscous organics.

The pressure drops in each side of shell and tube heat exchanger can be calculated from the derived equation below[4]:

$$\Delta P_t = N_p \left[8j_f \left(\frac{L}{d_i} \right) \left(\frac{\mu}{\mu_w} \right)^{-m} + 2.5 \right] \frac{\rho u_t^2}{2} \quad (2.10)$$

$$\Delta P_s = 8j_f \left(\frac{D_s}{d_e} \right) \left(\frac{L}{l_B} \right) \left(\frac{\mu}{\mu_w} \right)^{-0.14} \frac{\rho u_s^2}{2} \quad (2.11)$$

- where
- ΔP_t = tube-side pressure drop, Pa
 - ΔP_s = shell-side pressure drop, Pa
 - N_p = number of tube-side passes
 - u_t = tube-side velocity, m/s
 - j_f = dimensionless friction factor estimated from Figure 2.9 and Figure 2.10
 - μ_w = viscosity at the tube wall temperature, Pa.s
 - L = tube length, m
 - l_B = baffle spacing, m
 - D_s = shell-inside diameter, m
 - d_e = shell-side equivalent diameter, m
 - m = 0.14 for turbulent flow and 0.25 for laminar flow

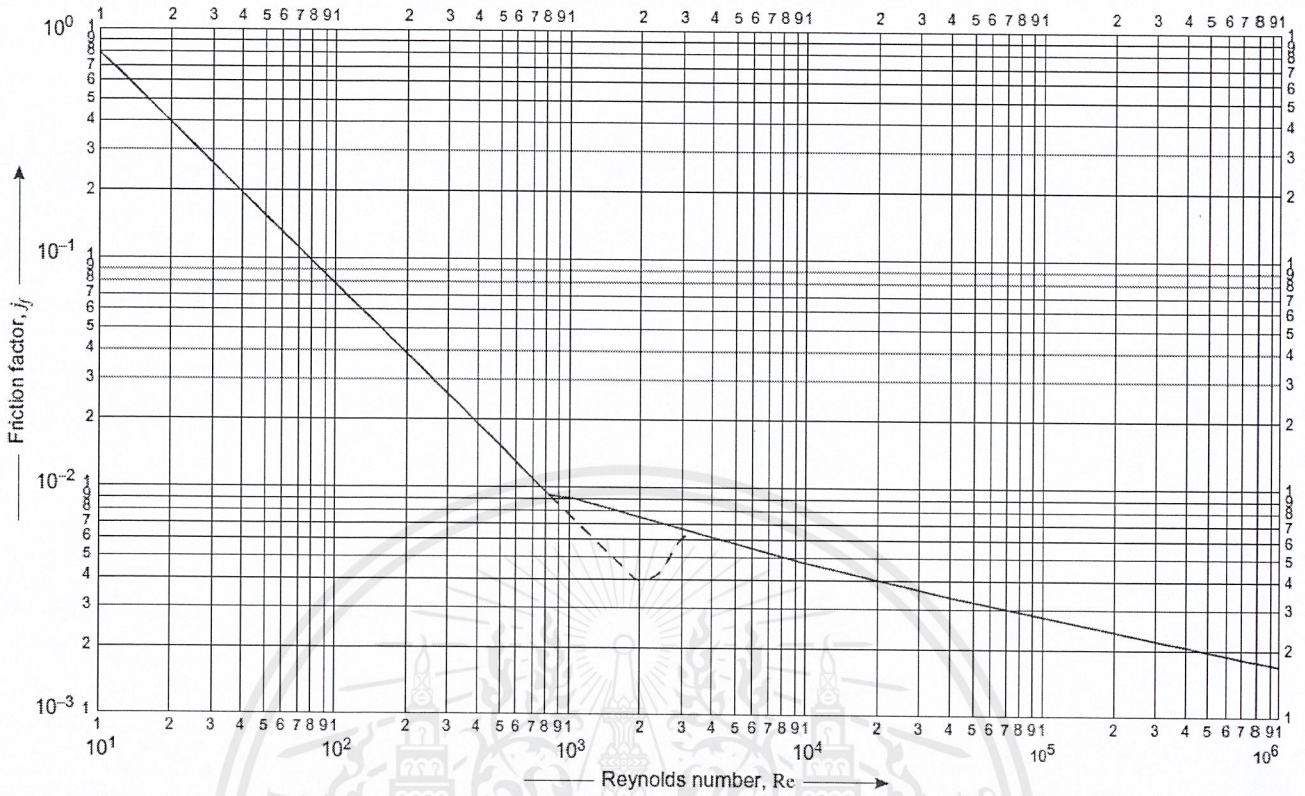


Figure 2.9 Tube-side friction factors.

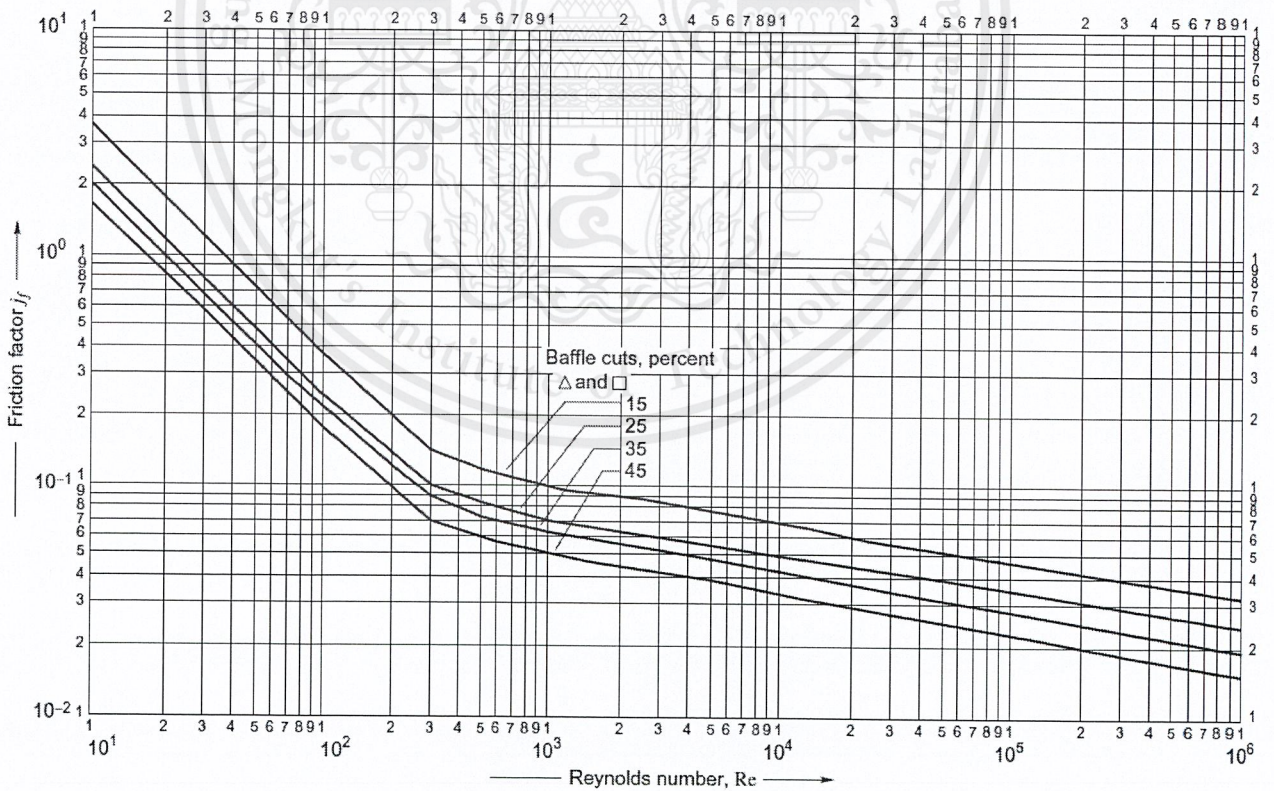


Figure 2.10 Shell-side friction factors, segmental baffles.

2.2 Piping system

After designing the piping arrangement and specifying the required equipment items from the related data such as a plot plan, the rough P&ID will be established, then the valve type and pipe size must be considered and selected to apply for the piping system.

2.2.1 Valve selection

valves are mechanical devices in a fluid flow or pressure system that specifically designed to direct, start, stop, mix, regulate the flow, pressure, or temperature of a process fluid.[11]

Proper valve selection requires a complete understanding of the properties of the media being controlled, the type of control needed, and the capabilities and limitations of the different valve types. Sealing performance and flow characteristics are important aspects in valve selection. An understanding of these aspects is helpful and often essential in the selection of the correct valve.[12] Three main valve characteristics are quick opening, linear, and equal percentage (Figure 2.11). Quick opening valves produce large changes as the valve initially opens. The rate of change decreases greatly over the later portion of valve travel. Equal percentage characteristics are opposite of quick opening. Large flow rate changes occur as the valve nears the open position. Linear characteristics occur where flow rate changes correspond directly to valve position movement.

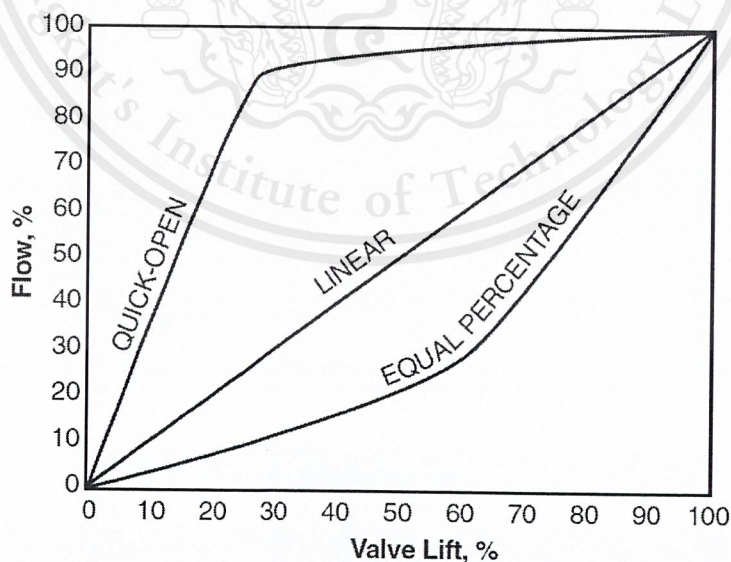


Figure 2.11 Typical inherent flow characteristics.[11]

The valves used for chemical process plant can be divided into two broad classes, depending on their primary function.[4] Each type can be used differently according to the suitability of their required process.

Table 2.3: Two Broad Classes of The Valves According to Their Primary Function

Shut-off Valves	Control Valves
Gate valve	Globe valve
Ball valve	Butterfly valve
Plug valve	Diaphragm valve

2.2.1.1 Shut-off valves

The Shut-off valves, or on-off valves, are used to stop or start the flow of the medium through the process. This valve types give a tight seal in a close position. They have a straight-through flow channel and low pressure drop when fully open. Automated on-off valves are also usually required for an emergency system when an emergency situation occurs, the system must be immediately shut off. Shut-off valves are such as gate valve, ball valve and plug valve as shown in Figure 2.12.

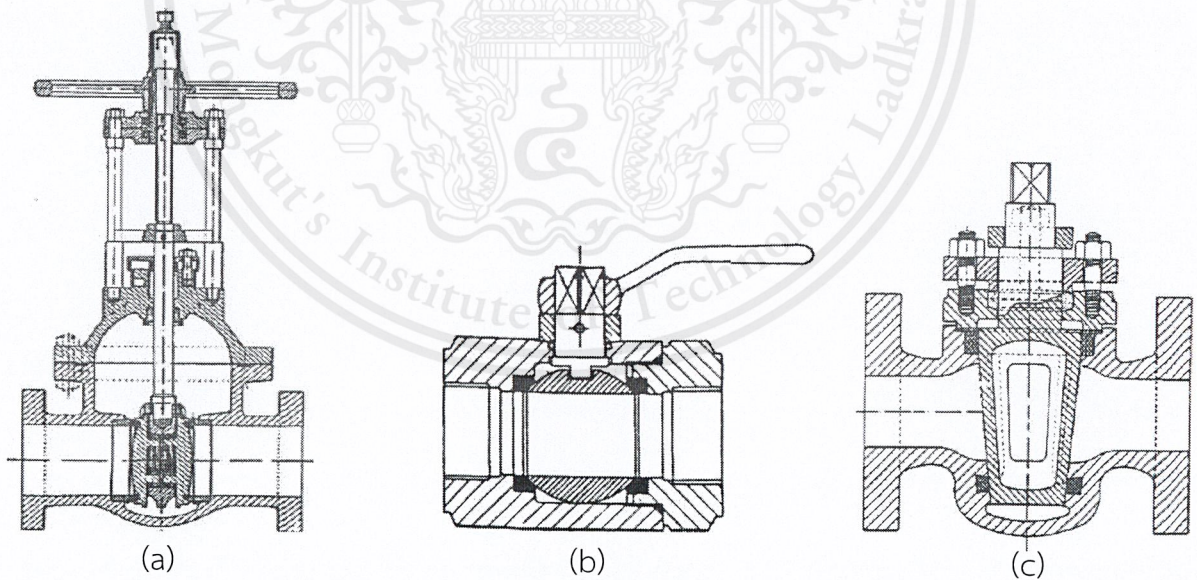


Figure 2.12 (a) Gate valve, (b) Ball valve and (c) Plug valve.

2.2.1.2 Control valves

The control valves, or throttling valve, are used to regulate the flow, temperature, or pressure of services. They give a smooth control over the full range of flow from open to closed and can hold any position within the stroke of the valve. They can act as on-off valves when the process system needs to be operated frequently. Control valves are such as globe valve, butterfly valve and diaphragm valve as shown in Figure 2.13.

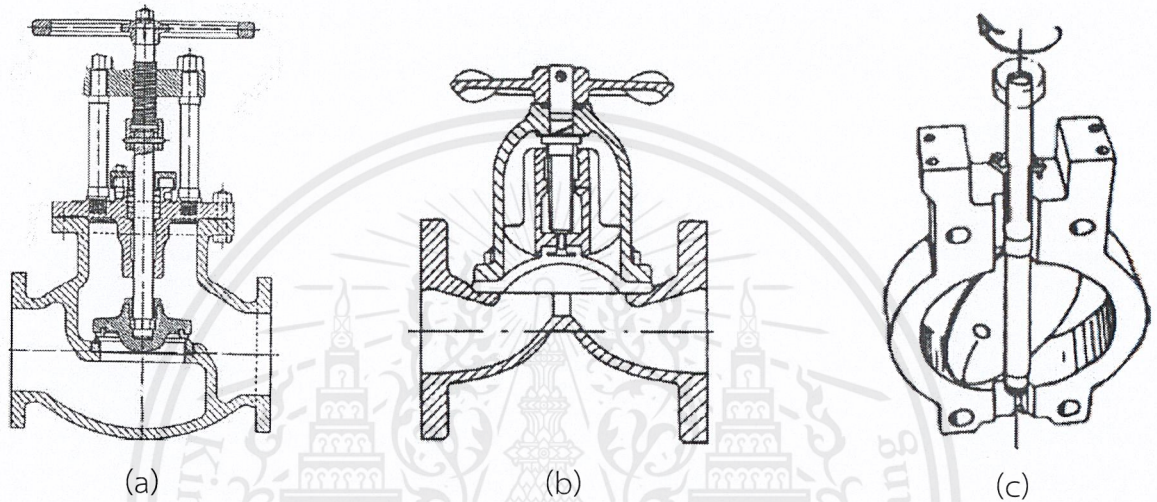


Figure 2.13 (a) Globe valve, (b) Butterfly valve and (c) Diaphragm valve.

2.2.2 Pipe size selection

The standard which is used for pressure piping design is ASME B31. The pipes are often specified by a schedule number, based on the thin cylinder formula. Schedule 40 pipe is commonly used for general purpose applications at low pressure (below 50 bar).[4] [6]

If the motive power to drive the fluid through the pipe is available free, for example when the pressure is let down from one vessel to another or there is sufficient head for gravity flow, the smallest pipe diameter that gives the required flow rate would normally be select.

If the fluid has to be pumped through a pipe, the size should be selected to give the least total annualized cost.

Table 2.4: Typical Pipe Velocities and Allowable ΔP for Pipe Sizing Consideration

	Velocity m/s	ΔP bar/m
Liquids, pumped (not viscous)	1-3	0.005
Liquids, gravity flow	-	0.0005

As a general guide, the safety factors of 20-30% on the friction factor will accommodate the change in roughness conditions for steel pipe with average service of 5-10 years, but will not compensate for severe corrosive conditions.[9]

2.3 Economic study

The Economic study of this project is divided into 2 topics: cost estimation and economic evaluation.

2.3.1 Cost estimation

2.3.1.1 Capital cost estimate classification

Capital cost estimation is an essential part of investment appraisal. The Association for the Advancement of Cost Estimating International (AACE International) is the professional association representing the cost engineering profession in the United States. AACE International classifies capital cost estimates into five classes according to their accuracy and purpose.

Table 2.5: Probable Accuracy Relative to the Cost of the Estimate [9]

Estimate Class	Project Definition (% of complete Definition)	Recommended Nomenclature	Purpose of Estimate	Accuracy (%)
Class 5	0-2	Order of magnitude estimate	screening	± 30 to ± 50
Class 4	1-15	Study estimate	feasibility, study	± 20 to ± 30
Class 3	10-40	Preliminary estimate	Budget authorization or cost control	± 10 to ± 25
Class 2	30-70	Definitive estimate	Control of bid or tender	± 5 to ± 15
Class 1	50-100	Detailed estimate	Check estimate, bid or tender	± 2 to ± 5

2.3.1.2 Component of capital costs

The fixed capital investment is the total cost of designing, constructing, and installing a plant and the associated modifications needed to prepare the plant site. The initial investment costs include:

→ The inside battery limits (ISBL)

They are the cost of providing and installing all the process equipment that makes up the new plant. The project costs are often estimated from ISBL cost. The direct field costs include:

- The major process equipment such as reactors, heat exchangers, pumps, vessels, etc.
- Bulk items such as piping, valves, instruments, structures, etc.
- Civil works such as foundations, buildings, bunds, etc.
- Installation labor and supervision

→ The outside battery limits (OSBL)

OSBL investment or Offsite cost includes the costs of the additions that must be made to the site infrastructure to accommodate adding a new plant or increasing the capacity of an existing plant. Offsite costs are typically estimated as a proportion of ISBL costs in the early stages of design. A typical number is 30% to 50% of ISBL investment. OSBL investments may include such as:

- Pipe bridges, feed and product pipelines
- Cooling tower, circulation pumps, cooling water mains, cooling water treatment plant
- Offices, canteens and central control rooms
- Workshops and maintenance facilities
- Tanker farms, loading facilities and analytical equipment

→ Engineering costs

The engineering costs include the costs of detailed design and other engineering services required to carry out the project. A rule of thumb for engineering costs is 30% of ISBL plus OSBL cost for smaller projects and 10% of ISBL plus OSBL cost for larger projects.

→ Contingency charges

Contingency charges are extra costs added into the project budget to allow for variation from the cost estimate. A minimum contingency charge of 10% of ISBL plus OSBL cost should be used on all projects.

2.3.1.3 Fixed capital costs estimation

→ Estimating purchased equipment costs

When more design information is available, the cost of a plant can be worked up from the cost of individual items of process equipment. Costs of single pieces of equipment are also often needed for minor revamp and debottlenecking projects. The correlations given in Appendix C, Table C1 can be used for preliminary estimates in form of equation 2.12, which is the cost curves for purchased equipment costs.

$$C_e = a + b S^n \quad (2.12)$$

where C_e = purchased equipment cost on a U.S. Gulf Coast basis, Jan. 2010

a, b = cost constants in Appendix C, Table C1

S = size parameter, units given in Appendix C, Table C1

n = exponent for that type of equipment

→ Estimating installed costs: the factorial method

Capital cost estimates for chemical process plants are often based on an estimate of the purchase cost of the major equipment items required for the process, the other costs being estimated as factors of the equipment cost. Generally, this method leads to a Class 4 estimate.

Sinnott, R. and Towler, G.[4] use Equation (2.13) for estimating the installed capital cost of major equipment on a carbon steel basis ($C_{e,i,cs}$) with materials factors (f_m). Table 2.6 give the typical factors for components of the capital cost.

$$C = \sum_{i=1}^{i=m} C_{e,i,cs} [(1 + f_p) f_m + (f_{er} + f_{el} + f_i + f_c + f_s + f_l)] \quad (2.13)$$

where $C_{e,i,CS}$ = purchased equipment cost of equipment i in carbon steel
 C = total plant ISBL capital cost (including engineering costs)
 M = total number of pieces of equipment

Table 2.6: Installation Factors for Estimation of Project Fixed Capital Cost

Installation Factors	Process Type		
	Fluids	Fluids-Solids	Solids
Major equipment, total purchase cost	C_e	C_e	C_e
f_{er} Equipment erection	0.3	0.5	0.6
f_p Piping	0.8	0.6	0.2
f_i Instrumentation and control	0.3	0.3	0.2
f_{el} Electrical	0.2	0.2	0.15
f_c Civil	0.3	0.3	0.2
f_s Structure and buildings	0.2	0.2	0.1
f_l Lagging, insulation, or paint	0.1	0.1	0.05

→ Location factors (L_{FA})

Most plant and equipment cost data are given on a U.S. Gulf Coast (USGC) or Northwest Europe (NWE) basis, as these are historically the main centers of the chemical industry, for which the most data are available. The cost of building a plant in any other location will depend on costs of shipping or transporting equipment to site, currency exchange rates, Import duties, etc. The example of location factors are given in Appendix C, Table C2.

$$\text{Cost of plant in location A} = \text{cost of plant on USGC} \times L_{FA} \quad (2.14)$$

where L_{FA} = location factor for location A relative to USGC basis

2.3.2 Economic evaluation

Project evaluation enables the technical and economic feasibility of a chemical process to be assessed using preliminary process design and economic evaluations.

2.3.2.1 Project costs

→ Variable costs (VC) of production

Variable costs of production are costs that are proportional to the plant output or operation rate. For most chemicals, the major variable costs are the costs of raw materials and utilities.

→ Annual operating costs (AOC) and maintenance costs

In addition to the fixed capital investment that was used to design and construct the plant, the owner needs to invest some capital in maintaining plant operations. Annual operating costs or working capital is the additional money needed to start the plant up and keep it running.

Maintenance costs is a fixed cost, as the plant must be kept in good repair regardless of the level of production. They include the cost of replacing or repairing parts and equipment as well as the cost of labor needed to carry out the maintenance work. Maintenance costs are typically estimated as a fraction of ISBL investment, ranging from 3% for a process that handles liquids.

→ Revenues (R)

The revenues for a project are the income earned from sales of main products and by-products. The production rate of main product is usually specified in the design basis.

2.3.2.2 Breakeven point

The breakeven point is the production level where total revenues equal total expenses. The breakeven analysis is commonly applied in make-or-buy decisions when a decision is needed about the source for manufactured components, services, etc. The breakeven analysis can also determine the required years to recover the initial investment and annual operating costs.

When fixed capital cost (FC) and variable cost (VC) are added, they form the total cost relation (TC) in Figure 2.14. A revenue relation identified as R . A linear revenue relation is commonly assumed.

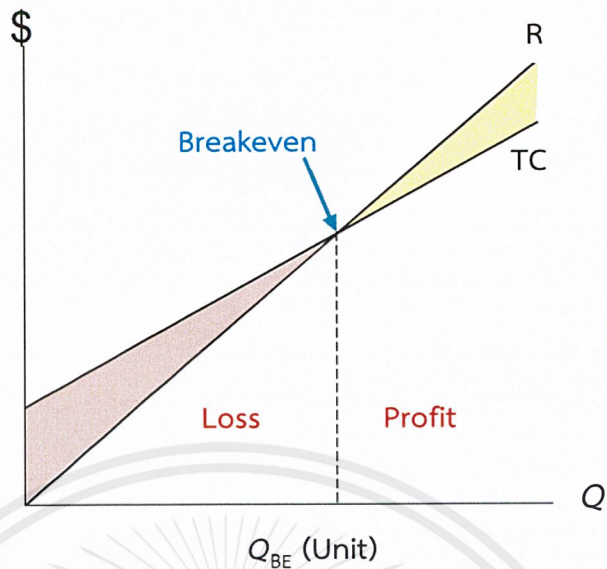


Figure 2.14 Breakeven point.

At some value of Q , the revenue and total cost relations will intersect to identify the breakeven point Q_{BE} (Figure 8.2). If $Q > Q_{BE}$, there is a profit; but if $Q < Q_{BE}$, there is a loss. For linear R and TC , the greater the quantity, the larger the profit. Profit is calculated as

$$\text{Profit} = \text{Revenue} - \text{Total Cost} = R - TC \quad (2.15)$$

The solution for Q_{BE} can be derived by setting the revenue (R) equal to total costs (TC) or indicating a profit of zero to find the breakeven quantity of production.[13]

$$R = TC$$

$$rQ = FC + VC = FC + vQ \quad (2.15)$$

where r = revenue per unit

v = variable cost per unit

Solve for the breakeven quantity $Q = Q_{BE}$ for linear R and TC functions.

$$Q_{BE} = \frac{FC}{r - v} \quad (2.16)$$

2.3.2.3 Payback period

The payback period (n_p) is the time, usually in years, it will take for estimated revenues and other economic benefits to recover the initial investment. Payback analysis is a tool to determine the payback period for an investment. However, breakeven and payback analyses are allied. They can be used in conjunction as Equation 2.17 to determine the payback period when a desired level of breakeven is specified as Blank, L. and Tarquin, A.[13] mentioned.

$$Q_{BE} = \frac{FC/n_p + AOC}{r - v} \quad (2.17)$$

where AOC = Annual operating cost

n_p = Payback period



CHAPTER III

METHODOLOGY

From the objective of this project, it needs to install a heat exchanger at the bottom of Cleavage reactor. When the process equipment is installed, any streams need to connect by using the piping system. In addition, the design engineer must be able to evaluate roughly cost to decide the project alternatives and optimize the design. Therefore, this project considers not only a heat exchanger design but also pipe sizing, valve selection and economic analysis. Microsoft's Excel program is the main tool that helps in all calculation. The overall procedure in this project is shown in Figure 3.1.

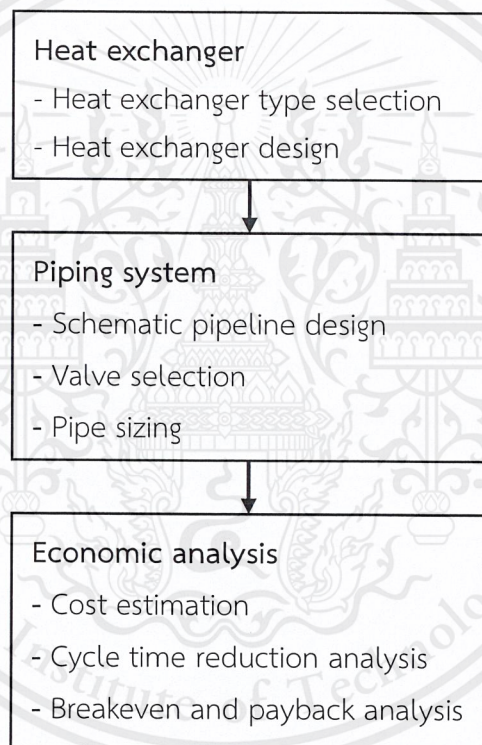


Figure 3.1 The overall procedure in this project.

3.1 Shell and tube heat exchanger design

The individual coefficients depend on the nature of the heat transfer process, the physical properties of the fluids, the fluid flow rates, and the physical arrangement of the heat-transfer surface. As the physical layout of the exchanger cannot be determined until the area is known, the trial and error procedure was performed to obtain the heat exchanger design. Figure 3.2 presents the step of heat exchanger design used in this project.

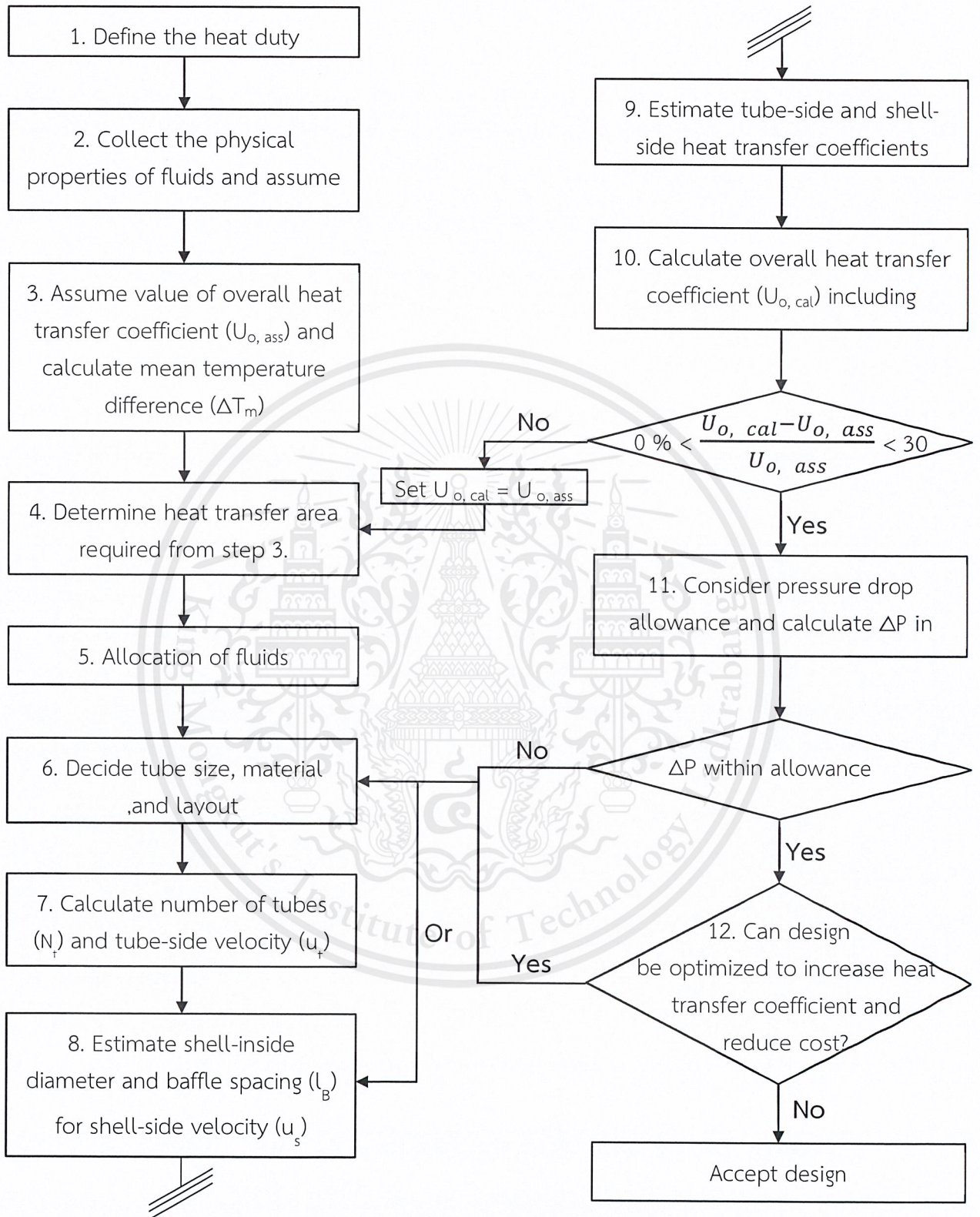


Figure 3.2 Design procedure for shell and tube heat exchanger.

The procedure for calculating the shell-side heat transfer coefficient for a single shell pass exchanger is given below:

- Calculate the area for cross-flow, A_s , for the hypothetical row of tubes at the shell equator, given by

$$A_s = \frac{(p_t - d_o)D_s l_B}{p_t}; \quad p_t \text{ is tube pitch} \quad (3.1)$$

- Calculate the shell-side velocity, u_s ,

$$u_s = \frac{\text{shell-side volumetric flow rate}}{A_s} \quad (3.2)$$

- Calculate the shell-side equivalent diameter (hydraulic diameter), d_e ,
For a square pitch arrangement:

$$d_e = \frac{4 \left(\frac{p_t^2 - \pi d_o^2}{4} \right)}{\pi d_o} = \frac{1.27}{d_o} (p_t^2 - 0.785 d_o^2) \quad (3.3)$$

For an equilateral triangular pitch arrangement:

$$d_e = \frac{4 \left(\frac{p_t}{2} \times 0.87 p_t - \frac{1}{2} \frac{\pi d_o^2}{4} \right)}{\pi d_o / 2} = \frac{1.10}{d_o} (p_t^2 - 0.917 d_o^2) \quad (3.4)$$

- Calculate the shell-side Reynolds number, Re ,

$$Re = \frac{\rho d_e u_s}{\mu} \quad (3.5)$$

- Calculate the shell-side heat transfer coefficient h_o by using Equation (3.6) and reading heat transfer factor, j_h , from Figure 3.4

$$Nu = \frac{h_o d_e}{k_f} = j_h Re Pr^{0.33} \left(\frac{\mu}{\mu_w} \right)^{-0.14} \quad (3.6)$$

The procedure for calculating the tube-side heat transfer coefficient, h_i , is similar to the shell-side calculation but easier calculation in area per pass and in hydraulic diameter of one tube. Heat transfer factor, j_h , of tube-side can be estimated from Figure 3.3. In case of the coefficient of water, the following equation has been developed and used for more accurate estimation.[4]

$$h_i = \frac{4,200(1.35 + 0.02t)d_t^{0.8}}{d_i^{0.2}} \quad (3.7)$$

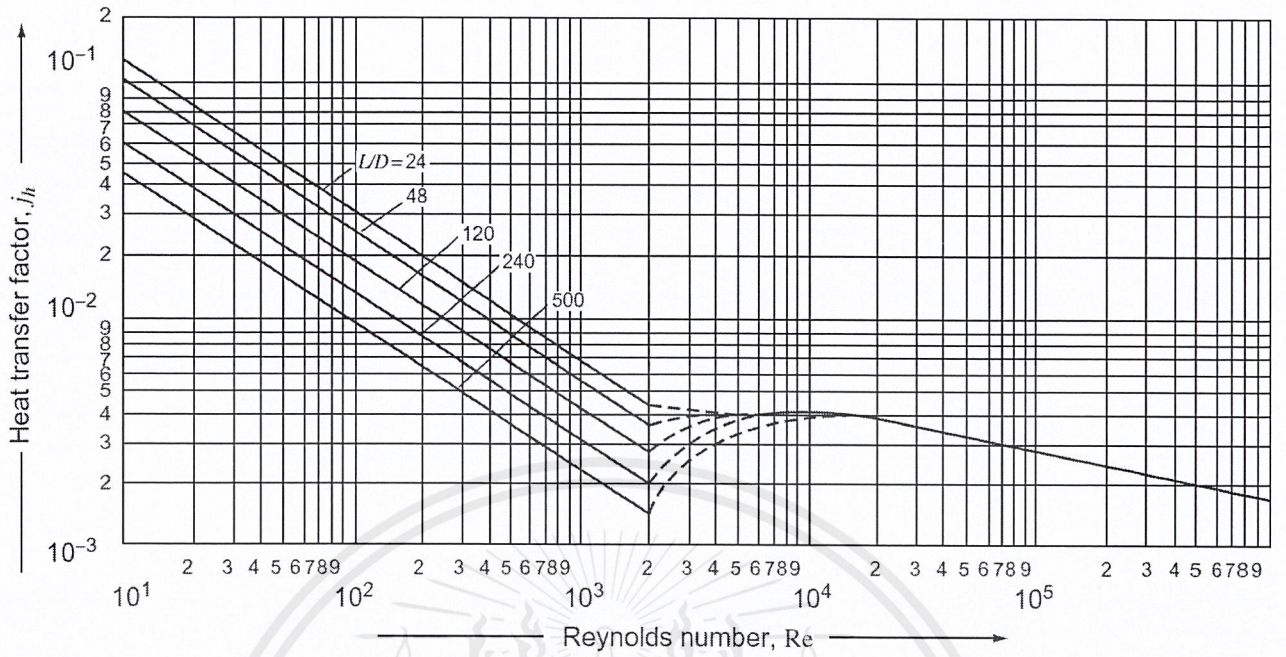


Figure 3.3: Tube-side heat transfer factor.

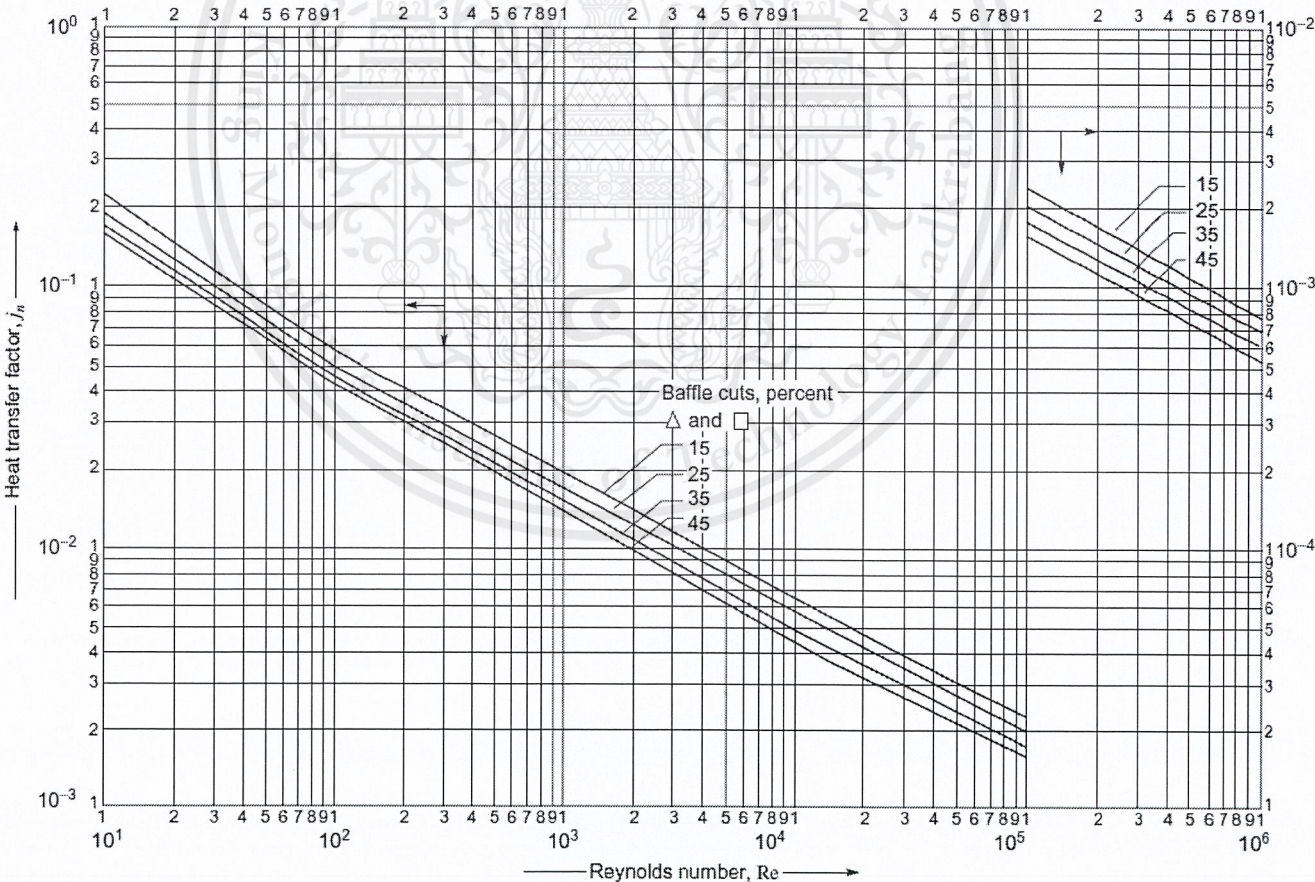


Figure 3.4: Shell-side heat transfer factor, segmental baffles.

3.2 Piping system construction

The construction of piping system procedure in this project scopes is shown in Figure 3.5:

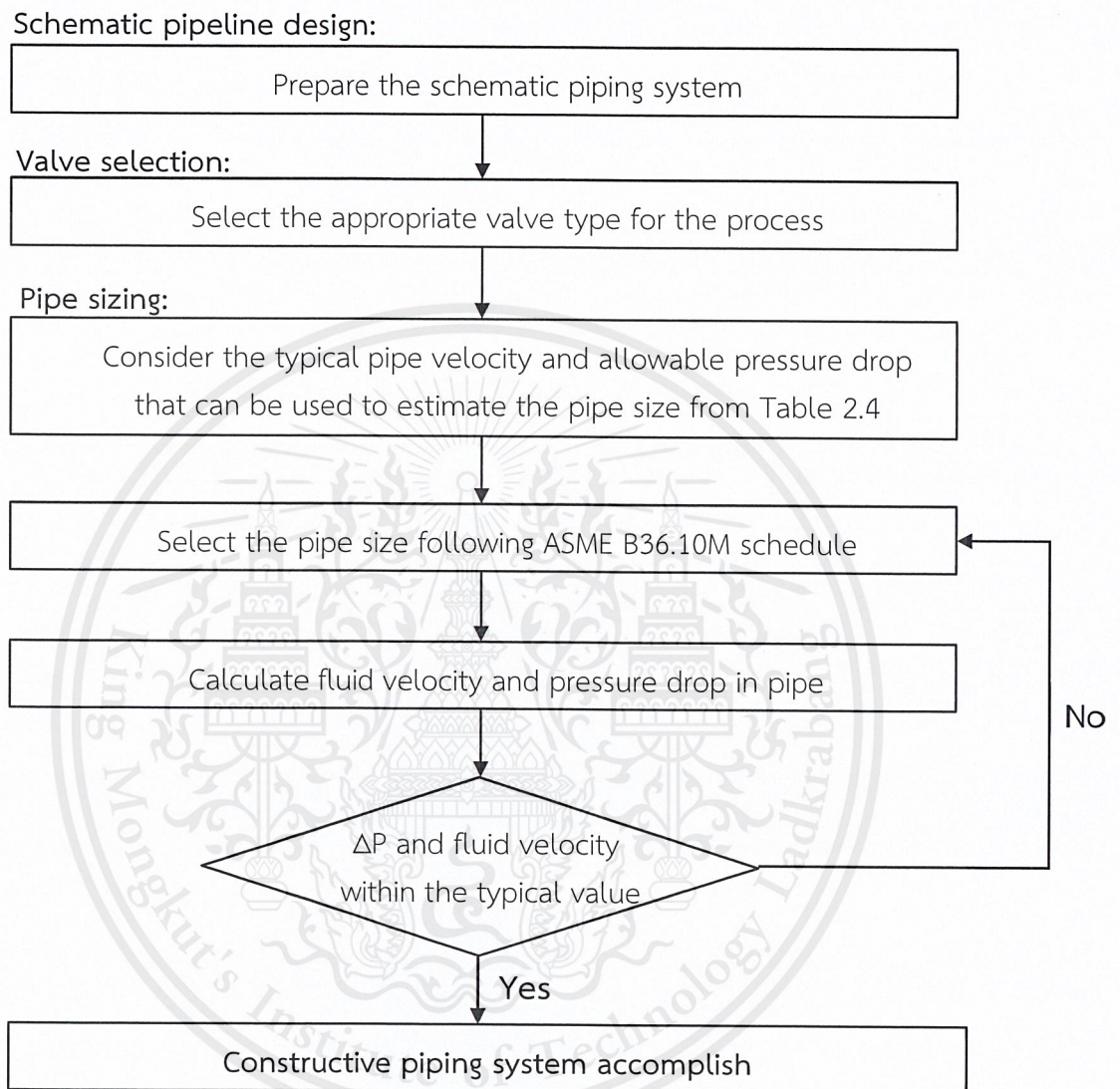


Figure 3.5 Steps for piping system construction.

3.3 Economic analysis

In order to analyze the payback period and breakeven point, the cost estimation and the increased annual production after the installation of heat exchanger need to be evaluated. When a desired level of breakeven is specified, the payback period can be determined by using in conjunction with the breakeven equation (Equation (2.17)).

3.3.1 Cost estimation

- Estimate fixed capital costs (FC)
 - Purchased equipment cost
 - ISBL installed capital cost including engineering costs and contingency charges
- Estimate annual operating costs (AOC)
 - Utilities supply or cooling water for process cooling
 - Maintenance cost
- Estimate variable costs (VC)
 - Raw material
 - Utilities
 - Electricity
- Estimate revenue (R) of production
 - Cost of the main products

3.3.2 Economic evaluation

- Compare the batch period of cleavage reactor between before and after installation of a heat exchanger
- Determine the increased annual production after improvement of this project
- Determine the payback period

CHAPTER IV

RESULTS AND DISCUSSION

This chapter is divided into 3 sections which are 4.1) heat exchanger design, 4.2) piping system and 4.3) economic study.

4.1 Heat exchanger design

4.1.1 Heat exchanger type selection

Heat exchangers can be classified in many different ways. In order to install a heat exchanger for cooling down the temperature of UR, three types of heat exchangers which are commonly used in industries have been considered to apply for this process. These include shell and tube heat exchanger (STHE), Gasketed plate heat exchanger, or plate and frame heat exchanger (PHE), and air-cooled heat exchanger (ACHE). The advantages and disadvantages of them are compared as listed in Table 4.1 for the consideration.

Table 4.1: Comparison of Performance Features for each Heat Exchanger Type

Types	Advantages	Disadvantages
STHE	<ul style="list-style-type: none">- Flexibility in designing- Wide range of pressure and temperature- Easy to maintain and repair	<ul style="list-style-type: none">- Need space to remove the bundle- PHE may be cheaper for pressure below 16 bar and temperature below 200 °C
PHE	<ul style="list-style-type: none">- Small size but high heat transfer surface area- Easy to inspect and clean and less maintenance- Reduce fouling problem	<ul style="list-style-type: none">- Gaskets increase the leakage risk- Maximum operating temperature and pressure are limited and high ΔP- Cannot handle corrosive or aggressive media
ACHE	<ul style="list-style-type: none">- Design is simpler compared to STHE- The fouling on the air side can be cleaned easily- Maintenance cost is normally less than water-cooled system	<ul style="list-style-type: none">- Low heat transfer coefficient of air- Required large heat transfer surfaces- Large space requirement around itself

The gaskets in PHE always increase the leakage risk of the process while the process or unreacted residue is the silane compound. If the silane compound leaks to the outside or contacts with moisture, it can react with water (H₂O) in atmosphere to form hydrochloric which is the highly corrosive material. In the part of ACHE, this type requires large heat transfer surfaces, due to the low heat transfer coefficient on the air side and the low specific heat of air, and required large space around itself for preventing the effect of released hot air to other process equipment in the plant. From the consideration, the STHE have been selected because of more flexibility in designing than PHE and smaller installation area than ACHE.

The selection of the utility supply or fluids for process cooling for heat exchanger depends on the process temperature target that required to cool down. The cooling water is sufficient for this process since the unreacted residue is needed to cool down from 143 °C to 50 °C.

4.1.2 TEMA type selection of shell and tube heat exchanger

Three types of STHE were compared the advantages and disadvantages as summarized in Table 4.2.

Table 4.2: Three Principal Types of Shell and Tube Heat Exchangers

Types	Advantages	Disadvantages
Fixed tube-sheet	<ul style="list-style-type: none"> - High degree of protection against contamination of streams - Possibility for mechanical tube-side cleaning - Usually the cheapest type 	<ul style="list-style-type: none"> - Chemical cleaning on the shell-side only - Thermal expansion problem
U-tube	<ul style="list-style-type: none"> - High degree of protection against contamination of streams - Possibility for mechanical shell-side cleaning 	<ul style="list-style-type: none"> - Clean fluid on the tube-side only - Chemical cleaning on the tube-side only
Floating head	<ul style="list-style-type: none"> - No problem in thermal expansion - Easy to clean on both sides 	<ul style="list-style-type: none"> - The most expensive type - Less heat transfer surface area compare with other types at the same size

From the allocation of the fluid streams, cooling water will be placed in the tube-side (discussed in the next section), so the U-tube exchanger is not suitable for this process because the cooling water side frequently requires cleaning by mechanical means. Although the floating head type can solve the thermal expansion problem and it is easy to clean at both sides, these advantages are not that necessary for this process because the difference between shell and tube mean metal temperatures from calculation is not greater than 50°C as mentioned in section 2.1.3 and the unreacted residue stream is not required to open the system for cleaning. Consequently, the fixed tube sheet exchanger has been chosen to apply for this process. For suggestion, if the differential thermal expansion is excessive for the fixed tubesheet exchanger, the expansion joint can be incorporated into the shell to prevent the thermal stress problem.

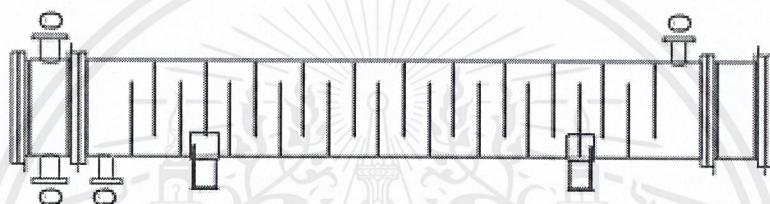


Figure 4.1 Heat exchanger type as TEMA designation: fixed tubesheet exchanger with removable channel and cover, single pass shell (figure from Aspen Exchanger Design and Rating V10 in Aspen plus V10 program).

The fixed tubesheet exchanger with removable channel and cover, single pass shell or AEL type following TEMA standard is chosen for this process as shown in Figure 4.1. For *A* head type (channel and removable cover), this type of header is desirable when cleaning of the inside of the tubes is expected to be frequent. The *L* rear end type (fixed tubesheet like “*A*” stationary head) is identical with *A* header. For *E* shell type (one shell pass), This shell is the most common for single-phase shell fluid applications and has the performance mentioned in the section 2.1.4.2, and therefore other shell types are not that necessary for this process.

4.1.3 A designed shell and tube heat exchanger

To install a heat exchanger for reducing time of unreacted residue discharge from cleavage reactor, the temperature of the unreacted residue from the cleavage reactor above 50 °C may cause the effect to the pump before sending to the waste treatment (see Figure 1.4). It is the reason for cooling down into 50 °C of hot stream outlet temperature (T_2) and kept at the residue drum before pumping.

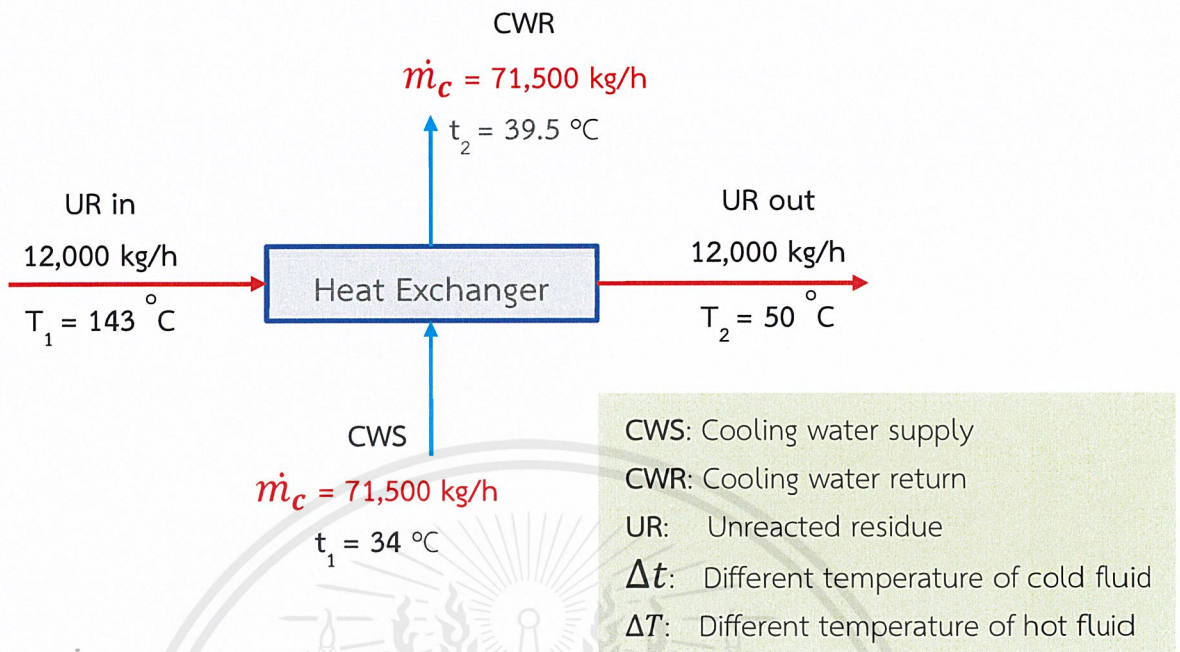


Figure 4.2 Schematic diagram for basic design of a cooler.

In basic design, the schematic diagram as shown in Figure 4.2 was drafted for determining the required specification and calculating the heat duty by thermal equilibrium equation (Equation (2.1)). The red line is the process stream that needed to cool down. From the cooling tower datasheet of the plant, the outlet temperature of cooling water is about 34 °C that is the assumed as cold inlet stream temperature into a process heat exchanger. A typical initial design point would be to assume a cooling water return temperature about 5.5 °C hotter than the cold inlet temperature of cooling water supply, and then the flow rate of cooling water can be determined. The heat duty from the calculation is 455 kW.

For the detailed design, Table 4.3 shows the physical properties of each fluid stream that were collected from the Aspen Exchanger Design and Rating V10 in Aspen plus V10 program, and the fouling factors were assumed from Appendix A, Table A2. In the correlations used to predict heat-transfer coefficients, the physical properties are usually evaluated at the mean stream temperature.

Table 4.3: Physical Properties of each Fluid Stream

Physical Properties	Unreacted Residue (Hot Stream)	Cooling Water (Cold Stream)
Mean temperature (°C)	96.50	36.75
Specific heat capacity; c_p (J/kg°C)	1,468.14	4,165.86
Density; ρ (kg/m ³)	933.84	982.55
Viscosity; μ (cP)	1.25	0.71
Thermal conductivity; λ (W/mK)	0.09	0.62
Fouling factor; R_f (W/m ² °C) ⁻¹	0.0002	0.0003
Inlet pressure (kg/cm ² g)	0.3	3.5

In fluid allocation, Table 4.4 lists the factors to consider for placing the fluid stream in the tube-side or shell-side.

Table 4.4: The Factors to Consider for Fluid Allocation

Factors	Unreacted Residue (Hot Stream)	Cooling Water (Cold Stream)
Stream temperature	Higher	Lower
Stream pressure	Lower	Higher
Fouling	Lower	Higher
Viscosity	Higher	Lower
Stream flow rate	Lower	Higher

■ : should be provided in tube-side ■ : should be provided in shell-side

The cooling water has been decided to allocate in the tube-side from the consideration. The corrosive factor was not concerned because the unreacted residue in the closed system is not the corrosive substance. It is also the reason to choose the carbon steel for the material of construction.

In the tube-side configuration, 1 inch of tube-outside diameter, 12 BWG of tube thickness, 10 ft of tube length, and triangular of tube arrangement have been specified according to the TEMA standard. Despite not having the corrosion allowance required for the carbon steel of tube part from the standard of TEMA, the corrosion allowance of ASM is 1 mm

for the design margin. The tube length was considered from the plot plan. The triangular pitch of tube arrangement was specified because high heat transfer rate will be obtained and the mechanical cleaning in the shell-side is not needed for fixed tubesheet exchanger. Consequently, the number of tubes were calculated, and the number of tube-side passes was specified for the tube-side velocity calculation, then the heat transfer coefficient on the tube-side stream can be calculated.

In the shell-side configuration, the shell-inside diameter was determined by calculating the bundle diameter and estimating the shell-bundle clearance. Then, the baffle spacing and baffle cut % were specified for calculating the velocity and heat transfer coefficient on the shell-side.

The consideration of allowable pressure drop in a heat exchanger is essential for the optimization in design. Accordingly, the design of tube-side and shell-side configuration have already concerned in this point. Table 4.5 shows the performance and more construction detail of a designed heat exchanger.

Table 4.5 Performance and construction detail summary of a designed heat exchanger

Performance			
Fluid allocation	Tube-side		Shell-side
Fluid name	Unreacted residue		Cooling water
Fluid flow rate; kg/h	12,000		71,500
Temperature in; °C	143		34
Temperature out; °C	50		39.5
Allowable pressure drops; bar	0.2		0.5
Pressure drop calculation; bar	0.05		0.32
Velocity calculation; m/s	1.55		0.2
Construction			
Tube outside diameter; in (mm)	1 (25.4)	Tube thickness; BWG	12
Number tube passes per shell	4	Shell pass	1
Tube arrangement	Triangular	Shell-inside diameter; inch	21.25
Tube length; ft (m)	10 (3.05)	Baffle spacing	30 % of D_s
Number of tubes	168	Baffle cut %	32%

Table 4.6 Comparison of a trial value and the calculated value of U_o

Heat transfer area			
Overall Heat transfer coefficient ($U_{o,ass}$); $W/m^2\ ^\circ C$	255	Heat transfer area ($A_{o,ass}$); m^2	40.02
Overall Heat transfer coefficient ($U_{o,cal}$); $W/m^2\ ^\circ C$	259.97	Heat transfer area ($A_{o,cal}$); m^2	39.25
		Error	1.95%

From the final calculation, the heat transfer area required from the overall heat transfer coefficient including fouling factor calculation will be obtained as shown in Table 4.6 with the error of 1.95 % from the assumed (trial) value.

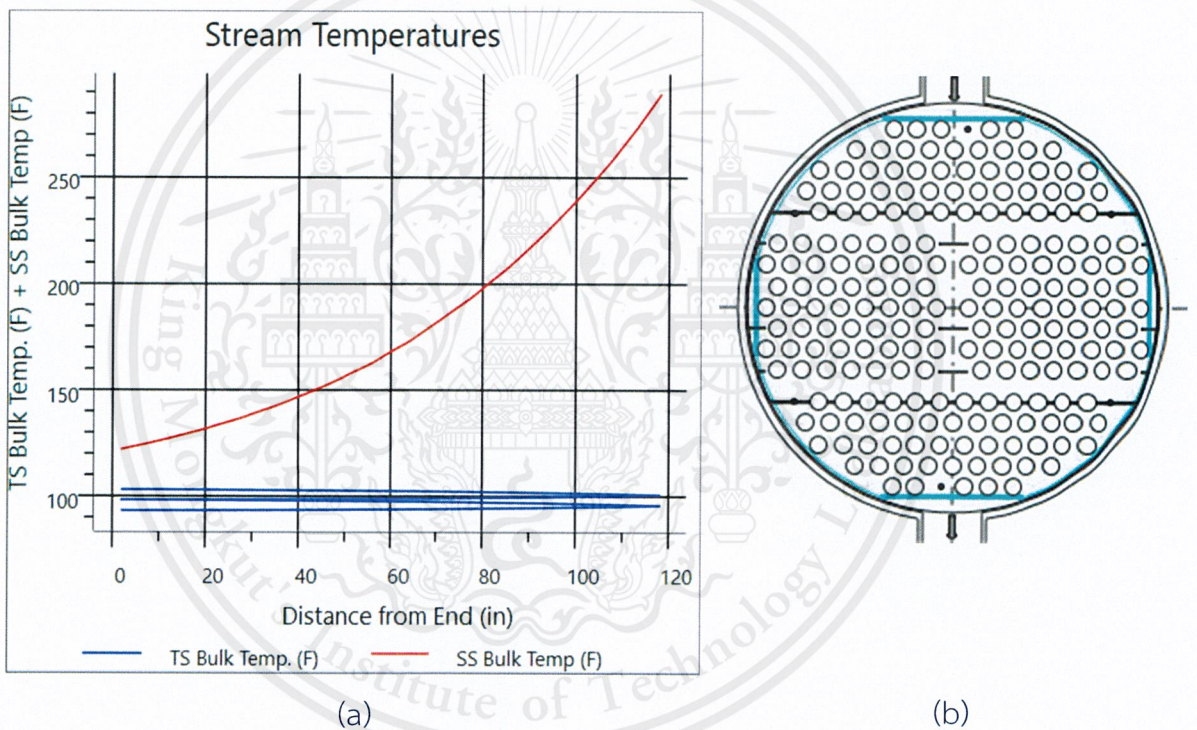


Figure 4.3 (a) Temperature profile and (b) tube layout (figure from Aspen Exchanger Design and Rating V10 in Aspen plus V10 program).

Finally, the Figure 4.3 (a) illustrates the temperature profile for 4 tube-side passes, 1 shell-side pass of shell and tube heat exchanger whereas the tube layout of triangle arrangement from the design is shown in Figure 4.3 (b).

4.2 Piping system results

4.2.1 Schematic piping system

Figure 4.4 illustrates the piping system after designing and specifying the required equipment items.

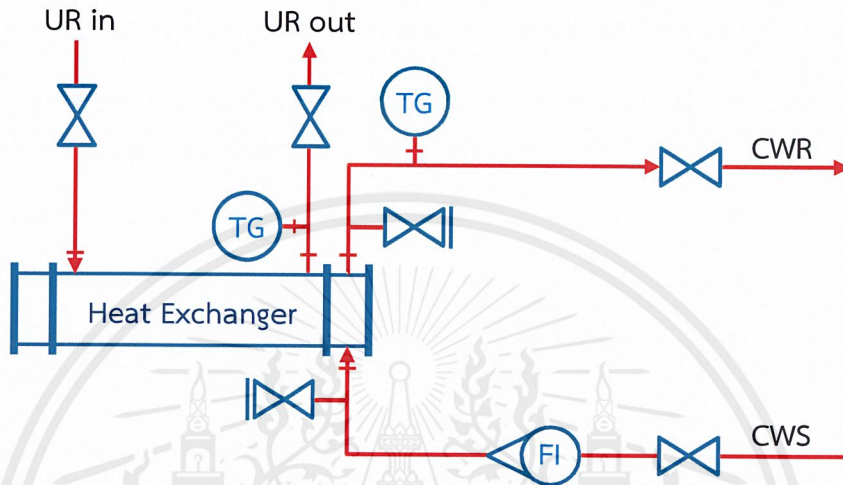


Figure 4.4 Schematic piping system.

In the valve selection, the pipeline as shown in Figure 4.4 was divided into unreacted residue line (Figure 4.5) and cooling water line (Figure 4.6).

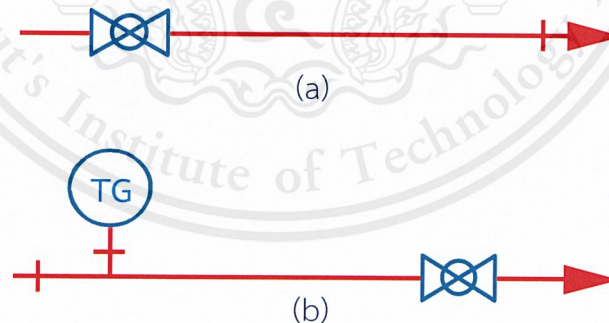


Figure 4.5 Pipeline of unreacted residue: (a) UR in and (b) UR out.

Manual ball valves are the best choice for on-off service since they provide a tight seal in the closed position and low resistance to the flow when open. In addition, ball valves require a quarter turn to open or close. For the pipeline of unreacted residue, ball valve was selected as the shut-off valve. They are always opened in normal operation.

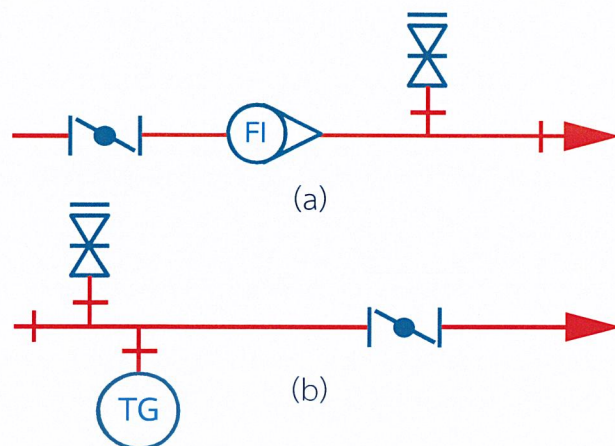


Figure 4.6 Pipeline of cooling water: (a) CWS and (b) CWR

For the pipeline of cooling water, the gate valves were selected for draining in CWS line and venting in the CWR line when shutdown and start-up operations required, respectively. The characteristic of the butterfly valve is equal percentage so that the butterfly valve was selected to manual control flow for gradually start-up and shutdown operations. This is because the fixed tubesheet exchanger needs to avoid the thermal shock effect from the different temperature of tube-side and shell-side, and this valve should fully open for normal operation in the CWS line. For manual control flow rate of cooling water, the butterfly valve that gives lower pressure loss than globe valve was applied in CWR line.

Table 4.7: Pipe Size Selection Summary

	UR Stream	CW Stream
Pipe size (Inch)	4	5
Safety factor	30 %	30 %
ΔP (bar/m)	0.00029	0.00216
Velocity (m/s)	0.44	1.56

From the trial-and-error calculation, the optimum pipe size within the typical allowable pressure drop and recommended velocity was selected, 4 inch for unreacted residue line and 5 inch for cooling water line as shown in Table 4.7. Safety factor of 30% was included to accommodate the change in roughness conditions.

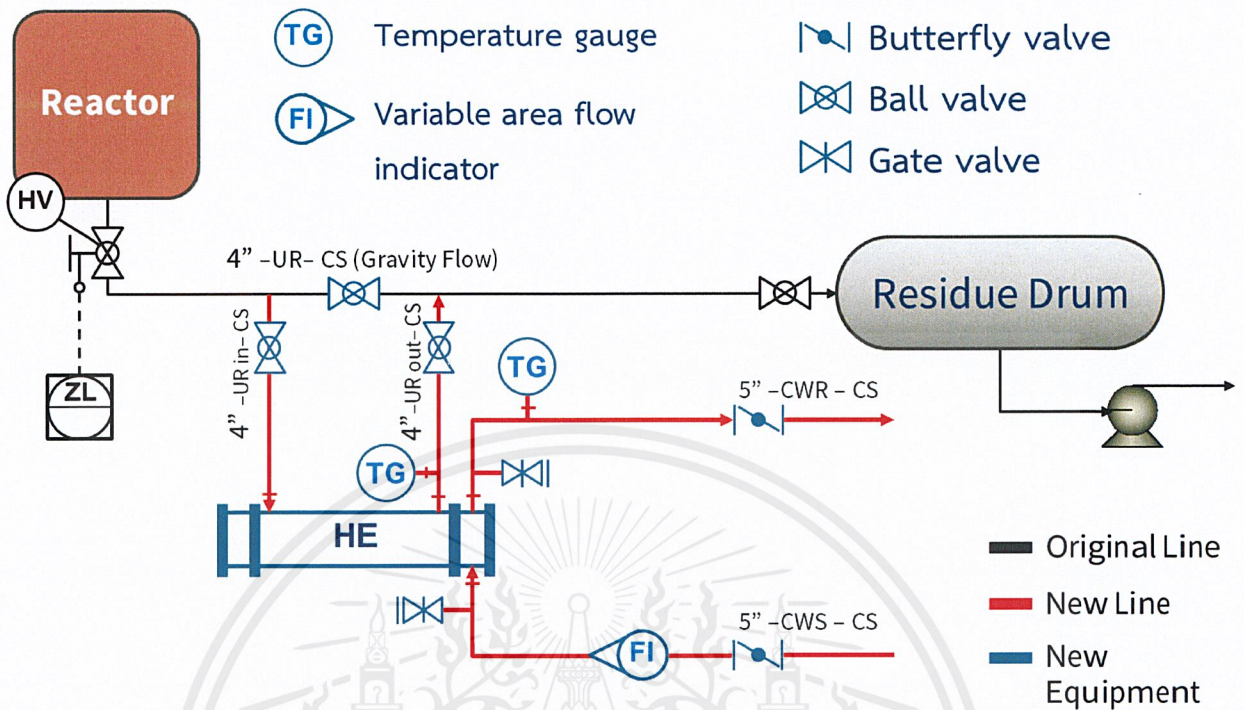


Figure 4.7 Constructive piping system summary.

Figure 4.7 represents constructive piping system summary or piping and instrumentation diagram (P&ID) that identify the arrangement of the process equipment, piping, instruments, valves and pipe size. In the normal operation, the butterfly valve at CWR line will be manually adjusted by hand when the temperature of unreacted residue, that read from the temperature gauge at UR out, changes from the targeted temperature. However, the automatic control element for this process is not concerned because it is not the serious unit as though the main production process.

4.3 Economic summary

4.3.1 Cost estimation

The following costs have been estimated for the breakeven and payback analysis in the economic evaluation. They include the fixed capital costs (FC), annual operating costs (AOC), variable costs per unit (v) and revenue per unit (r).

Table 4.8: Fixed Capital Costs Estimation

Total fixed costs (FC)	
Estimating method	The factorial method
Estimate class	Study estimate (class 4)
Purchased equipment cost	1,080,000 THB
Total fixed costs (FC)	4,310,000 ± 30 % THB

On account of the purchased equipment cost estimation, the cost of fixed tubesheet exchanger is equal about 1,080,000 THB. The total fixed capital costs (FC) from the calculation, after major process equipment cost estimated, are equal about 4,310,000 THB. The factorial method has been chosen for study and feasibility surveys of this project. At some point in the development of a design it is always necessary to get a real price quotation from an equipment vendor.

4.3.2 Economic evaluation

Table 4.9: Annual Operating Costs Estimation

Annual Operating Costs (AOC)	
1. Cooling water	71,500 kg/h 625,000 ton/yr 0.18 THB/ton = 110,000 THB/yr
2. Maintenance cost	= 103,500 THB/yr
Total annual operating costs (AOC)	= 213,500 THB/yr

The costs of cooling water are fixed per year as the results of the cooling water must be always supplied to circulate in the heat exchanger all the times, for reducing the fouling occurrence on the tube-side. In consequence, the annual operating costs for heat exchanger in this case include the utilities supply or cooling water and maintenance cost. The costs of water make-up and chemical treatment usually add about 0.18 THB/ton.

Table 4.10: Variable Costs Estimation

Variable Costs (VC)	
1. Raw material	Catalyst
2. Utilities	Steam N ₂
3. Electricity	Pump Agitator Oil unit
Total variable costs per unit (v) = 128,000 THB/batch	

The variable costs of this project are the cost of operating Cleavage unit which includes the cost of catalyst, utilities and electricity, as shown in Table 4.10. Total variable costs per unit (v) are equal about 128,000 THB/batch.

Table 4.11: Revenue Estimation

Revenue (R)	
1. Products	MCS-1 MCS-2 MCS-4
2. By-product	UR
Total revenue per unit (r) = 4,200,000 THB/batch	

The main product from Cleavage unit is the revenue for determining the possibility of this project. The total revenue per unit (r) is equal about 4,200,000 THB/batch.

The unreacted residue per batch of cleavage reactor is equal about 13.2 ton/batch. The flow rate of unreacted residue through a heat exchanger from design is 12 ton/h. Hence, the annual production before and after the installation of heat exchanger were considered in terms of cycle time reduction in which the results are summarized in Table 4.12. It can be seen that the installation of a heat exchanger at the bottom of Cleavage reactor can reduce the batch period from 11 days and 4 hours per batch to around 11 days and 1

hour per batch. This is equal to the increased annual production of 0.36 batch/yr or valuable about 1,236,000 THB/yr.

Table 4.12: Annual Production Before and After Improvement

Before improvement:		
Batch period	11.17	day/batch
Annual production	32.69	batch/yr
After improvement:		
Batch period	11.05	day/batch
Annual production	33.04	batch/yr
Increased annual production	= 0.36	batch/yr

In order to determine the payback period of this project, the lifetime of a heat exchanger was assumed of 10 years because exchanger shell, channels, and tubesheets should be typical designed for minimum of 10 years and then finding the breakeven quantity by equation 2.17.

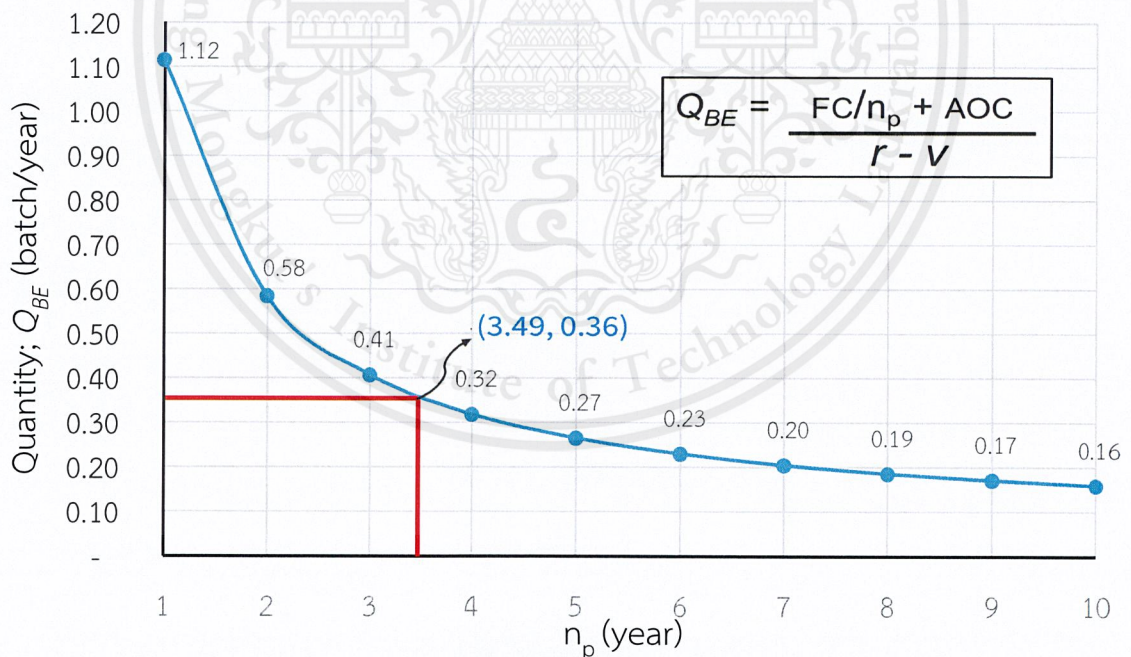


Figure 4.8 Breakeven chart.

According to Equation (2.17), the graph can be plotted between payback period and breakeven quantity, as shown in Figure 4.8. It was found that the annual production capacities of 0.36 batch/year can payback within 3 years and a half.

CHAPTER V

CONCLUSIONS

5.1 Conclusions

5.1.1 Heat exchanger design

The basic criterion of a heat exchanger design was performed to provide the heat duty under the allowable pressure drop. The other factors in design, such as process condition, cost, installation area, reliability, safety, etc. are included in the consideration. From the heat exchanger design, a fixed tubesheet exchanger with removable channel and cover, single pass shell (AEL type) is selected and applied for this process due to the requirement of the frequent cleaning on tube-side by mechanical method and high ability of the protection against contamination of streams. Moreover, the installation of a heat exchanger at the bottom of Cleavage reactor is also a debottlenecking project of silane monomers production that makes the capacity of the main products to increase.

5.1.2 Piping system

Any streams need to be connected by using the piping system when the process equipment is installed. The capital cost of a pipe depends on the pipe diameter and thus, the typical allowable pressure drop in pipe is the first parameter for estimating the optimum pipe size. The second parameter is the fluid velocity because the fluid in pipe at high velocity can damage the inside wall of pipe or cause the erosion to occur.

5.1.3 Economic study

In this project, the factorial method is used as an estimating method. From an economic analysis, it was found that the annual production after the installation of a heat exchanger can be increased around 0.36 batch/year or valuable about 1,236,000 THB/year. Finally, the annual production capacity as mentioned will pay back within 3 years and a half.

5.2 Suggestion

The design does not have a stereotype, so it depends on the process. Some detailed design, such as mechanical design and control system, of major process equipment, valves, piping and instrument should be confirmed by other field engineers such as mechanical engineer and instrument engineer. At some point in the development of a design, it is necessary to get a real price from the vendor for accuracy.

REFERENCES

- [1] H.-H. Moretto, M. Schulze, and G. Wagner, "Silicones", *Ullmann's Encyclopedia of Industrial Chemistry*. Wiley-VCH, Weinheim, pp. 22956–22994, 2007.
- [2] "Company Profile - Shin-Etsu Chemical," *Shin-Etsu Chemical Co., Ltd.* [Online]. Available: <https://www.shinetsu.co.jp/en/company/profile.html>.
- [3] K. Thulukkanam, *Heat Exchanger Design Handbook*, 2nd ed. Boca Raton: CRC Press, 2013.
- [4] G. Towler and R. Sinnott, *Chemical engineering design: principles, practice, and economics of plant and process design*, 2nd ed. Butterworth-Heinemann, 2013.
- [5] D. G. Kröger, *AIR-COOLED HEAT EXCHANGERS AND THERMAL-FLOW PERFORMANCE EVALUATION AND DESIGN*, vol. 1. PennWell, 2004.
- [6] R. H. Perry, D. W. Green, and J. O. Maloney, *Perry's Chemical engineers' Handbook*, 7th ed. McGraw-Hill, 1997.
- [7] R. K. Shah and D. P. Sekulic, *FUNDAMENTALS OF HEAT EXCHANGER DESIGN*. John Wiley & Sons, Inc., 2003.
- [8] Y. A. Çengel and A. J. Ghajar, "Heat and Mass Transfer: fundamentals & applications" McGraw-Hill Education, 2015.
- [9] A. K. Coker, *Ludwig's Applied Process Design for Chemical and Petrochemical Plants*, 4th ed. Gulf Professional Publishing, 2007.
- [10] E. U. Schlunder, *Heat Exchanger Design Handbook*. Hemisphere Publishing Corporation., 1983.
- [11] P. L. Skousen, *Valve Handbook*, 2nd ed. McGraw-Hill, 2004.
- [12] P. Smith and R. W. Zappe, *Valve Selection Handbook*, 5th ed. Gulf Professional Publishing, 2004.
- [13] L. Blank and A. Tarquin, *ENGINEERING ECONOMY*, 7th ed. McGraw-Hill, 2012.

APPENDIX A
DATA FOR HEAT EXCHANGER DESIGN

Table A.1: Typical Overall Heat Transfer Coefficients for Trial Estimation

Shell and Tube Heat Exchangers		
Hot Fluid	Cold Fluid	U (W/m ² °C)
Heat exchangers		
Water	Water	800-1,500
Organic solvents	Organic solvents	100-300
Light oils	Light oils	100-400
Heavy oils	Heavy oils	50-300
Gases	Gases	10-50
Coolers		
Organic solvents	Water	250-750
Light oils	Water	350-900
Heavy oils	Water	60-300
Gases	Water	20-300
Organic solvents	Brine	150-500
Water	Brine	600-1,200
Gases	Brine	15-250
Heaters		
Steam	Water	1,500-4,000
Steam	Organic solvent	500-1,000
Steam	Light oils	300-900
Steam	Heavy oils	60-450
Steam	Gases	30-300
Flue gas	Steam	30-100
Flue gas	Hydrocarbon vapors	30-100
Condensers		
Aqueous vapors	Water	1,000-1,500
Organic vapors	Water	700-1,000

Table A.2: Typical Values of Fouling Factors (Coefficients)

Fluid	Coefficient (W/m ² °C)	Factor (Resistance) (W/m ² °C) ⁻¹
River water	3,000-12,000	0.0003-0.0001
Sea water	1,000-3,000	0.001-0.0003
Cooling water (towers)	3,000-6,000	0.0003-0.00017
Town water (soft)	3,000-5,000	0.0003-0.0002
Town water (hard)	1,000-2,000	0.001-0.0005
Steam condensate	1,500-5,000	0.00067-0.0002
Steam (oil free)	4,000-10,000	0.0025-0.0001
Steam (oil traces)	2,000-5,000	0.0005-0.0002
Refrigerated brine	3,000-5,000	0.0003-0.0002
Air and industrial gases	5,000-10,000	0.0002-0.0001
Flue gases	2,000-5,000	0.0005-0.0002
Organic vapors	5,000	0.0002
Organic liquids	5,000	0.0002
Light hydrocarbons	5,000	0.0002
Heavy hydrocarbons	2,000	0.0005
Boiling organics	2,500	0.0004
Condensing organics	5,000	0.0002
Heat transfer fluids	5,000	0.0002
Aqueous salt solutions	3,000-5,000	0.0003-0.0002

Table A.3: Conductivity of Metals

Metal	Temperature (°C)	K_w (W/m °C)
Aluminum	0	202
	100	206
Blass (70 Cu, 30 Zn)	0	97
	100	104
	400	116
Copper	0	388
	100	378
Nickel	0	62
	212	59

Table A.3: Conductivity of Metals — (Cont.)

Metal	Temperature (°C)	K_w (W/m °C)
Stainless steel (18/8)	0-100	16
Carbon steel	40	60
	100	58
	260	51
Titanium	0-100	16



APPENDIX B
DATA FOR PIPING SYSTEM CONSTRUCTION

Table B.1: Carbon Steel Pipe Size

			Carbon Steel Pipe Thickness (mm)						
dn [■]	dn [■]	d _o	ASME B36.10M SCHEDULE*						
mm	inch	mm	20	40	60	80	100	STD	XS
6	1/8	10.3	0	1.73	0	2.41	0	0	0
8	1/4	13.7	0	2.24	0	3.02	0	0	0
10	3/8	17.1	0	2.31	0	3.2	0	0	0
15	1/2	21.3	0	2.77	0	3.73	0	2.77	3.73
20	3/4	26.7	0	2.87	0	3.91	0	2.87	3.91
25	1.00	33.4	0	3.38	0	4.55	0	3.38	4.55
32	1.25	42.2	0	3.56	0	4.85	0	3.56	4.85
40	1.50	48.3	0	3.68	0	5.08	0	3.68	5.08
50	2.00	60.3	0	3.91	0	5.54	0	3.91	5.54
65	2.50	73.0	0	5.16	0	7.01	0	5.16	7.01
80	3.00	88.9	0	5.49	0	7.62	0	5.49	7.62
90	3.50	101.6	0	5.74	0	8.08	0	5.74	8.08
100	4.00	114.3	0	6.02	0	8.56	0	6.02	8.56
125	5.00	141.3	0	6.55	0	9.53	0	6.55	9.53
150	6.00	168.3	0	7.11	0	10.97	0	7.11	10.97
200	8.00	219.1	6.35	8.18	10.31	12.7	15.09	8.18	12.7
250	10.00	273.0	6.35	9.27	12.7	15.09	18.26	9.27	12.7
300	12.00	323.8	6.35	10.31	14.27	17.48	21.44	9.53	12.7
350	14.00	355.6	7.92	11.13	15.09	19.05	23.83	9.53	12.7
400	16.00	406.4	7.92	12.7	16.66	21.44	26.19	9.53	12.7
450	18.00	457.0	7.92	14.27	19.05	23.83	29.36	9.53	12.7
500	20.00	508.0	9.53	15.09	20.62	26.19	32.54	9.53	12.7

Note: ■ Nominal diameter

* Extracted from carbon steel pipe data of ASME B36.10M-2000
(Revision of ASME B36.10M-1996)

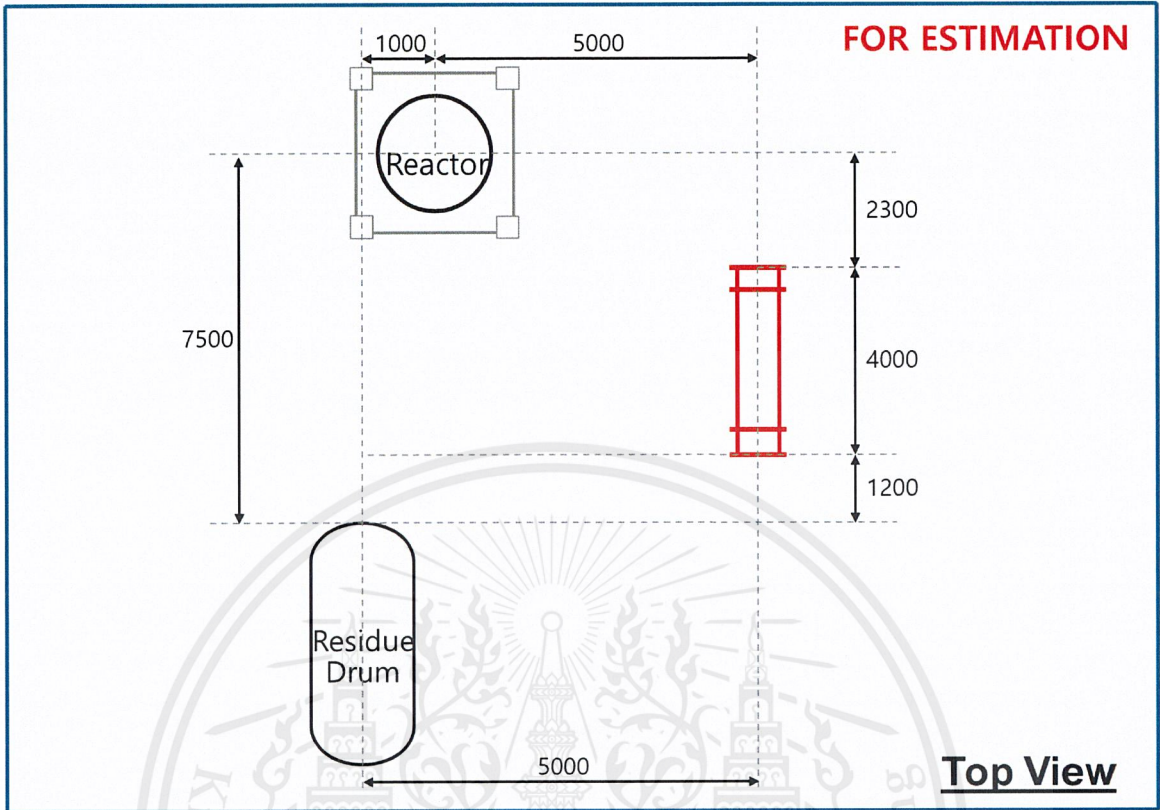


Figure B.1 Cleavage unit plot plan.

APPENDIX C
DATA FOR ECONOMIC ANALYSIS

Table C.1: Purchased Equipment Cost for Common Plant Equipment

Equipment	Units for Size, S	S_{lower}	S_{upper}	a	b	n
<i>Agitator & mixers</i>						
Propeller	driver power, kW	5.0	75	17,000	1,130	1.05
Spiral ribbon mixer	driver power, kW	5.0	35	30,800	125	2.0
Static mixer	liters/s	1.0	50	570	1,170	0.4
<i>Compressors</i>						
Blower	m ³ /h	200	5,000	4,450	57	0.8
Centrifugal	driver power, kW	75	30,000	580,000	20,000	0.6
Reciprocating	driver power, kW	93	16,800	260,000	2,700	0.75
<i>Crushers</i>						
Reversible hammer mill	t/h	30	400	68,400	730	1.2
Pulverizers	kg/h	200	4,000	16,000	670	0.5
Jaw crusher	t/h	100	600	-8,000	62,000	0.5
Gyratory crusher	t/h	200	3,000	5,000	5,100	0.7
Ball mill	t/h	0.7	60	-23,000	242,000	0.4
<i>Dryers</i>						
Direct contact Rotary ^x	m ²	11	180	15,000	10,500	0.9
Atmospheric tray batch	area, m ²	3.0	20	10,000	7,900	0.5
Spray dryer	evap rate, kg/h	400	4,000	410,000	2,200	0.7
<i>Evaporators</i>						
Vertical tube	area, m ²	11	640	330	36,000	0.55
Agitated falling film ^y	area, m ²	0.5	12	88,000	65,500	0.75
<i>Heat exchangers</i>						
U-tube	area, m ²	10	1,000	28,000	54	1.2
Floating head	area, m ²	10	1,000	32,000	70	1.2
Double pipe	area, m ²	1.0	80	1,900	2,500	1.0
Thermosiphon reboiler	area, m ²	10	500	30,400	122	1.1
U-tube Kettle reboiler	area, m ²	10	500	29,000	400	0.9
Plate and frame ^y	area, m ²	1.0	500	1,600	210	0.95

Table C.1: Purchased Equipment Cost for Common Plant Equipment — (Cont.)

Equipment	Units for Size, S	S_{lower}	S_{upper}	a	b	n
<i>Filters</i>						
Plate and frame	capacity, m ³	0.4	1.4	128,000	89,000	0.5
Vacuum drum	area, m ²	10	180	-73,000	93,000	0.3
<i>Furnaces</i>						
Cylindrical	duty, MW	0.2	120	80,000	109,000	0.8
Box	duty, MW	30	60	43,000	111,000	0.8
<i>Tanks</i>						
Floating roof	capacity, m ³	100	10,000	113,000	3,250	0.65
Cone roof	capacity, m ³	10	4,000	5,800	1,600	0.7
<i>Trays</i>						
Sieve trays ^z	diameter, m	0.5	5.0	130	440	1.8
Valve trays	diameter, m	0.5	5.0	210	400	1.9
Bubble cap trays	diameter, m	0.5	5.0	340	640	1.9

Note: x Direct heated

y Type 304 stainless steel

z Cost per tray, based on stack of 30 trays

Table C.2: Location Factors

Country	Region	Location Factor
United states	Gulf Coast	1.00
	East Coast	1.04
	West Coast	1.07
	Midwest	1.02
Canada	Ontario	1.00
	Fort McMurray	1.60
Mexico		1.03
Brazil		1.14
China	Imported	1.12
	Indigenous	0.61
Japan		1.26
South East Asia		1.12
Australia		1.21

Table C2: Location Factors — (Cont.)

Country	Region	Location Factor
India		1.02
Middle East		1.07
France		1.13
Germany		1.11
Italy		1.14
Netherlands		1.19
Russia		1.53
United Kingdom		1.02

The values in Table C2 give costs on a local basis in U.S. dollars. The location factors in Table C2 are based on 2003 data and can be updated by dividing by the ratio U.S. dollar/local currency in 2003 and multiply by the ratio U.S. dollar/local currency in year of interest.

For example, Convert the location factors of from 2003 to 29 October 2018

The exchange rate in 2003: 41.60 THB = 1 USD

The exchange rate on 29 October 2018: 33.14 THB = 1 USD

LF_A of South East Asia in 2003 = 1.12

$$LF_A \text{ on 29 October 2018} = \frac{1.12 \times 33.14}{41.60} = 0.89$$

APPENDIX D
DATA OF UNREACTED RESIDUE

Table D.1: Physical Properties by Aspen EDR V10 in Aspen Plus V10 Program

Temperature (°C)	Liquid Density (kg/m ³)	Liquid Specific Heat (kcal/kg °C)	Liquid Viscosity (cP)	Liquid Thermal Conductivity (W/m °C)
143.00	899.12	0.393	0.880	0.0822
138.84	902.35	0.389	0.898	0.0829
134.65	905.58	0.386	0.917	0.0836
130.41	908.81	0.382	0.940	0.0844
126.13	912.06	0.378	0.965	0.0851
121.80	915.31	0.374	0.994	0.0858
117.43	918.57	0.370	1.027	0.0865
113.01	921.84	0.366	1.064	0.0872
108.54	925.12	0.362	1.106	0.0879
104.02	928.41	0.358	1.154	0.0887
99.45	931.72	0.353	1.208	0.0894
94.82	935.04	0.349	1.270	0.0902
90.13	938.38	0.345	1.341	0.0909
85.38	941.74	0.340	1.423	0.0917
80.58	945.11	0.336	1.518	0.0924
75.70	948.50	0.331	1.628	0.0932
70.76	951.92	0.327	1.757	0.0939
65.75	955.36	0.322	1.909	0.0947
60.67	958.82	0.317	2.089	0.0955
55.51	962.31	0.313	2.304	0.0963
50.26	965.83	0.308	2.563	0.0971
44.93	969.38	0.303	2.879	0.0979
39.51	972.96	0.298	3.268	0.0987
34.00	976.59	0.292	3.752	0.0996

1) Composition (Molecular weight = 186.08)

- Tetramethyldichlorosilane 85.88 %
- Pentamethylchlorodisilane 9.52 %
- Trimethyltrichlorodisilane 3.30 %
- Dimethyltetrachlorodisilane 1.30 %

2) Physical and chemical properties

- Boiling point: 150.1 °C
- Vapor pressure: 4.97 mmHg (25 °C)
- Specific gravity: 0.991 (25 °C)
- Solubility in water: Reacts with water violently
- Odor: Pungent odor

3) Stability and reactivity

- Stability: Unstable
- Condition to avoid: Contact with water, alcohols, compound having active hydrogen atom or aqueous solutions of alkalis.
- Hazardous decomposition or by-product: Hydrogen chloride (Corrosive)

BIOGRAHPY

Name: Mr. Pornpiput Semjorn
Date of Birth: 09/20/1995
Address: 40/77 Rd. Phra Piya, Pa Tan, Muang Lopburi, Lop Buri, 15000
E-mail: semjornaim1995@gmail.com
Telephone: 091-885-2056

Academic Background:

- 2008-2010:
Winituksa School Under Patronage of Her Royal Highness Princess
Maha Chakri Sirindhorn, Lop Buri
- 2011-2013:
Triam Udom Suksa School, Bangkok

Working Experience:

- June 2018 – July 2018:
PTT Global Chemical Public Company Limited, Internship Program 2018
- August 2018 – November 2018:
Asia Silicones Monomer Limited, Co-operative Education Program 2018