Report of Cooperative Education

Optimization of Polyol Feeding Conditions to Reduce Cooling Time and Selection of Gear Reducers of Gear Pumps to Improve Pump Reliability

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Abstract

Polyol production consists of polyol and formulated polyol plants. Gear pump is used to transfer the polyols from polyol plant to blend with low-boiling point blowing agent and other additives at the formulated polyol plant for specialty products. Gear reducer of gear pump is installed to control pump speed. The current gear ratio is 2.78. The polyol plant and its equipment were originally designed for flexible polyols which are much less viscous than rigid polyols. The polyol plant produces 4 grades of rigid polyols, e.g.,Voranol RN482 which is mostly used. Transfer of viscous polyols causes suction loss, cavitation and low pump reliability. Thus, polyol temperature at the product tank increased to 80 – 90 °C to reduce its viscosity. Therefore, it takes long cooling time about 20 h at the formulated polyol plant to avoid the vaporization of low-boiling point blowing agent. In this project, polyol feeding conditions were optimized to reduce cooling time and finally increase the productivity. Cooling time can be reduced by decreasing polyol temperature at the product tank resulting in viscous based polyols, high suction loss and cavitation. Pump speed can be reduced by increasing gear ratio to prevent suction loss and cavitation. By using the optimum gear ratio, the temperature of Voranol RN482 at the product tank reduced from 80 to 55 °C. From lower optimum polyol temperature at the product tank, the cooling time of Voranol RN482 for 1 hour and 24 minutes was reduced. The benefits of this project are less operating time and more productivity about 161 ton/year. The result of pump reliability can be monitored after gear reducer replacement.

Keywords: Polyol, Cooling Time, Gear Reducer, Gear Pump, Pump reliability

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NOMENCLATURES

A_c	Cross sectional area (m^2)
A_s	Total surface area (m^2)
c_p	Specific heat capacity (kJ/kg·K)
c_{pi}	Specific heat capacity of inside fluid (kJ/kg·K)
c_{po}	Specific heat capacity of outside fluid (kJ/kg·K)
D	Pipe diameter (m^2)
D_e	Equivalent length (m)
D_a	Diameter of agitator (m)
D_{imp}	Impeller diameter (m)
f	Fanning friction factor
f_c	Fouling factor
f_i	Fouling factor of inside film
f_o	Fouling factor of outside film
g	Gravity acelleration (m/s^2)
H	Blender height (m)
h	Heat transfer coefficient of convection (W/m^2 · K)
h_i	Heat transfer coefficient of convection for inside film (W/m^2 · K)
h_o	Heat transfer coefficient of convection for outside film (W/m^2 · K)
h_f	Friction loss in piping system (m^2/s^2)
h_{fs}	Friction loss in suction pipe (m^2/s^2)
h_{fp}	Friction loss in pump (m^2/s^2)
K_c	Contraction loss coefficient
K_e	Expansion loss coefficient
K_f	Loss coefficient from fittings and valves
k	Thermal conductivity (W/m·K)
L	Length of piping system (m)
M	Mass of mixing fluid (kg)
$\dot{M}$	Mass flow rate (kg/h)

NOMENCLATURES (CONT.)

$\dot{M}_o$	Mass flow rate of chill water (kg/h)
N	Rotary speed (RPM)
$NPSH$	Net positive suction head (m)
$NPSHA$	Available net positive suction head (m)
$NPSHR$	Minimum required net positive suction head (m)
Nu	Nusselt number
n	Constant of viscosity model
P	Pressure (bar)
P_s	Absolut pressure at surface of reservoir (bar)
P_v	Available net positive suction head (bar)
ΔP	Pressure drop across piping system (bar)
Pr	Prandtl number
p	Spiral baffle pitch (m)
Re	Reynolds number
T	Fluid temperature (^{o}C)
$T(t)$	Target temperature at any time (^{o}C)
T_0	Reference temperature (^{o}C)
T_i	Initial temperature (^{o}C)
T_∞	Ambient temperature (^{o}C)
t	Time (h)
U	Overall heat transfer coefficient (W/m^2 · K)
V	Volume (m^3)
V_a	Maximum actual volume (m^3)
V_{max}	Maximum volume of based polyol to blender (% of blender volume)
$\dot{V}$	Volumetric flow rate (m^3/h)
$\bar{V}$	Average velocity of fluid (m/h)
$\bar{V}_e$	Effective velocity is calculated from 65% of flow rate (m/s)
W	Pump work (kW)

NOMENCLATURES (CONT.)

W_a	Width anular space (m)
x	Wall thickness (m)
Z	Height (m)
Z_s	Height between suction and reservoir surface (m)
ΔZ	Diferent height (m)

Greek Symbols

η	Pump efficientcy
ρ	Fluid density (kg/m^3)
μ	Fluid viscosity (cP)
μ_0	Viscosity of fluid at reference temperature (cP)
μ_w	Viscosity of fluid at wall temperature (cP)

CHAPTER I
INTRODUCTION

1.1 Background

Dow Chemical Company is a multinational chemical corporation. The products of the company consist of chemical, plastic and agricultural products. Dow services to consumer markets such as food, transportation, health and medicine, personal care and construction.

The 2 main businesses are styrene-butadiene latex and polyurethane business. Siam Synthetic Latex Co., Ltd., which is a joint venture between Dow Chemical and SCG Chemical, produces styrene-butadiene latex as the main product. Polyurethane business is managed by only Dow Chemical. The first plant is styrene-butadiene latex plant. Styrene-butadiene latex is produced from polymerization of styrene monomer, butadiene monomer and additives. The second plant is polyol plant. Polyols are produced from polymerization of oxide monomer in a batch process using potassium hydroxide catalyst. Four grades of fluid polyol products are Voranol RN482, RA440, RN490 and RH360. The viscous polyols are supplied to customers and the formulated polyol plant. The formulated polyol plant blends based polyols with additives. Polyol and isocyanate are used for polyurethane production, and are sold to customers without forming. The common form of polyurethane is foam which is classified to rigid foam and flexible foam. The application of rigid foam is insulation in the refrigerators and automotive parts. The flexible foam is used in furniture, bedding and carpet.

In the beginning, the polyol plant and its equipment were originally designed for flexible polyols which are much less viscous than rigid polyols. Gear pump is used to transfer the polyols from the polyol plant to blend with blowing agent and other additives at the formulated polyol plant for special applications. The polyol transfer process is shown in Figure 1.1. Currently, the polyol plant produces only rigid grades and therefore the pump cannot transfer viscous polyols efficiently. The effects of viscous transfer are loss suction and cavitation which relate to pump reliability. Thus, it is necessary to increase polyols temperature at the product tank to reduce the viscosity resulting in long cooling time at the formulated polyol plant to avoid the vaporization of low boiling point blowing agent. In this project, polyol temperature at the product tank and its flow rate to the formulated polyol plant will be optimized to reduce cooling time, blending cycle time, and finally to increase the productivity. The method to reduce pump speed is gear reducer replacement. Variable speed drive (VSD) is one method to reduce pump speed. Variable speed drive is not used because the limitation of area at main circuit control room. Equipment which must be concerned in this project are consist of gear pump, gear reducer, internal relief valve of gear pump, blender (agitated vessel) and its cooling jacket.

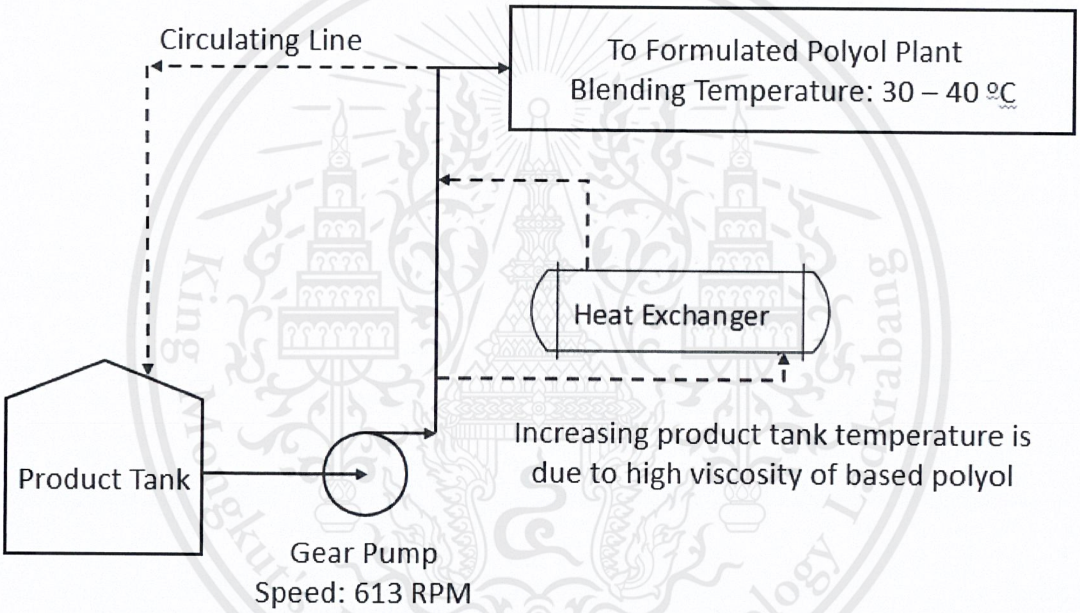


Figure 1.1 Polyol Transfer Process [Dow Chemical Company. 2016]

1.2 Objectives

1.2.1 To reduce the cooling time of based polyol in blending process before adding blowing agent at formulated polyol plant.

1.2.2 To improve pump reliability in transferring high viscosity based polyol from product tank to formulated polyol blender.

1.3 Scopes of Work

1.3.1 Find the optimum feeding conditions of based polyol (i.e., temperature at product tank, flow rate and pump discharge pressure) to reduce cooling time before adding blowing agent.

1.3.2 Estimate additional productivity of this project by cooling time calculation of formulated polyol blender at the formulated polyol plant.

1.3.3 Select new gear reducers to reduce speed of gear pumps for less pump failure at the optimum conditions.

1.4 Expected Outputs

1.4.1 To reduce cooling time of blending process in formulated polyol production and increase productivity of formulated polyol plant.

1.4.2 To improve pump reliability against high viscosity condition of polyol transfer process from product tank to formulated polyol blender.

CHAPTER II

LITERATURE REVIEW

Polyol and formulated polyol are specialty products of Dow Chemical. This project study polyol transfer process from product tank of polyol plant to blender of formulated polyol plant. Based polyol is product of polyols plant. Based polyol is transfer by gear pump of Viking pump. The flow phenomena of based polyol can be concerned by fluid mechanics background. After transfer process, based polyol must be cooled before adding blowing agent to prevent the vaporization of blowing agent. The blowing agent information are shown later. The phenomena of cooling process can be concern by heat transfer of agitated vessel and its jacket.

2.1 Polyol and Formulated Polyol [Dow Chemical Thailand, 2016]

Polyol is high molecular weight molecules of polyether hydrocarbon types. Polyether polyol is polymeric organic compound that is formed through the polymerization of oxide monomer with alcohol initiator and potassium hydroxide catalyst. Polyols are produced by first reaction of initiator and potassium hydroxide catalyst to form alkoxide ion. The reaction is called alkoxylation reaction as shown in reaction 2.1.

$$\mathrm{ROH + KOH \leftrightarrow RO^{-}K^{+} + H_2O} \qquad (2.1)$$

The reaction is an equilibrium reaction and the equilibrium is forced to the right of the above expression by flashing of water. Next reaction is propagation or oxide addition reaction. After forming alkoxide ion through the addition of potassium hydroxide to the initiator, the alkoxide is then reacted with desired oxide monomer to form polyol.

$$\mathrm{RO^{-}K^{+} + ROR \leftrightarrow RORO^{-}K^{+}} \qquad (2.2)$$

The oxide polymerization reaction is shown in below reaction. Last step is inhibition. Acid is the inhibitor of polymerization reaction which is stopped the reaction by neutralization.

$$\mathrm{RO^{-}K^{+} + n[ROR] \rightarrow RO[RO]_nH} \qquad (2.3)$$

The polyols are used for variety applications. The main application of Dow polyol is polyurethane foam which is produced by reaction of polyol and isocyanate. The polyol, which is mixed with any additive, is called formulated polyol. The formulated polyol is the raw material of polyurethane which is mixed with additives to improve polyurethane foam properties. The basic reaction of polyurethane are including with 2 reactions.

Gelling Reaction is the reaction which create the urethane polyol network as shown in Reaction 2.4 and 2.5.

$$\text{Polyol} + \text{Isocyanate} \xrightarrow{\text{Tin\&Amine Catalyst}} \text{Polyurethane} \qquad (2.4)$$

$$\text{R} - \text{OH} + \text{R} - \text{OCO} \xrightarrow{\text{Tin\&Amine Catalyst}} \text{R} - \text{NHCOO} \qquad (2.5)$$

Blowing Reaction is the reaction which create foam cellular structure as shown in reaction 2.6. Density is relate with water level.

$$\text{Water} + \text{Isocyanate} \xrightarrow{\text{Amine Catalyst}} \text{Urea} + \text{CO}_2 \qquad (2.6)$$

Foam structure is occurred from blowing reaction. Auxiliary blowing agent, which is one of the formulated polyol additives, are used to attain the desired density and softness of the foam that water only blown foams are not able to achieve. Auxiliary blowing agent is the low boiling point substance such as cyclopenthane, methyl chloride and carbondioxide. The vaporization of blowing agent will occur the bubble and structure of foam. The products are formulated polyol and isocyanate which are not require the bubble composition. So, high temperature based polyol must be cool down to prevent the vaporization of blowing agent in the blender before foam forming.

2.2 Principles of Fluid Mechanics [McCabe, W.L., Smith, J.C. and Harriott, P., 2005]

A fluid is a substance that does not permanently resist distortion. An attempt to change the shape of fluid is shear stress that results in layers of fluid sliding. During the change in shape, shear stresses exist. The magnitude of shear stress depends on the viscosity of the fluid and the rate of sliding. When a final shape has been reached, all shear stresses will have disappeared. A fluid in equilibrium is free from shear stresses.

At one temperature and pressure, a fluid possesses a definite density. Although the density of all fluids depends on the temperature and pressure. For incompressible fluid, the density changes only slightly with changes in temperature and pressure. If the changes in density are significant, the fluid is called compressible. Liquids are generally considered to be incompressible and gases are compressible. For compressible fluid, the density of a liquid can change appreciably depends on pressure and temperature. Also, gases with small percentage changing in pressure and temperature are being considered as incompressible fluids.

The pressure in a static fluid is present surface force exerted by the fluid against a unit area of the walls of its container. Pressure also exists at every point within a volume of fluid. It is a scalar quantity at any given point is the same in all directions.

Velocity is a vector. The velocity at a point has three dimentions. In many simple situations all velocity vectors in the field are parallel. So, only one velocity dimension is concern which may be taken as a scalar. This situation, which obviously is much simpler than the general vector field, is called one-dimensional flow. An example is steady flow through the straight pipe. The following discussion is based on the assumptions of steady one-dimensional flow.

2.2.1 Viscosity of Fluid

Viscosity is the quantity that describes flow resistance of fluid. In a Newtonian fluid, the shear stress is proportional to the shear rate, and the proportionality constant is called the viscosity. The viscosity increases with temperature some what more rapidly that predicted by simple kinetic theory. The aproximate calculation is shown in equation 2.7.

$$\frac{\mu}{\mu_0} = \left(\frac{T}{T_0}\right)^n \qquad (2.7)$$

2.2.2 Reynolds Number and Fluid Flow Phenomena

At low velocities fluids tend to flow without lateral mixing. There are neither cross-currents eddies. This regime is called laminar flow. At higher velocities turbulence appears and eddies form.

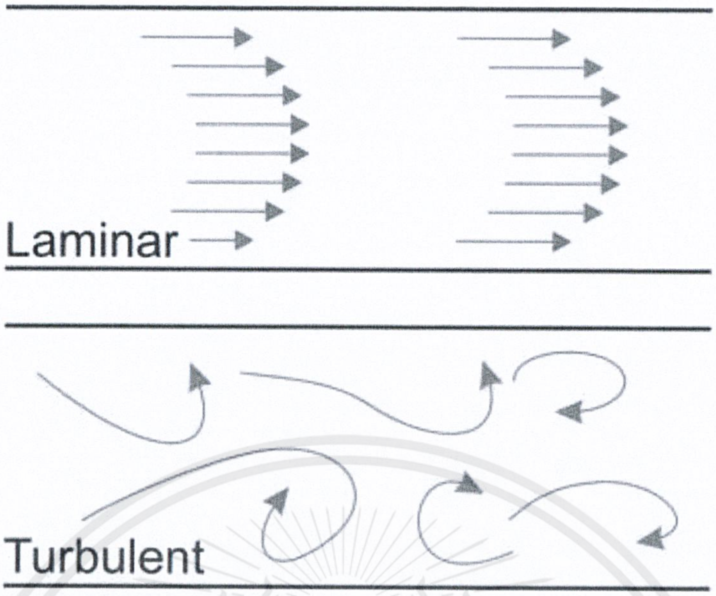


Figure 2.1 Laminar and Turbulent [vBulletin Solutions, Inc., 2016]

The transition from laminar flow to turbulent flow depends on four quantities including with the diameter of the tube, the viscosity, density, and average linear velocity of the fluid. Furthermore, these four factors can be combined into one group and that the change in the kind of flow occurs at a definite value of the group as shown in equation 2.8. The dimensionless group of variables called the Reynolds number as shown in below equation. The transition from laminar to turbulent flow actually may occur over a wide range of Reynolds numbers. In a pipe, flow is always laminar at Reynolds numbers below 2,100. If the laminar flow at such high Reynolds numbers is disturbed, however, say by a fluctuation in velocity, the flow quickly becomes turbulent.

$$\mathrm{Re} = \frac{\rho D \bar{V}}{\mu} \qquad (2.8)$$

Under normal conditions, the flow in a pipe or tube is turbulent at Reynolds numbers above 4,000. A transition region is found between 2,100 and 4,000 where the flow may be either laminar or turbulent depending upon conditions at the entrance of the tube and on the distance from the entrance.

2.2.3 Mechanical Energy Equation

An equation that describes the energy that occur in a flowing fluid may be derived by forming the scalar product of the local velocity with the equation of motion. The mechanical energy may also be added to the fluid by a pump or blower. In general, pump is used to transfer the incompressible fluid. For compressible fluid, blower and compressor are used to transfer it. Energy equation for potential flow called Bernoulli's equation as shown in equation 2.9. The mechanical terms represent conditions at the inlet (a) and outlet stations (b).

$$\frac{P_a}{\rho} + gZ_a + \frac{\overline{V}_a^{\,2}}{2} = \frac{P_b}{\rho} + gZ_b + \frac{\overline{V}_b^{\,2}}{2} \tag{2.9}$$

In frictional flow, the energy is not constant along a streamline but always decreases in the direction of flow and in accordance with the conservation of energy. An amount of heat equivalent to the loss in mechanical energy is generated.

Fluid friction can be defined as any conversion of mechanical energy to heat in a flowing stream. For incompressible fluids, the Bernoulli's equation is corrected for friction by adding a right term of friction loss (h_f) as shown in equation 2.10.

$$\frac{P_a}{\rho} + gZ_a + \frac{\overline{V}_a^{\,2}}{2} = \frac{P_b}{\rho} + gZ_b + \frac{\overline{V}_b^{\,2}}{2} + h_f \tag{2.10}$$

Friction loss (h_f) represents the loss of mechanical energy at all points between stations a and b. Friction is not convertible with the mechanical energy quantities. Friction appears in boundary layers because the work done by shear forces in maintaining the velocity gradients in both laminar and turbulent flow converted to heat by viscous action. Friction generated in unseparated boundary layer is called skin friction.

2.2.4 Friction of Fluid Flow in Pipe

In fluid flow, friction loss is the loss of pressure or head that occurs in pipe or duct flow due to the effect of the fluid viscosity near the surface of the pipe or duct. Friction loss in pipe is classified to 2 cause mainly. That called major loss and minor loss. Major loss is occurred from skin friction and minor loss is occurred from change in velocity or direction.

Loss of head is incurred by fluid mixing which occurs at fittings such as bends or valves, and by frictional resistance at the pipe wall. Where there are numerous fittings and the pipe is short, the major part of the head loss will be due to the local mixing near the fittings. For a long pipeline, on the other hand, skin friction at the pipe wall will predominate.

2.2.5 Roughness Effect

For calculation, the friction characteristic of pipe are summaries by friction factor chart which is called Moody Diagram.

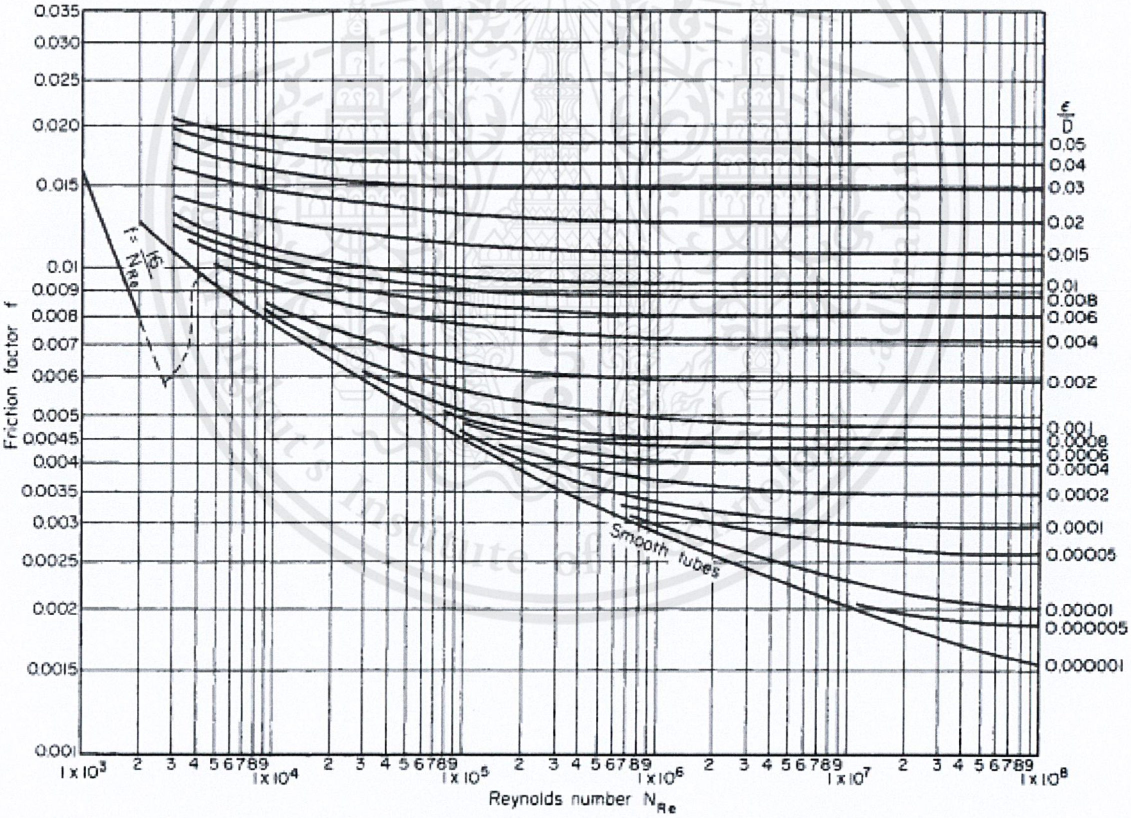


Figure 2.2 Moody's Diagram [Green, D.W., and Perry, R.H., 2008]

Table 2.1 Surface Roughness [Green, D.W., and Perry, R.H., 2008]

Materials	Surface Roughness (mm)
Drawn tubing (brass, lead, glass)	0.00152
Commercial steel or wrought iron	0.0457
Asphalted cast iron	0.122
Galvanized iron	0.152
Cast iron	0.259
Wood stove	0.183 – 0.914
Concrete	0.305 – 3.05
Riveted steel	0.914 – 9.14

Moody diagram in Figure 2.2 is the relation of fanning friction, roughness, pipe diameter and Reynolds number. Table 2.1 shows surface roughness of various pipe materials. For the laminar flow, the relation is the straight line with a slope -1. Function of that line can be written as equation 2.11.

$$f = \frac{16}{Re} \tag{2.11}$$

The others line is represent fanning friction of turbulent flow in different type of commercial pipes and diameter. The fanning factor from this chart is used to calculate the pressure drop from skin friction that is the major loss in fluid flow system.

2.2.6 Friction from Change in Velocity or Direction

Whenever the velocity of a fluid is changed, in either direction or magnitude, friction is generated in addition to the skin friction resulting from flow through the straight pipe. These effects cannot be calculated precisely, and it is necessary to really on empirical data. This type of friction are including with friction from expansion, contraction, fittings and valves. For fitting and valve, the friction loss is calculated from loss coefficient of each part. For other friction, the loss coefficient is calculated from equation.

2.2.7 Friction from Suddenly Expansion of Cross Section

Friction loss from suddenly contraction can be calculated by equation 2.12.

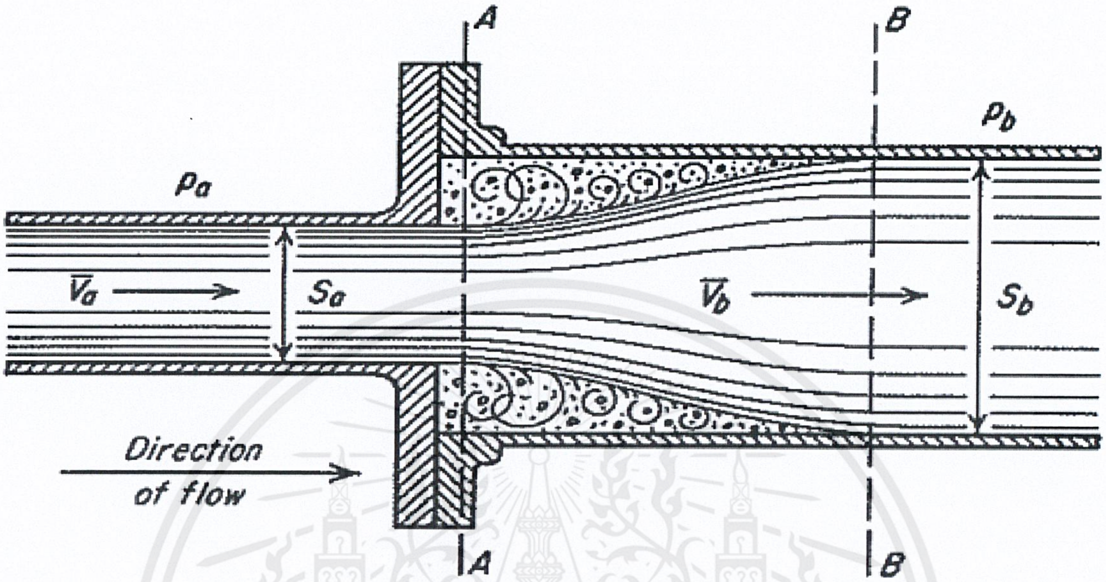


Figure 2.3 Flow at Sudden Expansion

[McCabe, W.L., Smith, J.C. and Harriott, P., 2005]

$$K_e = (1 - \frac{A_{ca}}{A_{cb}})^2 \qquad (2.12)$$

K_e is called expansion loss coefficient if the different of cross sectional area is large, K_e would be assume to be 1.

2.2.8 Friction Loss from Sudden Contraction of Cross Section

Friction loss from suddenly expansion can be calculated by equation 2.13.

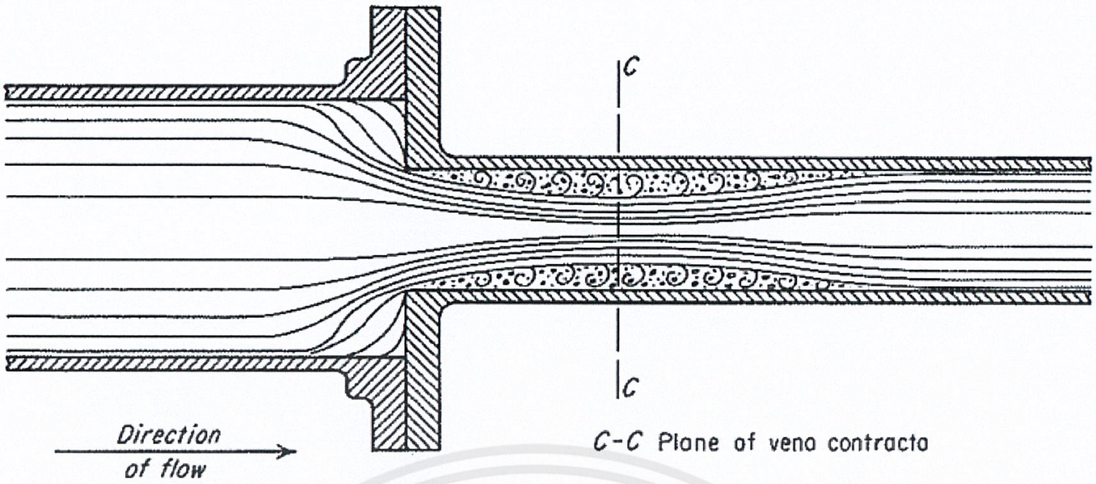


Figure 2.4 Flow at Sudden Contraction [McCabe, W.L., Smith, J.C. and Harriott, P., 2005]

$$K_c = 0.4(1 - \frac{A_{ca}}{A_{cb}}) \tag{2.13}$$

K_c is contraction loss coefficient if the different of cross sectional area is large, K_c would be assume to be 0.4.

2.2.9 Friction Loss from Fittings and Valves and Friction Loss Summation

Friction loss from fittings and valves are represent by K_f which is called loss coefficient from fittings and valves. In Bernoulli's equation, friction loss can be calculated from loss coefficient from fittings and valves summation as shown in equation 2.14.

$$h_f = (4f\frac{L}{D} + K_c + K_e + K_f)\frac{\bar{V}^2}{2} \tag{2.14}$$

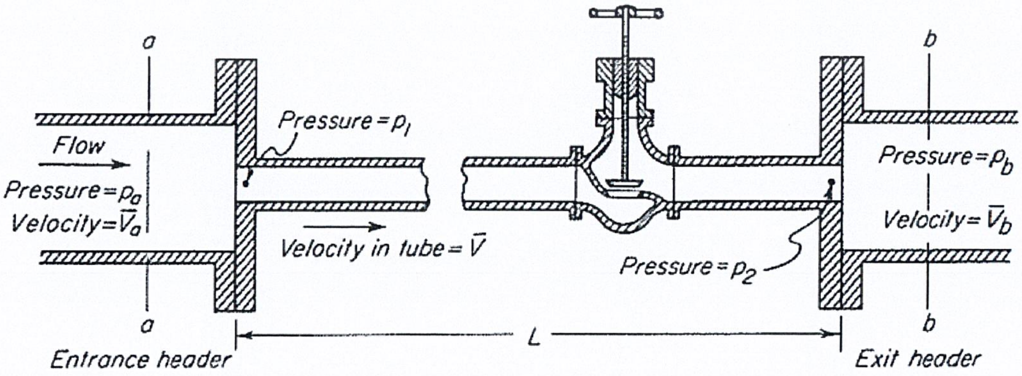


Figure 2.5 Flow with Friction Loss [McCabe, W.L., Smith, J.C. and Harriott, P., 2005]

The equation shows the form of friction loss in Bernoulli's equation. To write the equation for this assembly. Because size of pipe is not different and no pump work between a to b in Figure 2.5. Term of kinetic energy and work can be negligible and substitute the friction loss term become the equation which can be used to calculate pressure drop of the piping system to be equation 2.15.

$$\frac{P_a-P_b}{\rho}+g(Z_a-Z_b)=(4f\frac{L}{D}+K_c+K_e+K_f)\frac{\overline{V}^2}{2} \tag{2.15}$$

2.2.10 Pump Work in Bernoulli's Equation

Pump is used in flow system to increase the mechenical energy of the flow fluid, the increase being used to maintain flow, provide the kinetic energy, offset friction losses, and sometime increase the potential energy. Assume pump is installed between stations a and b.Pump work is present in Bernoulli's equation in term of W. In an actual pump not only are all the sources of fluid friction active, but mechanical friction occurs as well, in bearings and seals or stuffing boxes. The mechanical energy supplied to the pump as negative shaft work must be discounted by these friction losses to give the net mechanical energy actually available to the flowing fluid. Let h_{fp}, be the total friction in the pump per unit mass of fluid. Then the net-work of pump is $W-h_{fp}$which are denoted in efficiency or η. Net-work of pump can be calculated by equation 2.16 and 2.17.

$$\eta W = W - h_{fp} \tag{2.16}$$

$$\frac{P_a}{\rho}+gZ_a+\frac{\overline{V_a}^2}{2}+\eta W=\frac{P_b}{\rho}+gZ_b+\frac{\overline{V_b}^2}{2}+h_f \tag{2.17}$$

2.3 Pump

Pump is used to transfer fluid by increasing the mechanical energy of liquid that including with velocity, pressure, and elevation. The two major classes are positive-displacement pumps and centrifugal pumps. Pump classification is shown in Figure 2.6.

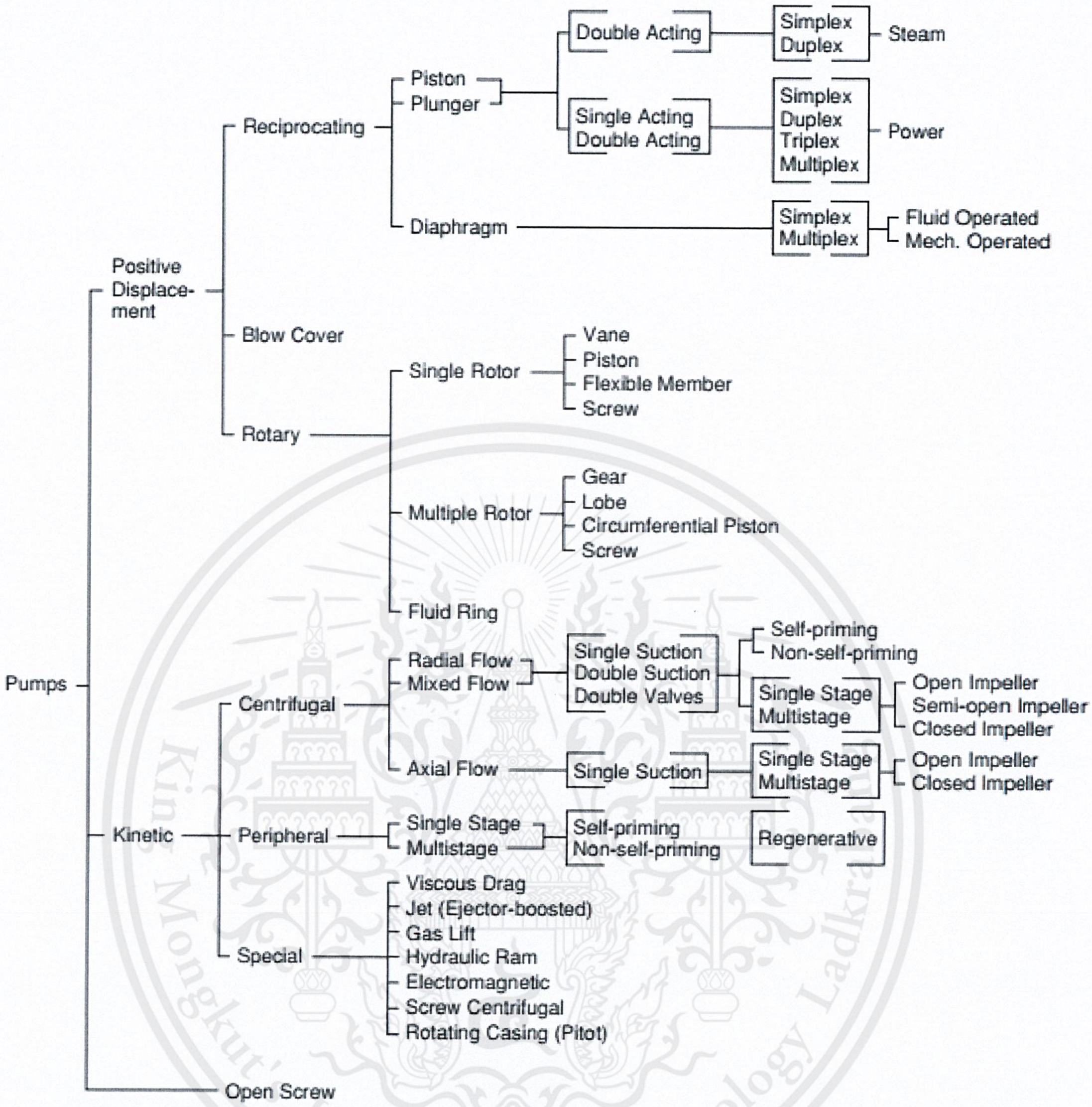


Figure 2.6 Pump Classifications [Green, D.W., and Perry, R.H., 2008]

Positive-displacement units apply pressure directly to the liquid by a reciprocating piston, or by rotating members which form chambers alternately filled by and emptied of the liquid. Centrifugal pumps generate high rotational velocities, then convert the resulting kinetic energy of the liquid to pressure energy. In pumps the density of liquid does not change appreciably and may be considered constant.

2.3.1 Rotary Pump [Ludwig, E.E., 1999]

The majority of this type are capable of handling only a clean solution essentially free of solids or high viscosity fluid. The designs using rubber or plastic parts for the pressure device can handle some suspended particles. In general, these pumps handle materials of a wide range of viscosity and can develop quite high pressures. In addition, the units can handle some vapor or dissolved gases mixed with the liquid being pumped. For specific performance characteristics of any type consult the appropriate manufacturer. These pumps are low in cost, require small space, and are self-priming. Suction and discharge heads are determined the same as for centrifugal pumps. Total head and capacity are used in selecting the proper rotary pump from a manufacturer's data or curves. Since viscosity is quite important in the selection of these pumps, it is sometimes better to select a larger pump running at low speeds than a smaller pump at high speeds when dealing with viscous materials.

As a general guide, speed is reduced 25-35 percent below rating for each tenfold increase in viscosity above 1000 SSU. Also, generally, the mechanical efficiency of the pump is decreased 10 percent for each tenfold increase in viscosity above 1000 SSU, and referenced to a maximum efficiency of 55 percent at this point.

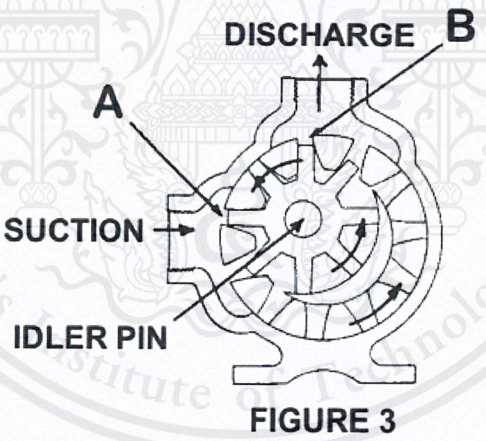


Figure 2.7 Internal Gear Pump [Viking Pump Inc., 2007]

Figure 2.7 shows mechanism of internal gear pump. Shaft rotation will determine which port is suction or discharge. Figure 2.7 shows the rotation of pump. At point A, liquid is drawn into the suction port. At point B, the liquid is forced out the discharge port. Reversing the rotation reverses the flow through the pump. When determining shaft rotation, always look from the shaft end of the pump. Unless otherwise specified, rotation is assumed to be clockwise, which makes the suction port on the right side of the pump. In general, motor is used to drive gear pump in form of direct drive, V belt drive and gear reducer drive. The gear reducer drive gear pump is concerned in this project as shown in Figure 2.8.

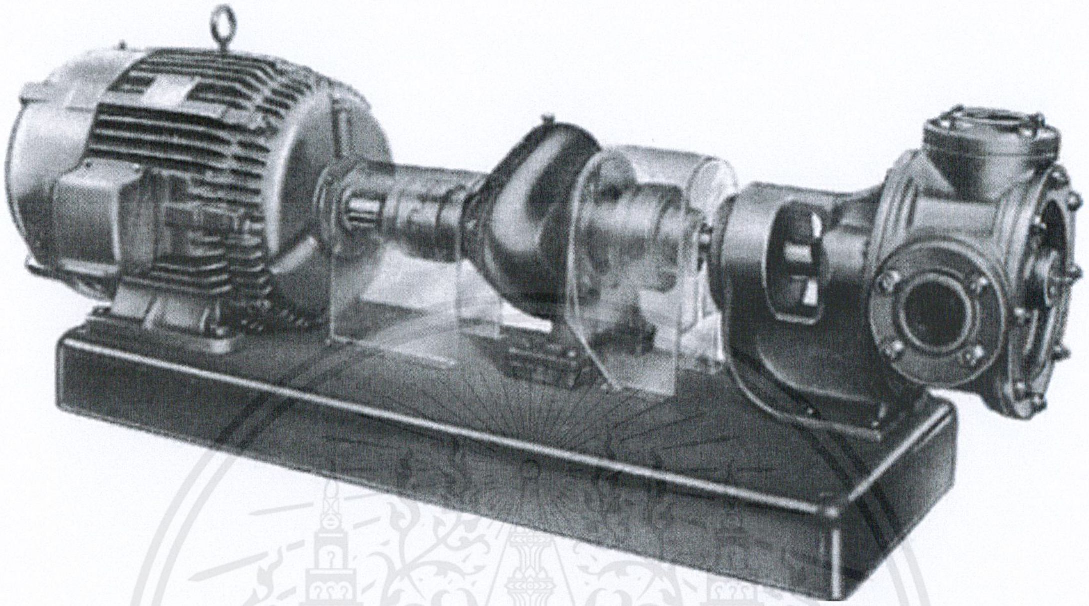


Figure 2.8 Reducer Drive Gear Pump [Viking Pump Inc., 2007]

2.3.2 Gear Pump Components [Viking Pump Inc., 2007]

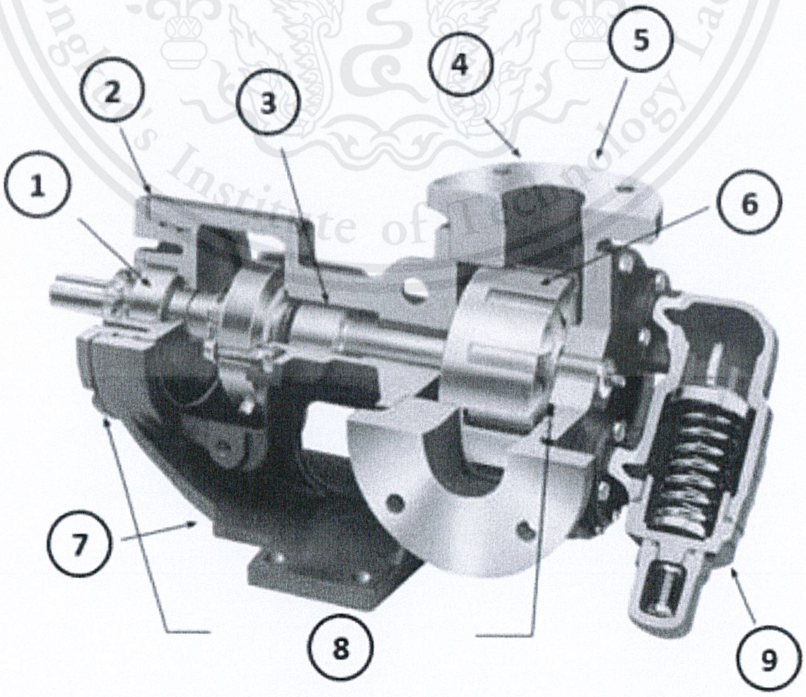


Figure 2.9 Pump Components [Viking Pump Inc., 2007]

The main components of internal gear pump are consist of variety parts as shown in Figure 2.9.

2.3.2.1 Double row ball or tapered bearing for axial thrust control

2.3.2.2 Large diameter threaded bearing housing allows easy removal of cartridge seals.

2.3.2.3 Seal chamber accepts packing and a variety of component, and cartridge style mechanical and lip seals, in both single and double mechanical seal configurations.

2.3.2.4 Pump casing can be rotated in 45° increments permitting eight different port positions. Opposite port casings also available.

2.3.2.5 Multiple port sizes, types, and ratings are available including threaded, raised and flat face flanged.

2.3.2.6 Optional steel rotors available for operation on viscous liquids.

2.3.2.7 One-piece cast bracket provides rigid foundation to maximize seal and bearing life.

2.3.2.8 Rotor end clearance can be adjusted to compensate for wear or for higher temperatures or viscosities by rotating the threaded bearing housing.

2.3.2.9 Internal relief valve standard. Return-to-tank and jacketed relief valves optional.

Viking pumps are positive displacement pump. That means when the pump is rotated, liquid will be delivered to the discharge side of the pump. If there is no place for this liquid to go, which can occurs from discharge line, is blocked or closed, pressure can build up until the motor stalls, the drive equipment fails, a pump part breaks or ruptures, or the piping bursts. Because of this, some form of pressure protection must be used with a positive displacement pump. That may be internal relief valve of gear pump.

2.3.3 Gear Reducers and Gear Motors [Viking Pump Inc., 2007]

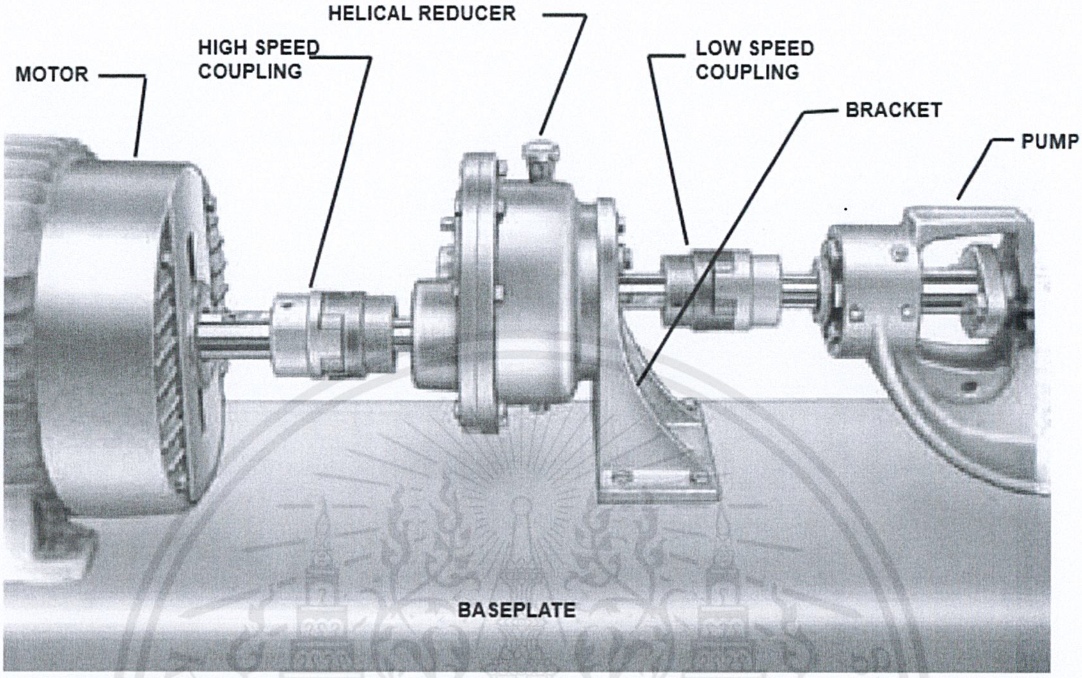


Figure 2.10 Typical Installation of Gear Reducer [Viking Pump Inc., 2007]

Typically the rotary power supply of a pump system is called a “Drive”. A gear reducer, also called a speed reducer or gear box as shown in Figure 2.10. Gear reducers are available in a broad range of sizes, capacities and speed ratios. The duty of gear reducer is to convert the input provided by motor into output of lower speed and correspondingly higher torque. There are many types of gear reducers using various gear types to meet application requirement. Sometimes this includes motor control devices such as inverters or starters. Some Gear Reducers come with a motor attached as a package. These are called gear motors. The 4 important specifications of gear reducer are shown below.

2.3.3.1 Input speed: Gear reducers are the best driven at input speeds common in industrial electric motors, typically 1200, 1800 or 2500 RPM. This provides sufficient splash for the reducer’s lubrication system, but not so much as to cause oil churning.

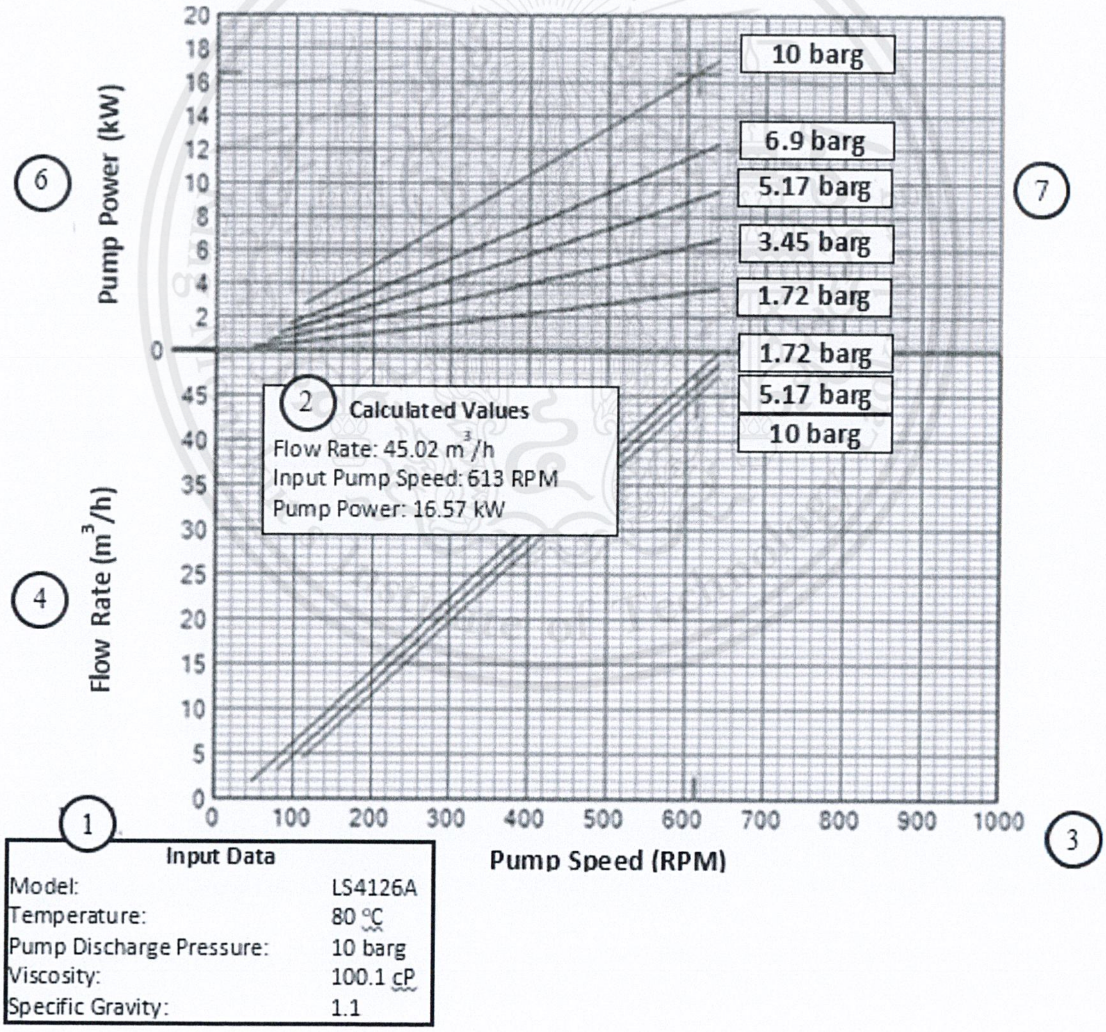
2.3.3.2 Output speed and torque: These are the key criteria for matching a gear reducer to the application needs.

2.3.3.3 Gear Ratio: The relation of input and output speed. Gear ratio is main factor of gear reducer selection.

2.3.3.4 Horsepower: A reducer input horsepower rating represents the maximum motor size the reducer is designed to handle.

2.3.4 Pump Performance [Crane Engineering, 2016]

The differential pressure performance curve is the characteristic curve of the gear pump. The curve is the relation of pump speed, flow rate, differential pressure and power input. These pumps provide a constant flow of fluid at a given pump speed, regardless of the discharge pressure required. The conditions of pump are shown on pump curve. The majority of positive displacement pump curves including with gear pump curve is shown in Figure 2.11.



Calculated Values
Flow Rate: 45.02 m^3/h
Input Pump Speed: 613 RPM
Pump Power: 16.57 kW

Input Data

Model:	LS4126A
Temperature:	80 °C
Pump Discharge Pressure:	10 barg
Viscosity:	100.1 cP
Specific Gravity:	1.1

Figure 2.11 Gear Pump Performance Curve [Viking Pump Inc., 2006]

2.3.4.1 Pump Information: Provides information about which pump this curve refers to such as pump model, size, etc.

2.3.4.2 Calculation Values: Data which are estimated from pump curve such as pump speed, volumetric flow rate, pump power.

2.3.4.3 Pump Speed: The conditions of fluid, which is transferred by gear pump, depend on speed. The speed would be the pump speed, not the motor speed. Gear reducers, v-belt drives, hydraulic motors, or variable speed drives are used to control the operating speed of the positive displacement pump including with gear pump. The pump speed information also states the maximum allowable speed for the pump, since several positive displacement pumps can’t run at full motor speeds.

2.3.4.4 Flow Rate or Pump Capacity: Pump capacity is the rate of liquid or slurry flow through a pump. For proper selection and corresponding operation, a pump capacity must be identified with the actual pumping temperature of the liquid in order to determine the proper power requirements as well as the effects of viscosity. The flow is dependent on the pump speed, so once that information is known, another data can be calculated. In this example, pump is operated at 613 RPM and working against a discharge pressure of 10 bar, the flow from this pump would be approximately 45 m^3/h.

2.3.4.5 Viscosity: All pumps are affected by the viscosity of the fluid. However, a positive displacement pump has the ability to handle more fluid viscosity than centrifugal pumps. Viscosity can have a large impact on the size and speed that a positive displacement pump can operate. Higher viscosities can limit the allowable pump speed and volumetric flow rate.

2.3.4.6 Pump Power: The amount of power, which needed for pump operation, is depend on the discharge pressure required and the viscosity of the fluid.

2.3.4.7 Pump Discharge Pressure: The pressure available at the discharge of a pump is a result of changing from mechanical energy to kinetic and potential energy. This represents the total energy given to the liquid by the pump. Pressure is the contour line in pump performance curve.

2.3.5 Net Positive Suction Head and Cavitation

Net positive suction head (NPSH) is the difference between the total absolute suction pressure at the pump suction nozzle when the pump is running and the vapor pressure at the flowing liquid temperature. It is very important consideration in pump selection which might handle liquids at or near their boiling points, or liquids of high vapor pressures. In a positive displacement pump the (NPSH). Suction pressure should be large enough to open the suction valve, to overcome the friction losses within the pump liquid end, and to overcome the liquid acceleration head. However, if the suction pressure is not greater than the vapor pressure of liquid. Some of fluid may flash inside the pump, the process called cavitation.

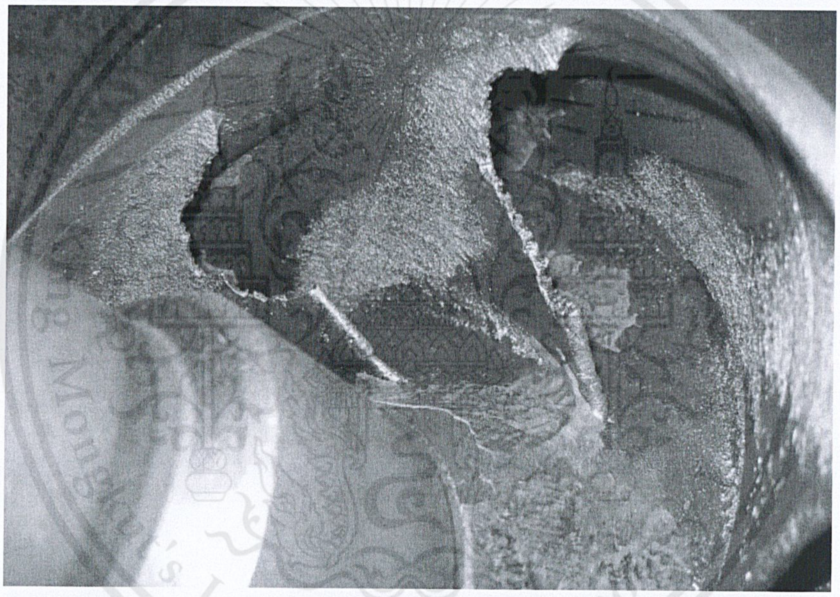


Figure 2.12 Impeller Vane Cavitation Damage [JAC Pump, 2005]

Cavitation is vapor phase formation of liquid. It occurs from pressure reduction at constant ambient temperature. The liquid is said to cavitate when vapor bubble form and grow. The vapor bubbles are formed at the places of lowest pressure and then suddenly disappear when the pressure increases in the further flow course. In the case that this process occurs near the impeller blades or pump surfaces the materials of construction are being attacked by implosion of the vapor bubbles as shown in Figure 2.12. Therefore this damage never appears at the place of origin of cavitation but at a point further away. The materials of construction are being pitted and can appear similar to the surface of sponge.

To avoid the cavitation, the pressure at the pump inlet must exceed the vapor pressure by NPSH. The minimum required of net positive suction head or NPSHR is specified by pump manufacturer. Available net positive suction head or NPSHA can be calculated by the equation 2.18.

$$NPSHA = \frac{1}{g}\left(\frac{P_s - P_v}{\rho} - h_{fs}\right) - Z_s \tag{2.18}$$

2.3.6 Affinity Laws [McCabe, W.L., Smith, J.C. and Harriott, P., (2005)]

When a complete set of performance curves is not available, the characteristics of a particular pump can be predicted from a similar pump and the theoretical equations for an ideal pump. The relationships of impeller size and speed to capacity, head, and power are called the affinity laws. Affinity laws are useful when an existing pump must be modified to give a higher or lower head or a different capacity. Affinity law equation is shown equation 2.19.

$$\frac{N_2 D_{imp2}}{N_1 D_{imp1}} = \frac{\dot{V}_2}{\dot{V}_1} \tag{2.19}$$

2.4 Heat Transfer of Agitated Vessel and Cooling Jacket

The most common type of jackets consists of an outer cylinder that surrounds part of the vessel. The heating or cooling medium circulates in the annular space between the jacket and vessel walls. The heat is transferred through the wall of the vessel. Circulation baffles can be used in the annular space to increase the velocity of the liquid flowing through the jacket, thus enhancing the heat transfer coefficient. Jackets may be one piece open chambers surrounding the main shell of the vessel, or they may be coil style, usually of the half-pipe design. The half-pipes are continuously welded to the shell and may be grouped in segments or sections of the shell to allow for the rather rapid conversion of a section from external heating to external cooling. It is so often the required condition for some batch reaction processes.

The rate of heat transfer to or from an agitated liquid mass in a vessel depends on the physical properties of the liquid, the properties of cooling and heating medium, the vessel geometry, and the degree of agitation. Many jacketed vessels are reactors which is designed to support exothermic or endothermic effects must be taken into account. Stirred tank reactors in which an exothermic reaction is performed may involve the removal of substantial amounts of heat from the reacting mixture. In this project, formulated polyol blender is concern as agitated vessel to calculate cooling time.

2.4.1 Heat Transfer in Batch Operation [Green, D.W., and Perry, R.H., 2008]

One typical application in heat transfer with batch operations is the cooling of blender which is cooling the products before the blending process. This subsection is concerned with the cooling of such systems in either unknown or specified periods. The assumptions of heat transfer calculation are shown below. The heat transfer equation is shown in equation 2.20.

- U is constant for the process and over the entire surface
- Liquid flow rates are constant
- Specific heats are constant for the process
- The heating or cooling medium has a constant inlet temperature
- Agitation produces a uniform batch fluid temperature
- No partial phase changes occur
- Heat losses are negligible

$$\ln \frac{T(t)-T_\infty}{T_i-T_\infty} = -\frac{\dot{M}_J c_{po}}{M c_{pi}}\left(\frac{K-1}{K}\right)t \qquad (2.20)$$

where $K = e^{\frac{UA}{\dot{M}_o c_{po}}}$

2.4.3 Overall Heat Transfer Coefficient [Cengel, Y.A., and Ghajar, A.J., 2015]

The overall heat transfer coefficient represents the total resistance to heat transfer from one fluid to another. The functional form of overall heat transfer coefficient can be derived for any particular geometry by performing a standard conduction analysis on the system of interest. Overall heat transfer coefficient is the summation of resistance factor from conduction, convection and fouling as shown in equation 2.21.

$$\frac{1}{U} = \frac{1}{h_o} + f_{co} + \frac{x}{k} + f_{ci} + \frac{1}{h_i} \qquad (2.21)$$

From equation 2.22 first term is resistance from convection of fluid in jacket. Next term is f_c which is fouling factor of fluid which resists to heat transfer. The middle term is resistance from heat conduction through wall. And the last term is resistance from convection of fluid in blender. Resistance from convection is present in term of heat transfer coefficient of convection which can be calculated from function of Nusselt number. The Nusselt number calculation method are shown in next topic.

2.4.2 Mixing and Agitation

Agitation is process which to induce motion of material specified way, usually in circulatory pattern inside container. Typically agitated vessel is shown in Figure 2.13. Mixing is random distribution into and trough one two or more separate phase. The objective of agitation is suspend solid particles, blending miscible liquid, disperse immiscible liquid and promote heat transfer between liquid and coil or jacket.

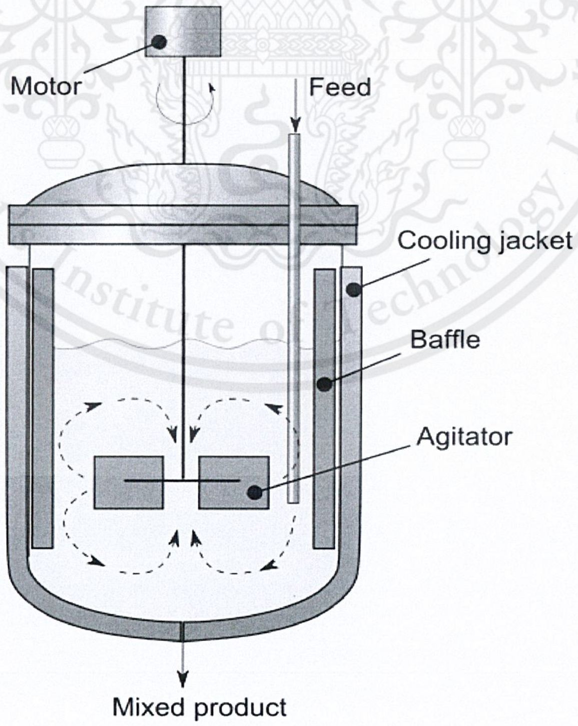


Figure 2.13 Typically Agitated Vessel [Wikimedia Commons. 2016]

Liquids are most agitated in some kind of vessel. The components of typically agitated vessel is shown in Figure 2.13.The impeller is mounted on an overhung sharp and driven by motor. Sometimes motor is directly connected to sharp but more often connected through speed reducer gear box. Other accessories such as coils, jacket and thermo well are included in agitated vessel.

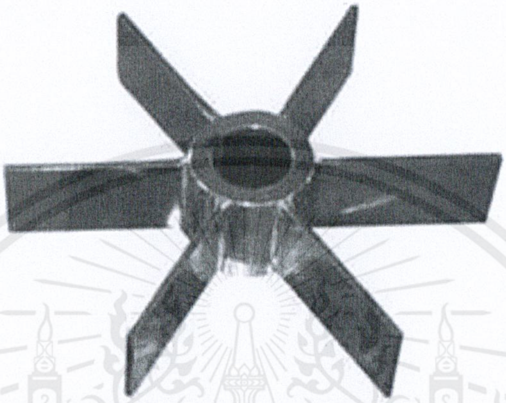


Figure 2.14 Flat Blade Turbine [Unimix Equipments Pvt. Ltd., 2013]

Radial-Flow Impellers: Radial-flow impellers have blades which are parallel to the axis of the drive shaft. The smaller multi-blade ones are known as turbines; larger, slower speed impellers, with two or four blades, are often called paddles. The diameter of a turbine is normally between 0.3 and 0.6 of the tank diameter. Turbine impellers come in a variety of types, such as curved-blade and flat-blade, as shown in Figure 2.14.

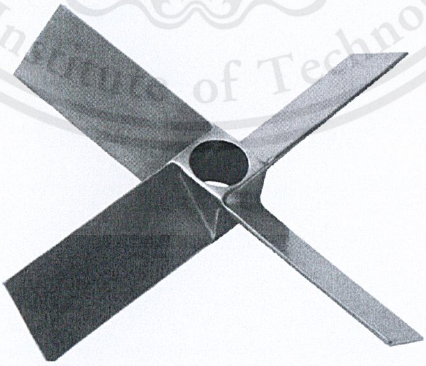


Figure 2.15 Pitched Blade Turbine [Fusion Fluid Equipment, llc., 2015]

Axial-Flow Impellers: Axial-flow impellers include all impellers in which the blade makes an angle of less than 90° with the plane of rotation. Propellers and pitched-blade turbines, as shown in Figure 2.15, are representative axial-flow impellers. The flow patterns of impellers is shown in Figure 2.16.

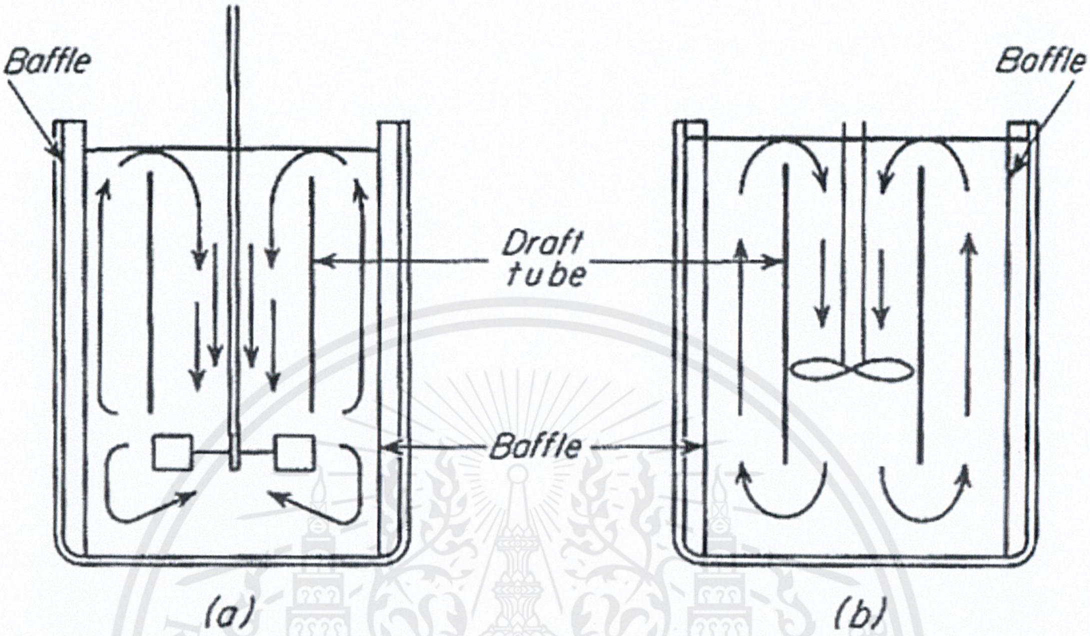


Figure 2.16 Flow Patterns [McCabe, W.L., Smith, J.C. and Harriott, P., 2005]

Baffled Tanks: For vigorous agitation of thin suspensions, the tank is provided with baffles which are flat vertical strips set radially along the tank wall. For Reynolds numbers greater than 2000 baffles are commonly used with turbine impellers and with on-centerline axial-flow impellers. The flow are quite different, but in both cases the use of baffles results in a large top-to-bottom circulation without vortex or severely unbalanced fluid forces on the impeller shaft. In the transition region, the width of the baffle may be reduced, often to one-half of standard width. If the circulation pattern is satisfactory when the tank is unbaffled but a vortex creates a problem, partial-length baffles may be used. The flow pattern may be affected by the baffles, but not always advantageously. When they are needed, the baffles are usually placed one or two widths radially off the tank wall, to allow fluid to circulate behind them and at the same time produce some axial deflection of flow.

2.4.2 Impeller Reynolds Number [Green, D.W., and Perry, R.H., 2008]

The presence or absence of turbulence in an impeller-stirred vessel can be correlated with an impeller. Reynolds number can be calculated from equation 2.22.

$$\mathrm{Re} = \frac{\rho {D_a}^2 N}{\mu} \tag{2.22}$$

Flow in the tank is turbulent when Re > 10,000. Thus viscosity alone is not a valid indication of the type of flow to be expected. Between Reynolds numbers of 10,000 and approximately 10 is a transition range in which flow is turbulent at the impeller and laminar in remote parts of the vessel; when Re < 10, flow is laminar only.

2.4.4 Coefficient Calculation in Agitated Vessel [Ludwig, E.E., 1999]

Heat transfer by forced convection in various situations can be correlated using the dimensionless criteria Nu, Re, Pr, and μ. Usually, a simple power function for agitated vessel with baffled and pitched blade turbine. Nusselt number calculation of agitated vessel is shown in equation 2.23.

$$\mathrm{Nu} = 0.54\mathrm{Re}^{0.67}\mathrm{Pr}^{0.33}\left(\frac{\mu}{\mu_w}\right)^{0.14} \tag{2.23}$$

For the baffled agitated vessel, $\left(\frac{\mu}{\mu_w}\right)^{0.14}$ can be neglect because well mixed assumption. Reynolds number of agitation can be calculated by impellor Reynolds number. Prandtl number is calculated by equation 2.24.

$$\mathrm{Pr} = \frac{c_p \mu}{k} \tag{2.24}$$

Nusselt number is used to calculated heat transfer coefficient of convection for inside film. Equation 2.25 is used to calculate heat transfer coefficient of convection.

$$\mathrm{Nu} = \frac{h_i D}{k} \tag{2.25}$$

2.4.5 Heat Conduction [Cengel, Y.A., and Ghajar, A.J., 2015]

Conduction is the transfer of energy from the energetic particles of a substance to the adjacent less energetic ones as a result of interactions between the particles. The rate of heat conduction through a medium depends on geometry of the medium, its thickness, and the material of the medium, as well as the temperature difference across the medium.

The thicker insulation affect to smaller heat transfer through the material. The rate of heat transfer through a plane layer is proportional to the temperature difference across the layer and the heat transfer area, but is inversely proportional to the thickness of layer.

Thermal conductivity is define as the rate of heat transfer through a unit thickness of material per unit area per temperature difference. The thermal conductivity od material is a measure of ability of the material to conduct heat. A high value of thermal conductivity indicates the material is a good heat conductor, and low value indicate that the material is poor conductor called insulator. The thermal conductivity of common material are shown in Table 2.2.

Table 2.2 The Thermal Conductivities of Some Common Material [Cengel, Y.A., and Ghajar, A.J., 2015]

Material	k (W/mK)
Diamond	2300
Silver	429.0
Copper	401.0
Gold	317.0
Aluminum	237.0
Iron	80.20
Mercury (l)	8.540
Glass	0.780
Brick	0.720
Water (l)	0.607
Human Skin	0.370
Wood	0.170
Helium (g)	0.152
Soft Rubber	0.130
Glass Fiber	0.043
Air (g)	0.026
Urethane, Rigid Foam	0.026

2.4.6 Coefficient Calculation in Baffled Jacketed [Ludwig, E.E., 1999]

In heat transfer application, the jacket is considered as a helical coil if certain factors are used for calculation heat transfer coefficient of convection. The equivalent heat transfer diameter is equal to 4 of width annular space. Velocities are calculated from the actual cross sectional of flow area which is calculated from pitch of spiral baffled. The effective mass flow rate is approximately 60 percent of total flow rate in the jacket. At the Reynolds number between 2100 and 10000, equation 2.26 can be used to calculate the Nusselt number and outside film coefficient.

$$\mathrm{Nu} = 1.86\mathrm{Re}^{0.33}\mathrm{Pr}^{0.33}\left(\frac{\mathrm{D_e}}{\mathrm{L}}\right)^{0.33}\left(\frac{\mu}{\mu_\mathrm{w}}\right)^{0.14} \qquad (2.26)$$

For the well mixed assumption, viscosity ratio can be neglect. Reynolds number of cooling jacket and Prandtl number is calculated by equation 2.27 equation 2.28, respectively.

$$\mathrm{Re} = \frac{\rho D_e \overline{V}_e}{\mu} \qquad (2.27)$$

$$\mathrm{Pr} = \frac{c_p \mu}{\mathrm{k}} \qquad (2.28)$$

Nusselt number is used to calculate heat transfer coefficient of convection for outside film by equation 2.29.

$$\mathrm{Nu} = \frac{\mathrm{h}_o \mathrm{D_e}}{\mathrm{k}} \qquad (2.29)$$

CHAPTER III
RESEARCH METHODOLOGY

The methodology of this project consist of 8 parts as shown below. First, raw data are collected. Pump discharge pressure can be calculated to select the optimum polyol feeding conditions. Then, gear reducer is selected to reduce pump speed by increasing gear ratio. The new conditions must be compared with limited conditions. From optimum conditions, the cooling time can be calculated to estimate additional productivity from this project.

3.1 Data Collection

The required data of this project are collected from process flow diagram, P&ID, plot plan of polyol and formulated polyol plant, pump data sheet, gear reducer data sheet, laboratory data and blender drawing. Five required data are shown below. Raw data of this project except viscosity are shown in Appendix A.

3.1.1 Viking gear pump specification

3.1.2 Polyol piping specification

3.1.3 Viscosity data of based polyol from laboratory

3.1.4 Gear ratio from The Dorris Company

3.1.5 Blender drawing and design

3.2 Concerning of Gear Reducer Replacement

3.2.1 Temperature and based polyol flow rate

3.2.2 Pump discharge pressure and pipe specification

3.2.3 Gear ratio of gear reducer from Dorris data sheet

3.2.4 Pump power and limit of motor

3.2.5 Based polyol mass flow rate and maximum ventilation of blender

3.2.6 Based polyol transfer time and time limit

3.2.7 Set pressure of gear pump internal relief valve

3.3 Viscosity Model Estimation

Viscosity model is plot from the data from laboratory and fit with a power equation of viscosity of liquid and gas equation. The results of viscosity model are shown in

Appendix B. Equation 3.1 is used to identify the constant of viscosity model (n) and use to estimate the viscosity at each condition.

$$\frac{\mu}{\mu_0} = \left(\frac{T}{T_0}\right)^n \tag{3.1}$$

3.4 Pump Discharge Pressure Calculation across Pipe Friction

Pump discharge pressure is calculated from pressure drop of piping system. Pressure drop can be calculated from Bernoulli's equation. The flow of polyol is laminar because of polyol viscosity. The calculation steps are shown below and in Appendix C.

3.4.1 Vary temperature and to find the optimum point. The range which selected are from 40 to 80 °C and 25 m^3 to 40 m^3.

3.4.2 Used viscosity model to estimate the viscosity of each condition.

3.4.3 Convert volumetric flow rate to superficial velocity that used to calculate Reynolds number by equation 3.2.

$$\overline{V} = \frac{\dot{V}}{A_c} \tag{3.2}$$

3.4.4 Calculate Reynolds number of fluid flow in pipe from equation 3.3.

$$Re = \frac{\rho D \overline{V}}{\mu} \tag{3.3}$$

3.4.5 Reynolds number from calculation represent the laminar flow of polyol which fanning friction is calculated from equation 3.4.

$$f = \frac{16}{Re} \tag{3.4}$$

3.4.6 Calculate friction loss from equation 3.5.

$$h_f = \left(4f\frac{L}{D} + K_c + K_e + K_f\right)\frac{\overline{V}^2}{2} \tag{3.5}$$

K_e and K_c can be neglected because the contraction and expansion are not present in the system.

3.4.7 Convert the friction loss and the static loss (loss from different heights) to the term of pressure drop by equation 3.6.

$$\frac{\Delta P}{\rho} + g\Delta H = h_f \tag{3.6}$$

From equation 3.6, the first term is pressure head, the second term is static head, and the last term is friction from skin friction, fittings and valves in system.

3.4.8 Discharge pressure is calculated by pressure drop from pipe and pipe discharge pressure which is 0.5 bar in blender.

3.5 Gear Pump Performance Curve

Gear pump performance curve is obtained from viking pump selection tool. The curve is the relation of pump speed, volumetric flow rate, pressure and power input of gear pump. Pump curve can be used to estimate unknown parameter from the relation and another parameter. First, pump speed is estimated from temperature, flow rate, and pressure by using pump curve. Calculated pump speed is used to calculate optimum gear ratio of gear pump. Then, the nearest gear ratio of the Dorris company is selected to calculate the optimum conditions. Optimum conditions are compared with limited conditions. The steps of Viking pump selection tool using is shown in Appendix D. Gear ratio of gear reducer can be calculated from ratio of motor speed and pump speed as shown in equation 3.7.

$$Gear\ Ratio = \frac{Motor\ Speed}{Pump\ Speed} \tag{3.7}$$

3.6 Steps for Gear Reducer Selection

New gear reducers are select to reduce speed of gear pumps because of maximum allowable speed of pump. The maximum speed of pump is depending on polyol viscosity. In addition, the viscosity of polyol affect to pressure drop of piping system which must concern. The steps to select new gear reducer are shown on Figure 3.1.

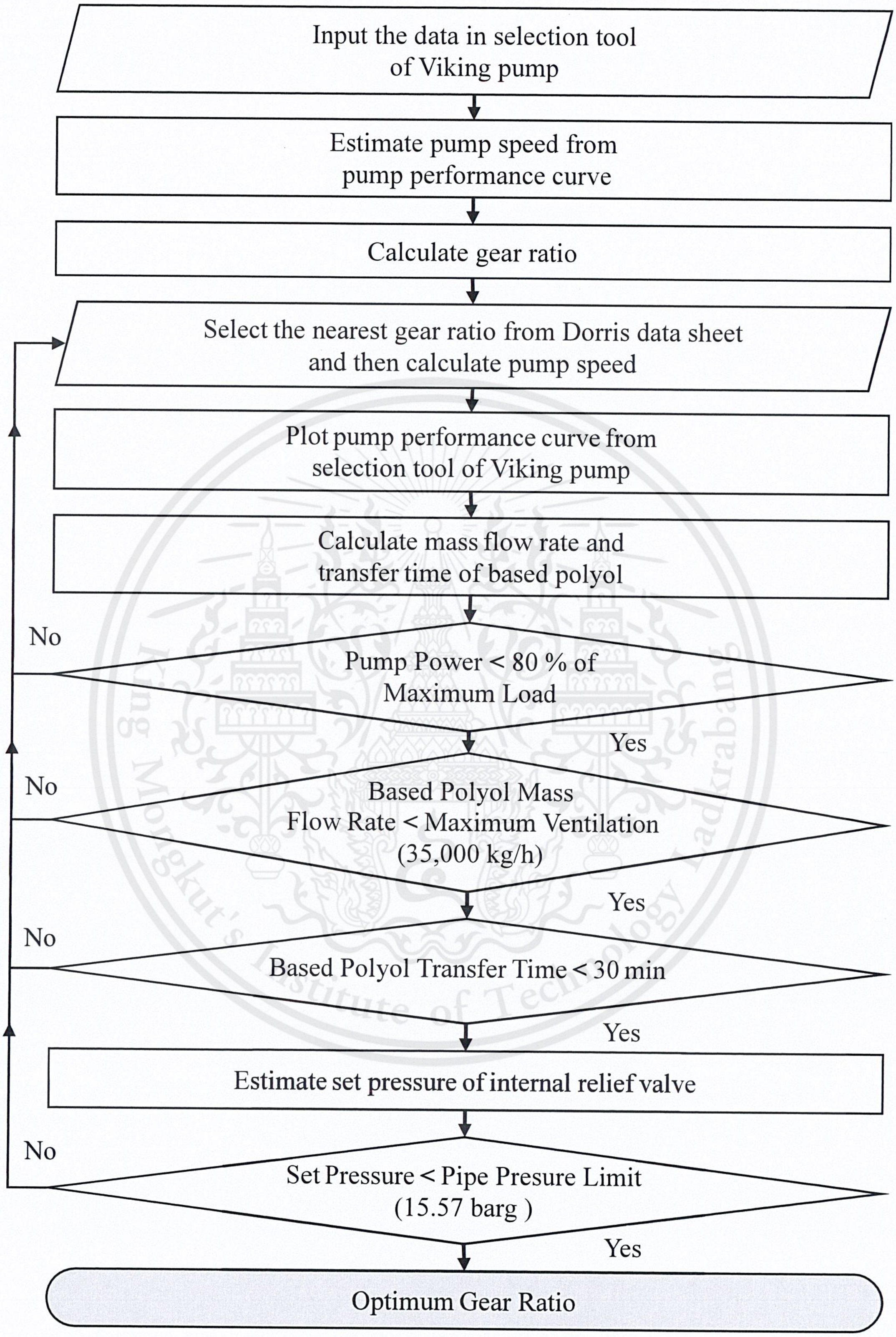


Figure 3.1 Gear Selection Flow Chart

3.7 Mass Flow Rate and Transfer Time Calculation

Ventilation and transfer time are limitation of gear reducer replacement. Mass flow rate of polyol is calculated and compared with maximum ventilation of formulated polyol blender. The maximum ventilation of formulated polyol blender is 35,000 kg/h for each grade. The transfer time is one of limitation condition. Two loading process of formulated polyol blender are loading process from raw material drums and transfer process from based polyol product tanks. Loading time is around 30 minutes. The transfer time from calculation must not greater than loading time to avoid loss step time in production. Mass flow rate and transfer time calculation steps are shown below and in Appendix E.

3.7.1 Convert volumetric flow rate to mass flow rate by density by equation 3.8.

$$\dot{M} = \rho\dot{V} \tag{3.8}$$

3.7.2 Consider limiting mass flow rate of blender from ventilation system design. Mass flow rate must less than 35,000 kg/h.

3.7.3 Calculate maximum actual volume of each grade of based polyol by using equation 3.9 and maximum amount of based polyol to the blender (% of Blender Volume) in Table 3.1.

Table 3.1 Maximum Amount of Based Polyol to the Blender (% of Blender Volume) [Dow Chemical Thailand, 2016]

Based Polyol Grades	**V_{max} (% of Blender Volume)**
Voranol RN482	64.7
Voranol RA440	62.7
Voranol RN490	45.0
Voranol RH360	84.2

$$V_a = \frac{V_{max}}{100} \times V \tag{3.9}$$

3.7.4 Calculate transfer time by using equation 3.10, volumetric flow rate and maximum volume of each grade.

$$t = \frac{V_a}{\dot{V}} \tag{3.10}$$

3.7.5 Consider time which is lower than 30 min except Voranol RH360 because Voranol RH360 is low usage in production plan of formulated polyol.

3.8 Set Pressure Estimation of Internal Relief Valve [Viking Pump Inc., 2010]

The chart in Figure 3.2 shows the performance of Viking internal relief valves. These charts show the relationship between the capacity, cracking pressure, and full bypass pressure. The design steps of set pressure is shown on Appendix F.

3.8.1 On the relief valve chart for LS size of pump, draw a horizontal line at specified volumetric flow rate.

3.8.2 Draw a vertical line of pressure.

3.8.3 Through the point of intersection of these two lines, draw a line parallel to the nearest diagonal relief valve line directly to the right of the point.

3.8.4 Read the full bypass relief valve setting at the intersection with the horizontal axis.

3.8.5 Multiply value by 1.1. Viking recommends a relief valve setting which is 10% greater than what is shown in the charts to account for any variations in the spring rate of the spring.

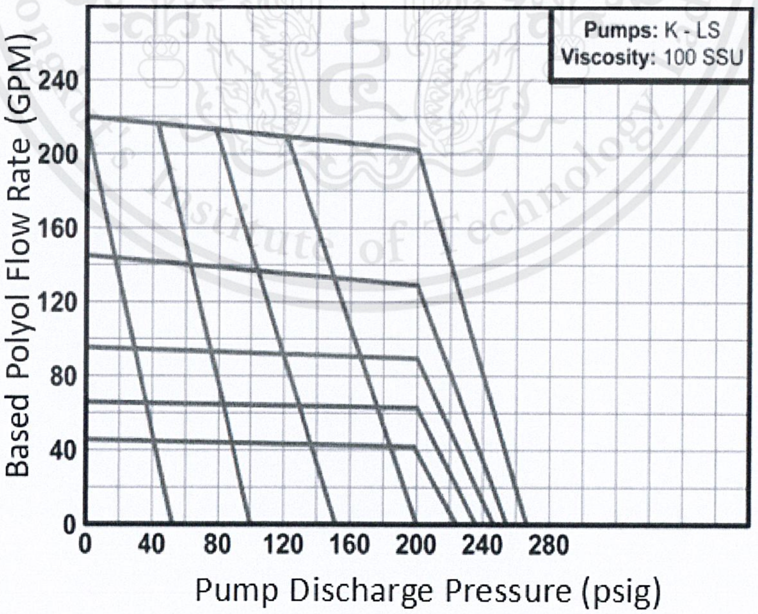


Figure 3.2 Pressure Relief Valve Performance Curve [Viking Pump Inc., 2010]

3.9 Cooling Time Calculation

Cooling time is calculated from heat transfer of batch agitated vessel with chilled water jacket. The calculation is refer to lumped system of fluid in blender and the jacket is fluid flow in anular pipe. Cooling time calculation steps are shown below. The example of calculation is shown in Appendix G.

Assumptions

- U is constant for the process and over the entire surface.
- Liquid flow rates are constant.
- Specific heats are constant for the process.
- The heating or cooling medium has a constant inlet temperature.
- Agitation produces a uniform batch fluid temperature.
- No partial phase changes occur.
- Heat losses are negligible.

3.9.1 Calculate Prandtl number of polyol and cooling water by equation 3.11

$$\mathrm{Pr} = \frac{c_p \mu}{k} \tag{3.11}$$

Inside Film Calculation

3.9.2 Calculate Reynolds Number by equation 3.12

$$\mathrm{Re} = \frac{\rho {D_a}^2 N}{\mu} \tag{3.12}$$

3.9.3 Calculate Nusselt number from Reynolds number and Prandtl Number by equation 3.13

$$\mathrm{Nu} = 0.54\mathrm{Re}^{0.67}\mathrm{Pr}^{0.33} \tag{3.13}$$

3.9.4 Calculate heat transfer coefficient of convection by equation 3.14

$$\mathrm{Nu} = \frac{h_i D}{k} \tag{3.14}$$

Outside Film Calculation

3.9.5 Calculate cross sectional area which is used to calculate velocity of fluid by equation 3.15

$$A_c = W_a p \tag{3.15}$$

3.9.6 Calculate equivalent length by equation 3.16

$$D_e = 4W_a \tag{3.16}$$

3.9.7 Calculate Reynolds number by equation of jacket with spiral baffle as shown in equation 3.17

$$Re = \frac{\rho \overline{V}_e D_e}{\mu} \tag{3.17}$$

3.9.8 Calculate Nusselt number by Reynolds number, Prandtl number and equivalent length from equation 3.18

$$Nu = 1.86 Re^{0.33} Pr^{0.33} \times \left(\frac{D_e}{H}\right)^{0.33} \tag{3.18}$$

3.9.9 Calculate heat transfer coefficient of convection by equation 3.19

$$Nu = \frac{h_o D_e}{k} \tag{3.19}$$

Heat Transfer Calculation

3.9.10 Calculate overall heat transfer coefficient from heat transfer coefficient of convection in vessel and jacket by using equation 3.20

$$\frac{1}{U} = \frac{1}{h_o} + \frac{x}{k} + \frac{1}{h_i} \qquad (3.20$$

3.9.11 Calculate time of cooling by the equation 3.21

$$\ln \frac{T(t) - T_\infty}{T_i - T_\infty} = -\frac{\dot{M}_o c_{po}}{M c_{pi}} \left(\frac{K-1}{K}\right) t \tag{3.21}$$

where $K = e^{\frac{UA}{M_o c_{po}}}$

CHAPTER 4
RESULTS AND DISCUSSION

4.1 Pressure Drop

Pressure drop is calculated by Bernoulli's equation. Diameter of polyol pipe is 3 inches for Voranol RH360, RA440 and RN 490. Diameter is 4 inches for Voranol RN492. Pipe thickness is standard 40 schedule. Material of polyol pipe is carbon steel, its roughness is 0.00005 m. Pressure drop is caused by skin friction and friction loss from fittings and valves. Temperature of polyol affects to its viscosity which are calculated from viscosity model. Polyol is high viscosity fluid. So, the flow pattern of polyol is laminar flow. In laminar flow calculation, roughness of pipe does not affect to friction loss and pressure drop. Pressure drop data at the optimum temperature of Voranol RN482, RA440, RN490, and RH360 from calculation is shown on Table 4.1, Table 4.2, Table 4.3 and Table 4.4, respectively.

Table 4.1 Pressure Drop in Piping System of Voranol RN482

Based Polyol Temperature at Product Tank (°C)	**Based Polyol Flow Rate (m^3/h)**	**Based Polyol Viscosity (cP)**	**Pressure Drop (barg)**
55	25	1,346	7.12
	30		8.35
	35		9.59
	40		10.83

Table 4.2 Pressure Drop in Piping System of Voranol RA440

Based Polyol Temperature at Product Tank (°C)	**Based Polyol Flow Rate (m^3/h)**	**Based Polyol Viscosity (cP)**	**Pressure Drop (barg)**
75	25	627	9.13
	30		10.78
	35		12.46
	40		14.15

Table 4.3 Pressure Drop in Piping System of Voranol RN490

Based Polyol Temperature at Product Tank (°C)	Based Polyol Flow Rate (m³/h)	Based Polyol Viscosity (cP)	Pressure Drop (barg)
50	25	589	7.13
	30		8.41
	35		9.70
	40		11.01

Table 4.4 Pressure Drop in Piping System of Voranol RH360

Based Polyol Temperature at Product Tank (°C)	Based Polyol Flow Rate (m³/h)	Based Polyol Viscosity (cP)	Pressure Drop (barg)
45	25	488	7.29
	30		8.59
	35		9.91
	40		11.26

4.2 Pump Discharge Pressure and Set Pressure

Pump discharge pressure is calculated from pressure drop and blender pressure. The pressure in blender is 0.5 barg. The pump discharge pressure at the optimum temperature of Voranol RN482, RA440, RN490, and RH360 pump is shown on Table 4.5, Table 4.6, Table 4.7 and Table 4.8, respectively. Maximum pressure of pump is 13.8 bar. Only pump discharge pressure which lower than maximum pressure of pump is considered. Moreover, set pressure of internal relief valve is estimated by pressure relief valve performance curve of Viking pump. Internal relief valve is pressure relief device of polyol transfer process. The set pressure must be less than pipe pressure limit which is 15.57 barg to prevent pipe rupture from over pressure. The pump discharge pressure, based polyol flow rate and based polyol temperature at the product tank are used to estimate pump speed and gear ratio by gear pump performance curve.

Table 4.5 Pump Discharge Pressure of Voranol RN482

Based Polyol Temperature at Product Tank (°C)	Based Polyol Flow Rate (m³/h)	Pump Discharge Pressure (barg)	Set Pressure (barg)
55	25	7.62	13.8
	30	8.85	15.5
	35	10.09	17.2
	40	11.33	17.2

From Table 4.5, Pump discharge pressure which is higher than 13.8 bar can be neglected. The set pressure must be less than pipe limit pressure or 15.57 barg. At the optimum conditions, temperature is 55 °C. Flow rate is 30 m³/h. Pump discharge pressure is 8.85 barg.

Table 4.6 Pump Discharge Pressure of Voranol RA440

Based Polyol Temperature at Product Tank (°C)	Based Polyol Flow Rate (m³/h)	Pump Discharge Pressure (barg)	Set Pressure (barg)
75	25	9.63	15.5
	30	11.28	17.2
	35	12.96	18.9
	40	14.65	20.7

From Table 4.6, Pump discharge pressure which is higher than 13.8 bar can be neglected. The set pressure must be less than pipe limit pressure or 15.57 barg. At the optimum conditions, temperature is 75 °C. Flow rate is 25 m³/h. Pump discharge pressure is 9.63 barg.

Table 4.7 Pump Discharge Pressure of Voranol RN490

Based Polyol Temperature at Product Tank (°C)	Based Polyol Flow Rate (m³/h)	Pump Discharge Pressure(barg)	Set Pressure (barg)
50	25	7.63	12.1
	30	8.91	15.5
	35	10.20	17.2
	40	11.51	17.2

From Table 4.7, pump discharge pressure which is higher than 13.8 bar can be neglected. The set pressure must be less than pipe limit pressure or 15.57 barg. At the optimum conditions, temperature is 50 °C. Flow rate is 30 m^3/h. Pump discharge pressure is 8.91 barg.

Table 4.8 Pump Discharge Pressure of Voranol RH360

Based Polyol Temperature at Product Tank (°C)	Based Polyol Flow Rate (m^3/h)	Pump Discharge Pressure(barg)	Set Pressure (barg)
45	25	7.79	12.1
	30	9.09	15.5
	35	10.41	17.2
	40	11.76	18.9

From Table 4.8, Pump discharge pressure which is higher than 13.8 bar can be neglected. The set pressure must be less than pipe limit pressure or 15.57 barg. At the optimum conditions, temperature is 45 °C. Flow rate is 30 m^3/h. Pump discharge pressure is 9.09 barg.

4.3 Pump Performance Curve and Gear Reducer Selection

Relation of speed and flow rate is shown on pump performance curve. Pump performance curve is produced by manufacturer or Viking pump in this case. For user, pump curve can be plot by selection tool of Viking pump in the model and size of each pump. The speed, flow rate, pump discharge pressure and pump power are shown in pump performance curve. Pump speed from pump performance curve is used to calculate gear ratio. The obtained calculated gear ratio is compared with Dorris data sheet to select the nearest gear ratio.

From Dorris data sheet, the optimum gear ratio of Voranol RN482, RA440, RN490, and RH360 are 3.63, 4.00, 3.63 and 3.63, respectively. The pump performance of Voranol RN482, RA440, RN490, and RH360 are shown in Figure 4.1, 4.2, 4.3 and 4.4, respectively.

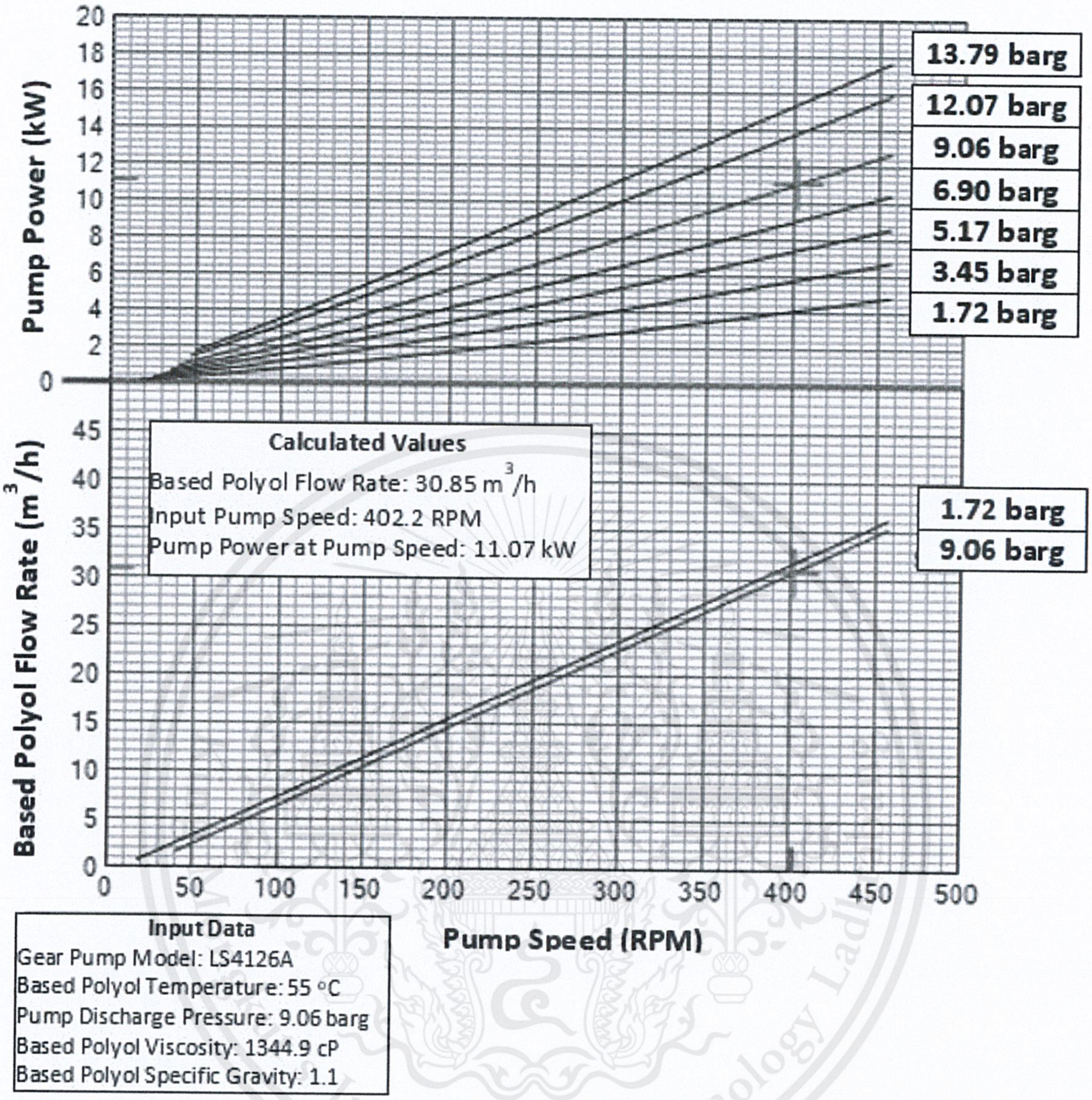
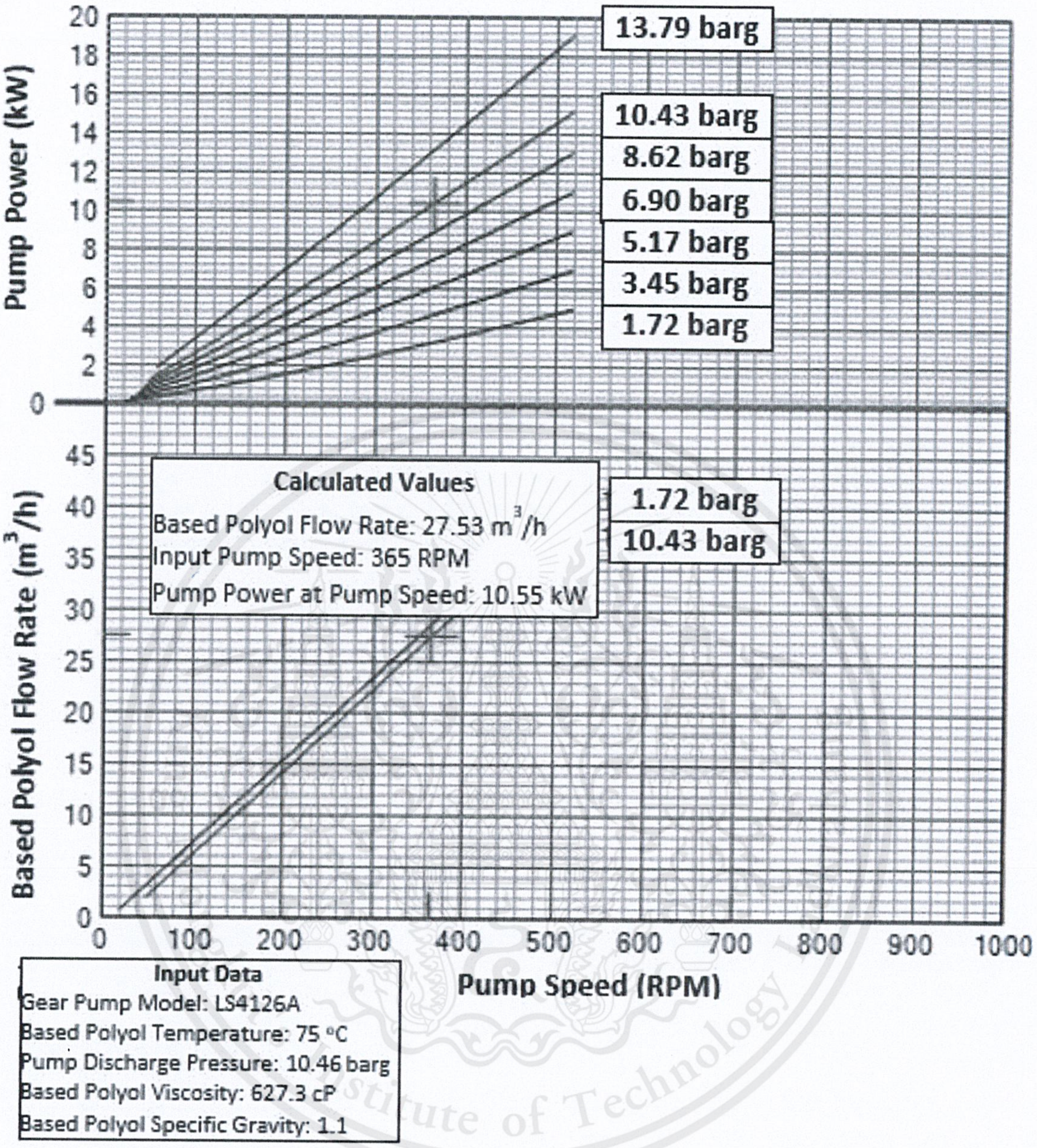


Figure 4.1 Optimum Pump Performance Curve of Voranol RN482



Calculated Values

Based Polyol Flow Rate: 27.53 m^3/h

Input Pump Speed: 365 RPM

Pump Power at Pump Speed: 10.55 kW

Input Data

Gear Pump Model: LS4126A

Based Polyol Temperature: 75 °C

Pump Discharge Pressure: 10.46 barg

Based Polyol Viscosity: 627.3 cP

Based Polyol Specific Gravity: 1.1

Figure 4.2 Optimum Pump Performance Curve of Voranol RA440

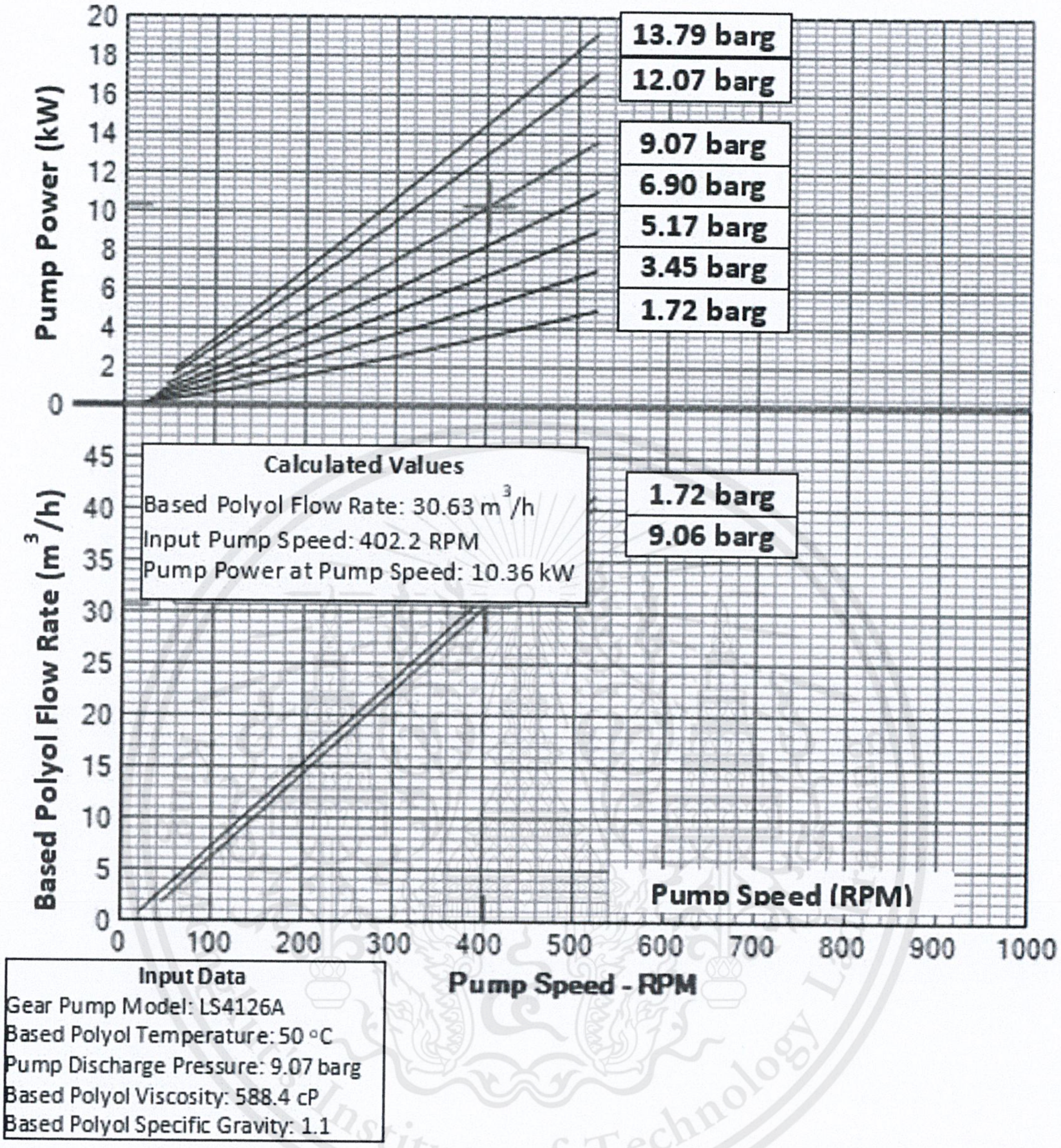
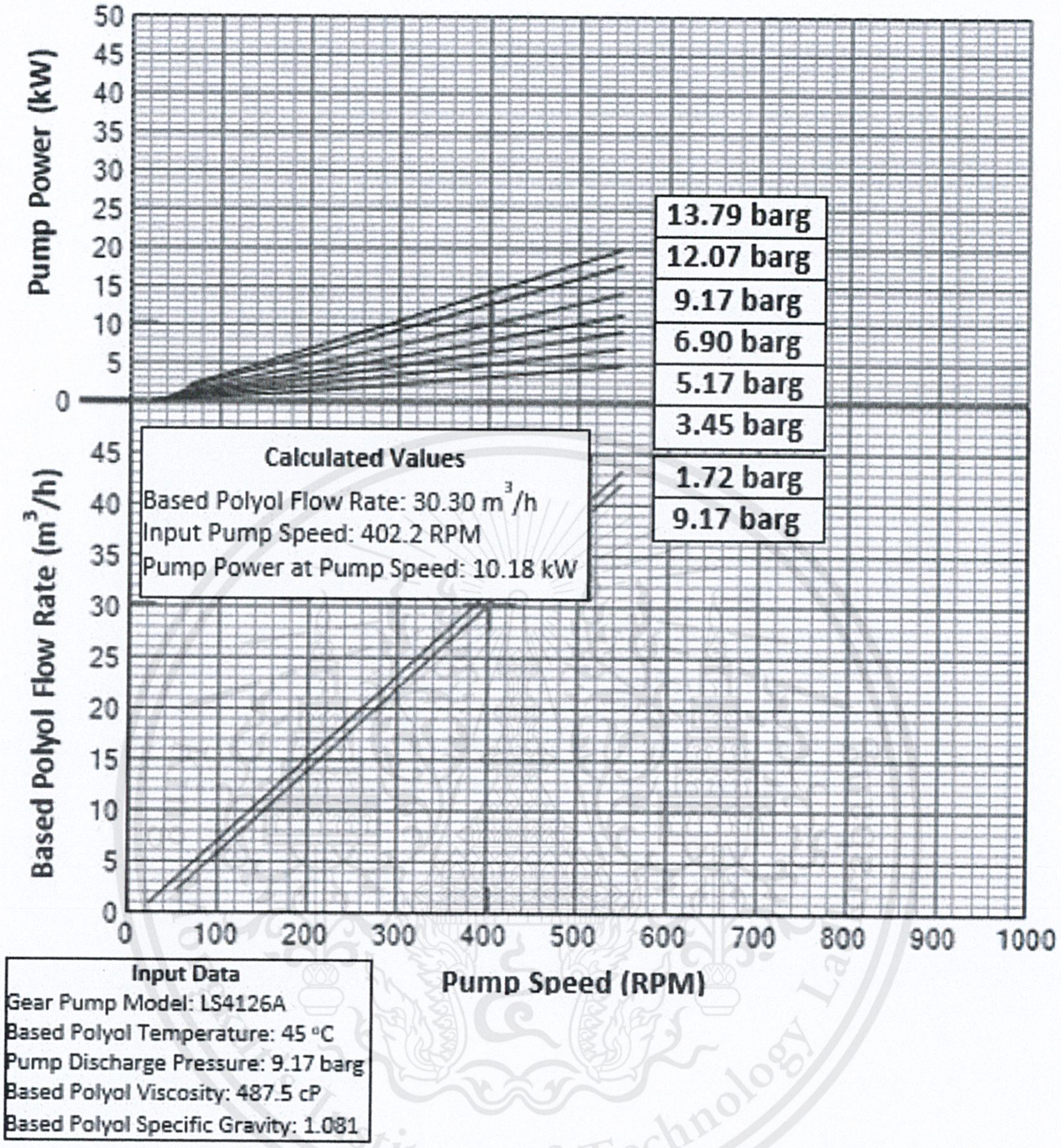


Figure 4.3 Optimum Pump Performance Curve of Voranol RN490



Calculated Values

Based Polyol Flow Rate: 30.30 m^3/h

Input Pump Speed: 402.2 RPM

Pump Power at Pump Speed: 10.18 kW

Input Data

Gear Pump Model: LS4126A

Based Polyol Temperature: 45 °C

Pump Discharge Pressure: 9.17 barg

Based Polyol Viscosity: 487.5 cP

Based Polyol Specific Gravity: 1.081

Figure 4.4 Optimum Pump Performance Curve of Voranol RH360

From pump performance curves, the conditions are considered with the design limit of pump, piping system and blender. The proposed conditions consist of based polyol temperature at the product tank, based polyol flow rate and pump discharge pressure. The maximum pump discharge pressure is 13.8 bar which is the specification of Viking pump. Then, based polyol mass flow rate and transfer time are calculated. The based polyol mass flow rate must be less than maximum ventilation which is 35,000 kg/h for each grade. Based polyol transfer time must be less than 30 minutes. Except for Voranol RH360 because Voranol RH360 is low amount raw material in production plan of formulated polyol production. The transfer time is the limiting step if it is greater than 30 minutes. The pump power of must be less than 80 percent of motor power which is 14.8 kW. At optimum point, all data which required for gear reducer selection must available from all limit as shown in Table 4.9.

Table 4.9 Optimum Based Polyol Feeding Conditions

Based Polyol Grades	Based Polyol Temp. (°C)	Pump Discharge Pressure (barg)	Based Polyol Flow Rate (m^3/h)	Based Polyol Mass Flow Rate (MT/h)	Gear Ratio	Pump Power (kW)	Based Polyol Transfer Time (min)
Voranol RN482	55	9.06	30.85	34	3.63	11.07	25
Voranol RA440	75	10.46	27.53	31	4.00	10.55	27
Voranol RN490	50	9.07	30.63	34	3.63	10.36	18
Voranol RH360	45	9.17	30.30	33	3.63	10.18	34

4.3 Cooling Time Calculation

To confirm the accuracy of cooling time calculation, the data from calculation are compared with actual cooling time from formulated polyol plant. Data of cooling time is collected from formulated polyol blender. Two blenders of formulated polyol plant are 22 and 10 ton blenders. The results of cooling time calculation and experiment are shown in Figure 4.5 and 4.6, respectively.

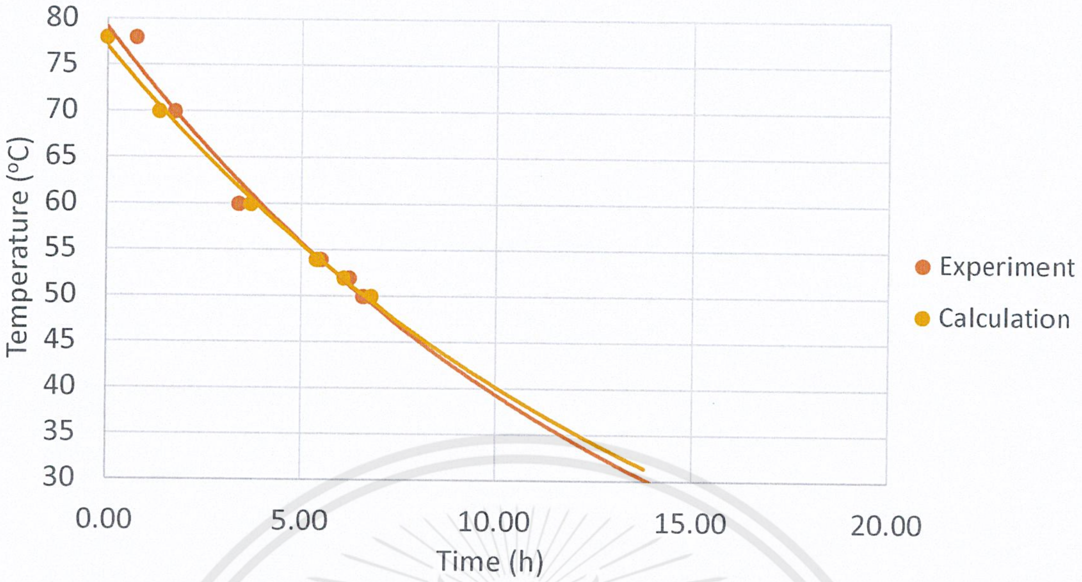


Figure 4.5 Cooling time of 22 tons blender

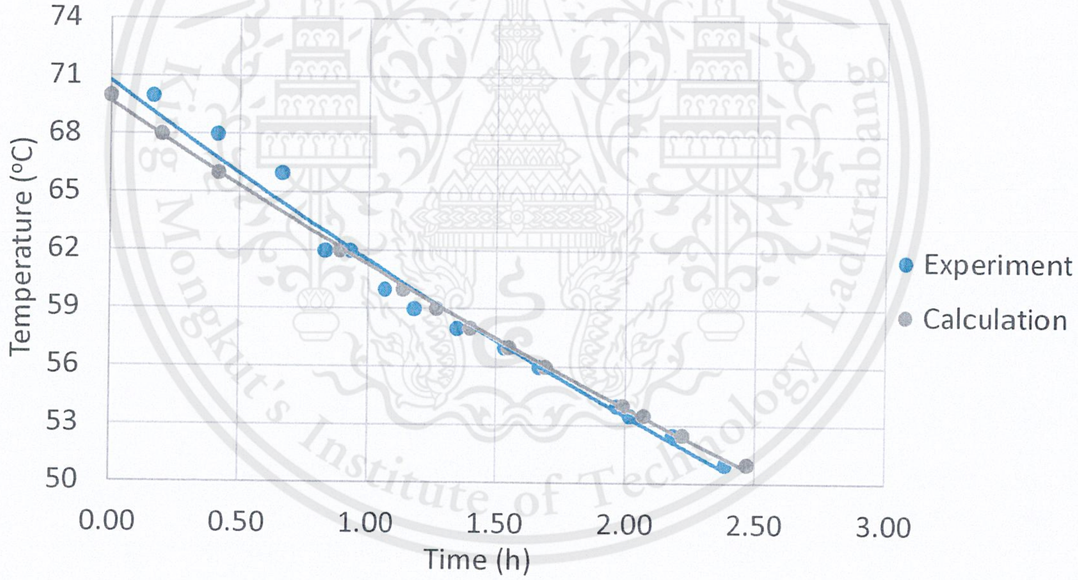


Figure 4.6 Cooling Time of 10 tons blender

From Figure 4.5 and 4.6, the results from calculation is close to experimental results. This heat transfer model can be used to calculate the accuracy cooling time. The cooling time affect to productivity of formulated polyol plant. Voranol RN482 is mostly used in formulated polyol production. The cooling time is calculated with using Voranol RN482 data. The productivity of new conditions for Voranol RN482 is shown in Table 4.10.

Table 4.10 Cooling Time and Productivity of Voranol RN482

Data		**Values**
Voranol RN482 Temperature at Product Tank (°C)	**Current Operation**	80
	Design Operation	55
Cooling Time per Batch	**Current Operation**	17 h 54 min
	Design Operation	16 h 30 min
Cooling Time Reduction per Batch		1 h 24 min
Additional Productivity (MT/year)		161
Additional Productivity (batch/year)		7

From Table 4.10, the benefit of project is based on Voranol RN482. The cooling time is calculated from initial temperature and final temperature which is 30 °C. The current initial temperature is 80 °C. The proposed initial temperature is 55 °C. When the initial temperature is reduce from 80 to 55 °C, the cooling time is also reduce 1 hour and 24 min for each batch. Productivity increment is 7 batch/year or 161 ton/year of formulated polyol.

CHAPTER V

CONCLUSION

5.1 Conclusion

The optimum conditions of 4 grades of polyol transfer are shown in Table 5.1. The optimum temperature of Voranol RN482 at the product tank is 55 °C while the normal temperature is 80 °C. By decreasing of the temperature, the cooling time of Voranol RN482 per batch about 1 hour and 24 minutes reduced. The additional productivity of formulated polyol plant is 161 tons per year.

Table 5.1 Required Data for Gear Reducer Selection at Optimum Polyol Feeding Conditions

	Voranol RN482	**Voranol RA440**	**Voranol RN490**	**Voranol RH360**
Based Polyol Temperature at Product Tank (°C)	55	75	50	45
Pump Discharge Pressure (barg)	9.06	10.46	9.07	9.17
Based Polyol Flow Rate (m^3/h)	30.85	27.53	30.63	30.30
Based Polyol Mass Flow Rate (ton/h)	34	31	34	33
Gear Ratio	3.63	4.00	3.63	3.63
Power Load (kW)	11.07	10.55	10.36	10.18
Based Polyol Transfer Time (min)	25	27	18	34
Set Pressure of Internal Relief Valve (barg)	15.50	15.50	15.50	15.50

5.2 Project Suggestions

The optimum conditions from this project can be obtained by gear reducer replacement. Further works after replacement of gear reducer are as follows:

5.2.1 Monitor the cooling time at formulated polyol plant after gear reducer replacement and cross check with the calculation.

5.2.2 Monitor number of pump failures after gear reducer replacement and compare with previous records.

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APPENDIX

APPENDIX A
RAW DATA

1. Gear Pump Specification

Specification of pump, motor, gear reducer, and internal relief valve from pump template and Viking data sheet are used to estimate performance of pump and to see pump curve. Specification of each pump compositions are shown in Table A.1, A.2, A.3 and A.4.

Table A.1 Pump Specification [Viking Pump Inc., 2016]

Speed (rpm)	613
Viscosity (cP)	200
Temperature (°C)	40
Capacity (m^3/h)	45
Discharge Pressure (barg)	4.9
Pump Efficiency	0.85

Table A.2 Motor Specification [Viking Pump Inc., 2016]

Speed (rpm)	1460
Differential Head	330
Hz	50
Horse Power (kW)	18.5

Table A.3 Gear Reducer Specification [Viking Pump Inc., 2016]

Gear Ratio	2.378
Horse Power	50

Table A.4 Pressure Relief Valve Specification [Viking Pump Inc., 2016]

Material	Stainless Steel
Set Pressure (barg)	10.35

2. Piping Specification and System Data

Polyol piping specifications from data sheet are Standard weight, weld, carbon steel, ASTM A53 type E grade B and Pressure limit margin 85%. Pressure limit is relate to temperature as shown in Table A.5. Piping system data is worst case data classified to 4 case follow 4 grades of polyol.

Table A.5 Pressure Limit of Polyol Pipe [The Dow Chemical Company, 2016]

Temperature (°C)	**Maximum Pressure (bar)**
-29	197.0
38	19.7
121	16.9
149	10.3

Table A.6 Piping System Data [The Dow Chemical Company, 2016]

Grade		**Voranol RN482**	**Voranol RA440**	**Voranol RN490**	**Voranol RH360**
Pipe Material		Carbon Steel			
Roughness		0.00005			
Diameter (m)		0.1020	0.0779	0.0779	0.0779
Area (m^2)		0.0082	0.0048	0.0048	0.0048
Length (m)		170	163.0	160	128.5
Fittings & Valves	**90°**	25	25	25	25
	Tee Through Flow	4	2	2	2
	Tee Branched Flow	6	6	6	6
	BV	7	7	7	7
	GV	4	4	4	4

Table A.7 Loss Coefficient of Fittings and Valves [Metro Pumps and Systems, Inc., 2015]

Fittings & Valves	**Loss Coefficient**	
	3 in	**4 in**
90º Bend	0.54	0.51
Tee Through Flow	0.36	0.34
Tee Branched Flow	1.08	1.02
Ball Valve	0.05	0.05
Gate Valve	0.14	0.14

3. Gear Reducer Model

Gear ratio of gear reducer indicate the output speed or pump speed. The gear ratios of gear reducer each model from The Doris Company are shown in Table A.8.

Table A.8 Gear Reducer Model [The Doris Company, 2009]

Gear Reducer Models	**Gear Ratios**
9013	1.315
9015	1.551
9019	1.907
9020	2.049
9022	2.205
9024	2.378
9028	2.788
9030	3.032
9033	3.310
9036	3.630
9040	4.000
9042	4.208
9044	4.435
9047	4.682
9049	4.952

4. Blender and Agitator Specification

Specification of blender and agitator is used for heat transfer calculation. Cooling time of blender is estimated from heat transfer calculation and data monitoring. The specifications of are shown in Table A.9.

Table A.9 Blender and Agitator Specification [The Dow Chemical Company, 2016]

Material	Carbon Steel
Cylinder Height (m)	3.6
Inside Diameter (m)	3
Blender Volume (m^3)	20
Cone Height (m)	0.86
Cone Volume (m^3)	2.03
Wall Thickness (mm)	30
Diameter (m)	0.22
Jacket Baffled Type	Spiral Baffled
Width Area (m)	0.12
Baffled Pitch (m)	0.5
Impeller Type	Pitch Blade Turbine
Diameter (m)	1.067
Agitator Speed (RPM)	56

5. Polyol Properties

Polyol Properties, which are heat capacity and thermal conductivity, are used to calculate heat transfer coefficient of convection in formulated polyol in blender. Polyol heat capacity and thermal conductivity are shown in Table A.10 and A.11, respectively.

Table A.10 Specific Heat Capacity of Polyol [The Dow Chemical Company, 2016]

Temperature (ºC)	**Heat Capacity**	
	BTU/lb	**J/kg ºC**
20	0.4781	1111.99
40	0.4981	1158.51
60	0.5181	1205.02
80	0.5381	1251.54
100	0.5581	1298.06
120	0.5781	1344.58

Table A.11 Thermal Conductivity of Polyol [The Dow Chemical Company, 2016]

Temperature (ºC)	**Thermal Conductivity (W/mK)**
100	0.1230
65	0.1248
40	0.1260
35	0.1263

6. Chill Water Properties

Chill water properties is used to calculate heat transfer coefficient of convection of cooling jacket. Table A.12 show temperature and flow rate of chill water at formulated polyol plant. The compositions of chill water are 50wt% ethylene glycol with water. Ethylene glycol is added to reduce melting point. Viscosity, specific heat capacity and thermal conductivity are shown in Table A.12, A.16 and A.14, respectively.

Table A.12 Chilled Water Conditions [The Dow Chemical Company, 2016]

Substance	50wt% Ethylene Glycol
Supply Temperature (ºC)	2
Temperature @ MRU (ºC)	7
Volumetric Flow Rate (m^3/h)	10

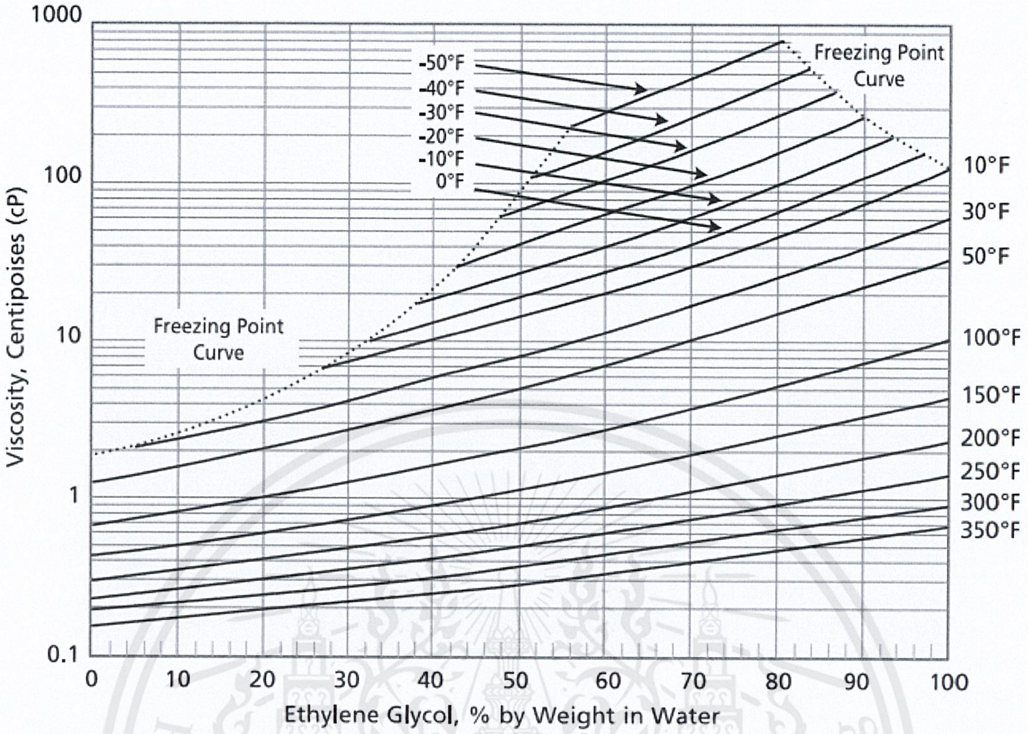


Figure A.1 Viscosities of Aqueous Ethylene Glycol [ME Global, 2008]

$$\log_{10} \mu = A - B/(x + C) \quad \text{(A.1)}$$

where x = Weight % of ethylene glycol

Table A.13 Viscosity Calculation Constant of Ethylene Glycol [ME Global, 2008]

Temperature (°F)	**A**	**B**	**C**
-50	-0.7829	516.0300	-219.2940
-40	-1.0896	556.5090	-228.7280
-30	-1.3278	586.1330	-236.6760
-20	-1.6731	666.7630	-252.2230
-10	-2.5987	992.9100	-295.4990
0	-2.2552	817.5420	-279.9330
10	-2.7898	1029.3290	-310.4160
30	-3.7702	1495.1860	-368.9300
50	-4.4899	1941.3090	-422.7680
100	-3.9684	1596.0920	-420.2830
150	-3.6196	1368.6200	-420.7610

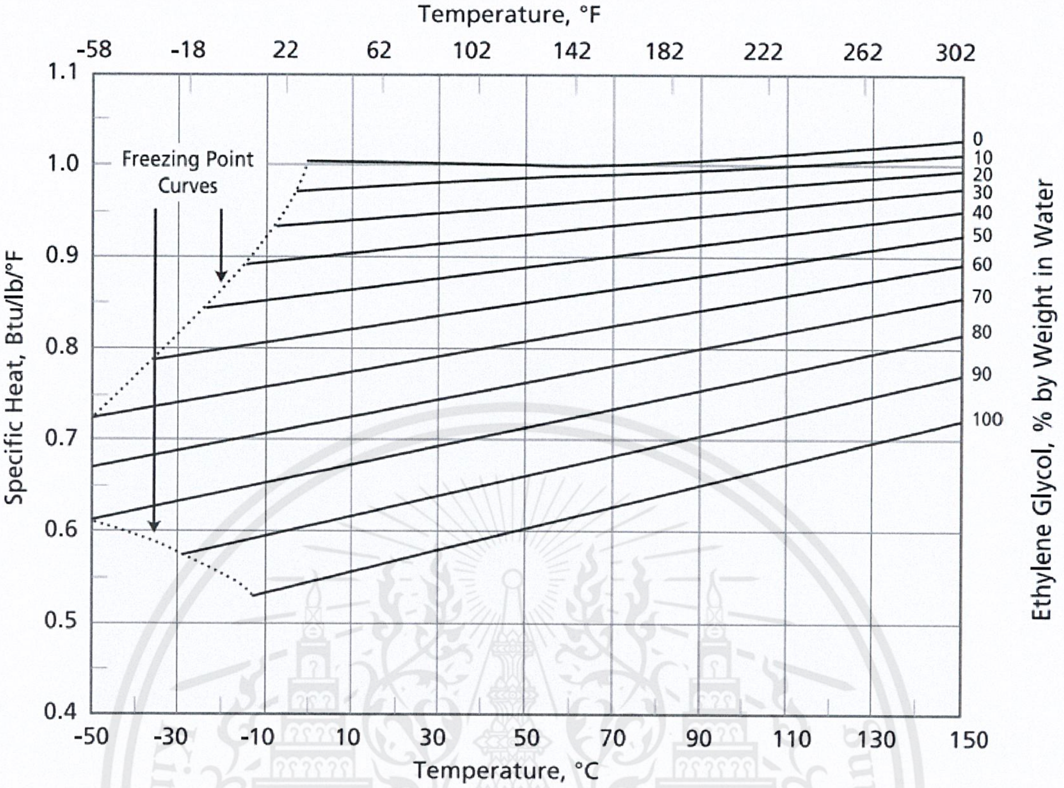


Figure A.2 Specific Heats of Aqueous Ethylene Glycol [ME Global, 2008]

$$C_p = A + BT + CT^2 \qquad \text{(A.2)}$$

where T = Temperature (°C)

Table A.14 Heat Capacity Constant of Aqueous Ethylene Glycol [ME Global, 2008]

Temperature (°C)	A	B (x10^4)	C (x10^6)
0	1.0038	-2.2459	2.6257
10	0.9724	1.8001	0.5705
20	0.9358	3.9963	0.0000
30	0.8989	5.1554	0.0000
40	0.8586	6.2639	0.0000
50	0.8149	7.3219	0.0000
60	0.7677	8.3293	0.0000
70	0.7171	9.2863	0.0000
80	0.6630	10.1930	0.0000
90	0.6056	11.0490	0.0000
100	0.5447	11.8540	0.0000

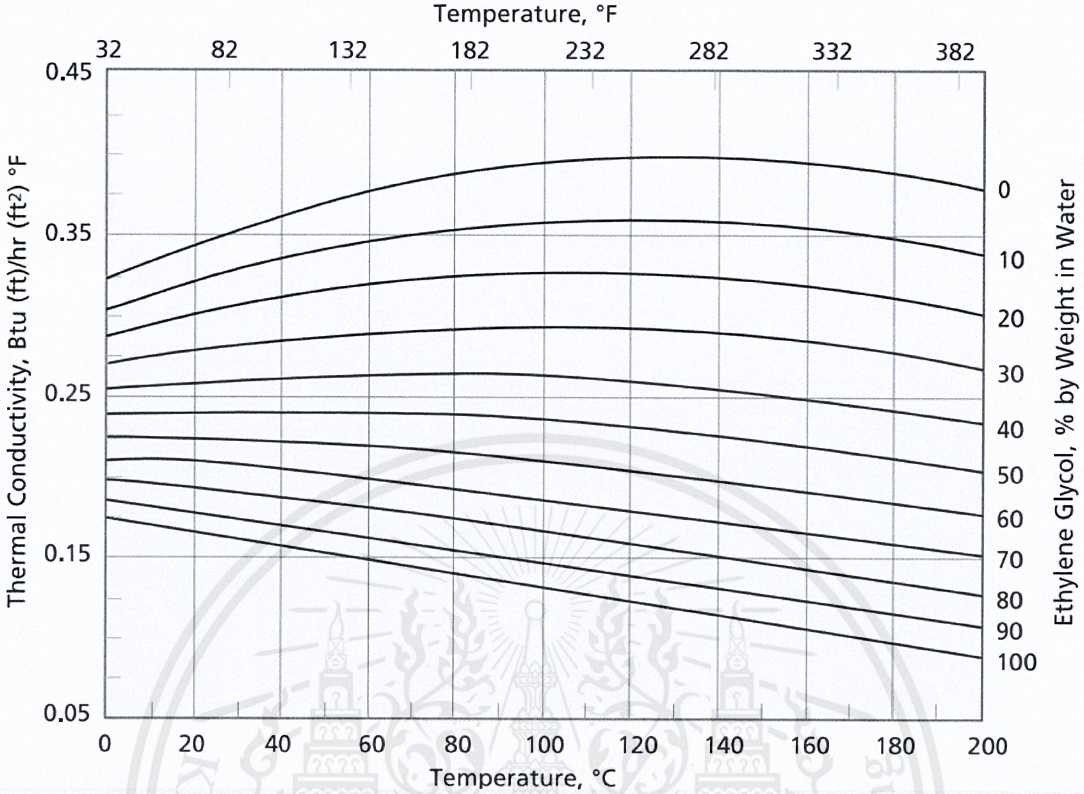


Figure A.3 Thermal Conductivities of Aqueous Ethylene [ME Global, 2008]

$$k = A + BT + CT^2 \qquad (A.3)$$

where T = Temperature (°C)

Table A.15 Thermal Conductivity Constant of Ethylene Glycol [ME Global, 2008]

Temperature (°C)	A	B (x10^4)	C (x10^6)
0	0.3225	11.5240	-4.3629
10	0.3043	8.9729	-3.6114
20	0.2870	6.6350	-2.9292
30	0.2704	4.5096	-2.3160
40	0.2546	2.5973	-1.7722
50	0.2395	0.8976	-1.3975
60	0.2252	0.5896	-0.8920
70	0.2117	-1.8633	-0.5560
80	0.1990	-2.9247	-0.2890
90	0.1870	-3.7733	-0.0912
100	0.1758	-4.4092	0.0374

APPENDIX B
VISCOSITY MODEL

Viscosity model of polyol is the relation between viscosity and temperature. The viscosity curve is plotted with the power equation which is used to estimate viscosity of polyol in pressure drop calculation. The viscosity models of based polyol are created refer to Table B.1 which shows viscosity data from laboratory at any temperature. Figure B.1, B.2, B.3 and B.4 show viscosity model of 4 grades of polyol. The Viscosity model of Voranol RH360, RA440, RN482 and RN490 are shown in equation B.1, B.2, B.3 and B.4, respectively.

Table B.1 Viscosity Data from Laboratory [The Dow Chemical Company, 2016]

Products	**Voranol RN482**	**Voranol RA440**	**Voranol RN490**	**Voranol RH360**
Temp. [C]	**Viscosity [cp]**	**Viscosity [cp]**	**Viscosity [cp]**	**Viscosity [cp]**
0	N/A	N/A	N/A	N/A
10	2729543	136058094	206178	67912
20	123421	1986294	16538	6982
25	45550	509432	7341	3357
30	20174	167586	3780	1845
40	5581	28998	1327	718
50	2060	7437	589	345
60	912	2447	303	190
70	458	956	173	114
80	252	423	106	74
90	149	206	69	50
100	93	109	47	35
110	61	61	33	26
120	41	36	24	20
130	29	22	18	15
140	21	14	14	12
150	15	9	11	9
160	11	6	9	8
170	9	4	7	6
180	7	3	6	5
190	5	2	5	4
200	4	2	4	4

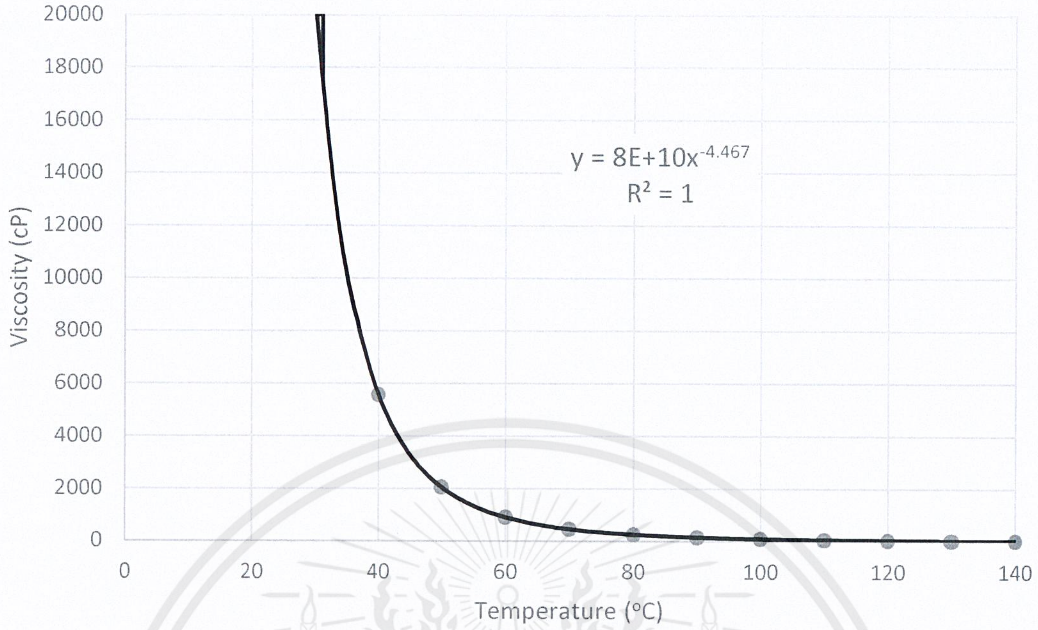


Figure B.1 Viscosity of Voranol RN482

$$\mu = 80000000000T^{-4.467} \qquad \text{(B.3)}$$

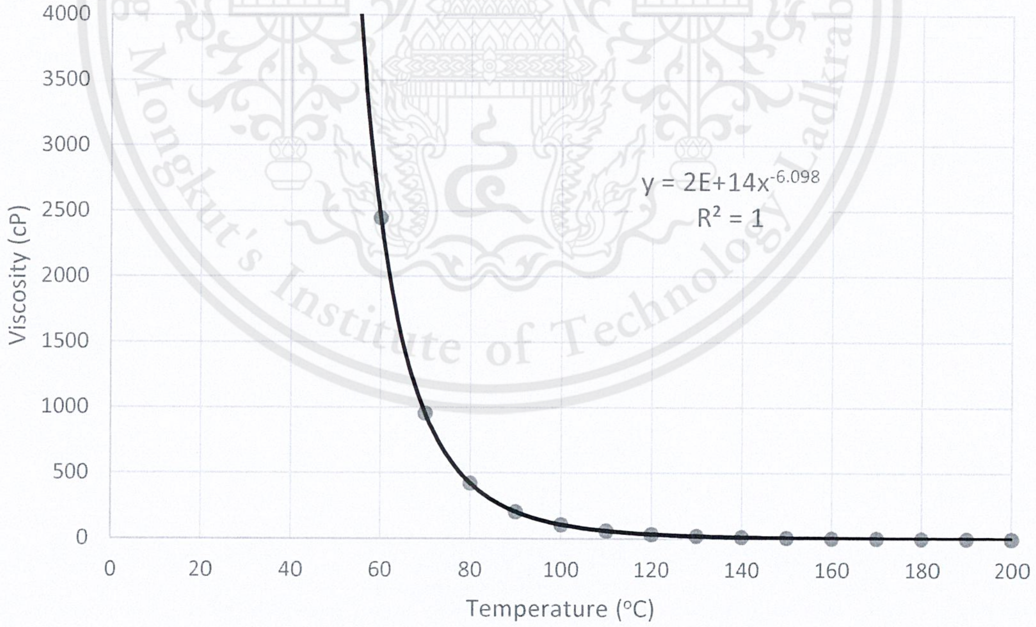


Figure B.2 Viscosity of Voranol RA440

$$\mu = 200000000000000T^{-6.098} \qquad \text{(B.2)}$$

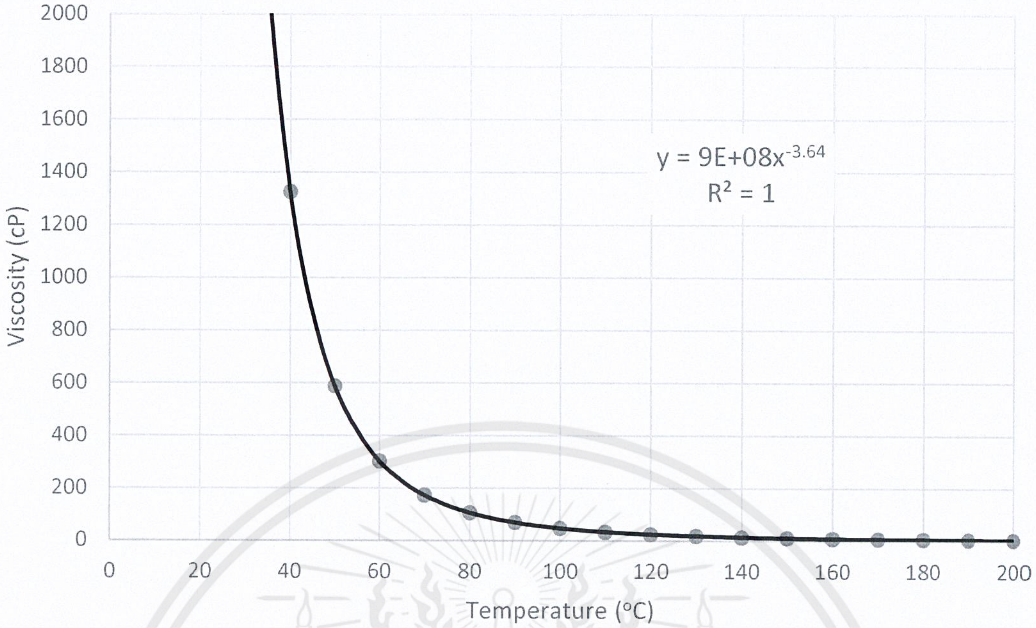


Figure B.3 Viscosity of Voranol RN490

$$\mu = 900000000T^{-3.64} \tag{B.4}$$

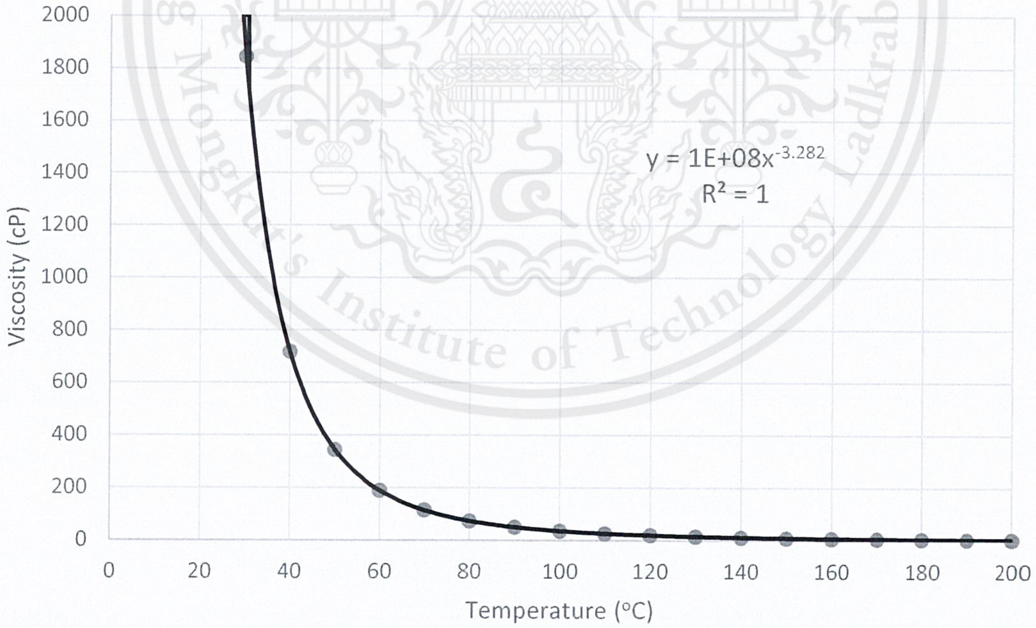


Figure B.4 Viscosity of Voranol RH360

$$\mu = 100000000T^{-3.282} \tag{B.1}$$

Example of Calculation

1. Calculate viscosity of Voranol RN482 at 55 °C from viscosity model as shown in Figure B.3 or equation B.3.

$$\mu = 80000000000T^{-4.467} \quad \text{(B.3)}$$

$$= 80000000000(55)^{-4.467}$$

$$= 1{,}346\ cP$$

APPENDIX C

PRESSURE DROP AND PUMP DISCHARGE PRESSURE CALCULATION

Example of Calculation

1. Vary temperature and flow rate to find the optimum point. The range which selected are from 40 to 80 °C and 25 m^3 to 45 m^3, respectively.

2. Convert volumetric flow rate to superficial velocity that are used to calculate Reynolds number by equation 3.2.

$$\bar{V} = \frac{\dot{V}}{A_c} \tag{3.2}$$

$$= \frac{30\ {}^{m^3}\!/_{h}}{0.00477\, m \times 3600\ {}^{s}\!/_{h}}$$

$$= 1.7475\ {}^{m}\!/_{s}$$

3. Calculate Reynolds number of fluid flow in pipe from equation 3.3.

$$Re = \frac{\rho D\bar{V}}{\mu} \tag{3.3}$$

$$= \frac{1081\ {}^{kg}\!/_{m^3} \times 0.078\, m \times 1.745\ {}^{m}\!/_{s} \times 1000\ {}^{cP\cdot m\cdot s}\!/_{kg}}{488\ cP}$$

$$= 302$$

4. Reynolds number from calculation represent the laminar flow of polyol which fanning friction is calculated from below equation.

$$f = \frac{16}{Re} \tag{3.4}$$

$$= \frac{16}{302}$$

$$= 0.053$$

5. Calculate friction loss from below equation but only skin friction is concerned.

$$h_f = \left(4f\frac{L}{D} + K_c + K_e + K_f\right)\frac{\bar{V}^2}{2} \tag{3.5}$$

$$= \left(4\frac{160\,m}{1.745\,m} + (27 \times 0.54) + +(4 \times 0.36) + (4 \times 1.08) + (7 \times 0.05) + (\times 0.14)\right)\frac{1.7475^2\,m^2}{2}$$

$$= 696.676\ {m^2}/{s^2}$$

6. Convert the friction loss and the static loss (loss from different heights) to the term of pressure drop by Bernoulli's equation.

$$\Delta P = \rho\left(h_f + g\Delta H\right) \qquad (3.6)$$

$$= \left[696.676\ {m^2}/{s^2} + \left(9.81\,{m}/{s^2} \times 10\,m\right)\right] \times 1081\ {kg}/{m^3} \times 10^{-5}\ {bar \cdot s^2}/{kg \cdot m}$$

$$= 8.59\ \mathrm{bar}$$

The results of pressure drop of Voranol RN482, RA440, RN490 and RH360 are shown in Table C.1, C.2, C.3, and C.4, respectively.

7. Discharge pressure is calculated by pressure drop from pipe and pipe discharge pressure which is 0.5 bar in blender.

$$P_1 = \Delta P + P_2$$

$$= 8.59\ bar + 0.5\ bar$$

$$= 9.09\ bar$$

The results of pump discharge pressure of Voranol RN482, RA440, RN490 and RH360 are shown in Table C.5, C.6, C.7, and C.8, respectively.

Table C.1 Pressure Drop Calculation of Voranol RN482

Temp. (°C)	Flow (m^3/h)	Velocity (m/s)	Visc. (cP)	Re	Fanning Factor	Friction Loss (m^2/s^2)	Pressure Drop (bar)
40	25	0.8495	5581	17	0.9368	2254.5459	25.88
	30	1.0194		20	0.7807	2707.2858	30.86
	35	1.1893		24	0.6691	3160.6360	35.85
	40	1.3592		27	0.5855	3614.5965	40.84
45	25	0.8495	3298	29	0.5535	1335.2942	15.77
	30	1.0194		35	0.4613	1604.1838	18.73
	35	1.1893		40	0.3954	1873.6837	21.69
	40	1.3592		46	0.3460	2143.7938	24.66
50	25	0.8495	2060	46	0.3457	836.8871	10.28
	30	1.0194		56	0.2881	1006.0952	12.15
	35	1.1893		65	0.2470	1175.9137	14.01
	40	1.3592		74	0.2161	1346.3424	15.89
55	25	0.8495	1346	71	0.2259	549.3658	7.12
	30	1.0194		85	0.1882	661.0697	8.35
	35	1.1893		99	0.1613	773.3839	9.59
	40	1.3592		113	0.1412	886.3083	10.83
60	25	0.8495	912	104	0.1531	374.8999	5.20
	30	1.0194		125	0.1276	451.7107	6.05
	35	1.1893		146	0.1094	529.1316	6.90
	40	1.3592		167	0.0957	607.1629	7.76
65	25	0.8495	638	149	0.1071	264.4933	3.99
	30	1.0194		179	0.0892	319.2227	4.59
	35	1.1893		209	0.0765	374.5624	5.20
	40	1.3592		239	0.0669	430.5123	5.81
70	25	0.8495	458	208	0.0769	192.1026	3.19
	30	1.0194		250	0.0641	232.3539	3.63
	35	1.1893		291	0.0549	273.2154	4.08
	40	1.3592		333	0.0481	314.6872	4.54
75	25	0.8495	337	283	0.0565	143.1753	2.65
	30	1.0194		340	0.0471	173.6412	2.99
	35	1.1893		396	0.0404	204.7173	3.33
	40	1.3592		453	0.0353	236.4036	3.68
80	25	0.8495	252	378	0.0424	109.2264	2.28
	30	1.0194		453	0.0353	132.9024	2.54
	35	1.1893		529	0.0303	157.1887	2.81
	40	1.3592		604	0.0265	182.0853	3.08

Table C.2 Pressure Drop Calculation of Voranol RN440

Temp. (°C)	Flow (m^3/h)	Velocity (m/s)	Visc. (cP)	Re	Fanning Factor	Friction Loss (m^2/s^2)	Pressure Drop (bar)
40	**25**	1.4554	28998	4	3.7188	32973.6560	363.79
	30	1.7465		5	3.0990	39572.8153	436.38
	35	2.0376		6	2.6563	46173.4507	508.99
	40	2.3287		7	2.3243	52775.5621	581.61
45	**25**	1.4554	14140	9	1.8133	16087.7129	178.04
	30	1.7465		11	1.5111	19309.6836	213.49
	35	2.0376		12	1.2952	22533.1303	248.94
	40	2.3287		14	1.1333	25758.0531	284.42
50	**25**	1.4554	7437	17	0.9538	8470.5921	94.26
	30	1.7465		20	0.7948	10169.1386	112.94
	35	2.0376		23	0.6813	11869.1612	131.64
	40	2.3287		27	0.5961	13570.6598	150.36
55	**25**	1.4554	4159	30	0.5334	4745.1084	53.28
	30	1.7465		36	0.4445	5698.5582	63.76
	35	2.0376		42	0.3810	6653.4840	74.27
	40	2.3287		48	0.3334	7609.8859	84.79
60	**25**	1.4554	2447	51	0.3138	2798.9289	31.87
	30	1.7465		61	0.2615	3363.1428	38.07
	35	2.0376		71	0.2241	3928.8327	44.30
	40	2.3287		82	0.1961	4495.9987	50.54
65	**25**	1.4554	1502	83	0.1926	1725.0837	20.06
	30	1.7465		100	0.1605	2074.5286	23.90
	35	2.0376		116	0.1376	2425.4495	27.76
	40	2.3287		133	0.1204	2777.8464	31.64
70	**25**	1.4554	956	131	0.1226	1104.5710	13.23
	30	1.7465		157	0.1021	1329.9133	15.71
	35	2.0376		183	0.0875	1556.7316	18.20
	40	2.3287		209	0.0766	1785.0260	20.71
75	**25**	1.4554	627	199	0.0805	731.5699	9.13
	30	1.7465		239	0.0671	882.3120	10.78
	35	2.0376		278	0.0575	1034.5301	12.46
	40	2.3287		318	0.0503	1188.2243	14.15
80	**25**	1.4554	423	295	0.0543	499.5591	6.57
	30	1.7465		354	0.0452	603.8990	7.72
	35	2.0376		413	0.0388	709.7150	8.89
	40	2.3287		472	0.0339	817.0070	10.07

Table C.3 Pressure Drop Calculation of Voranol RN490

Temp. (°C)	Flow (m^3/h)	Velocity (m/s)	Visc. (cP)	Re	Fanning Factor	Friction Loss (m^2/s^2)	Pressure Drop (bar)
40	25	1.4554	1327	94	0.1701	1211.4484	14.41
	30	1.7465		113	0.1418	1459.2313	17.13
	35	2.0376		132	0.1215	1708.8452	19.88
	40	2.3287		150	0.1063	1960.2902	22.64
45	25	1.4554	864	144	0.1108	797.0398	9.85
	30	1.7465		173	0.0923	961.9410	11.66
	35	2.0376		202	0.0792	1128.6732	13.49
	40	2.3287		231	0.0693	1297.2365	15.35
50	25	1.4554	589	212	0.0755	550.4445	7.13
	30	1.7465		254	0.0629	666.0266	8.41
	35	2.0376		297	0.0539	783.4397	9.70
	40	2.3287		339	0.0472	902.6840	11.01
55	25	1.4554	416	300	0.0534	395.7943	5.43
	30	1.7465		360	0.0445	480.4463	6.36
	35	2.0376		420	0.0381	566.9295	7.32
	40	2.3287		480	0.0334	655.2437	8.29
60	25	1.4554	303	411	0.0389	294.5629	4.32
	30	1.7465		494	0.0324	358.9687	5.03
	35	2.0376		576	0.0278	425.2055	5.76
	40	2.3287		658	0.0243	493.2734	6.51
65	25	1.4554	227	551	0.0291	225.8971	3.56
	30	1.7465		661	0.0242	276.5698	4.12
	35	2.0376		771	0.0208	329.0735	4.70
	40	2.3287		881	0.0182	383.4082	5.30
70	25	1.4554	173	721	0.0222	177.8994	3.04
	30	1.7465		865	0.0185	218.9725	3.49
	35	2.0376		1010	0.0158	261.8766	3.96
	40	2.3287		1154	0.0139	306.6118	4.45
75	25	1.4554	135	927	0.0173	143.4742	2.66
	30	1.7465		1112	0.0144	177.6623	3.03
	35	2.0376		1298	0.0123	213.6814	3.43
	40	2.3287		1483	0.0108	251.5316	3.85
80	25	1.4554	106	1172	0.0136	118.2276	2.38
	30	1.7465		1407	0.0114	147.3664	2.70
	35	2.0376		1641	0.0097	178.3362	3.04
	40	2.3287		1876	0.0085	211.1370	3.40

Table C.4 Pressure Drop Calculation of Voranol RH360

Temp. (°C)	Flow (m^3/h)	Velocity (m/s)	Visc. (cP)	Re	Fanning Factor	Friction Loss (m^2/s^2)	Pressure Drop (bar)
40	25	1.4554	718	171	0.0937	837.2926	10.11
	30	1.7465		205	0.0781	1010.1528	11.98
	35	2.0376		239	0.0669	1184.8135	13.87
	40	2.3287		273	0.0585	1361.2748	15.78
45	25	1.4554	488	251	0.0636	576.0620	7.29
	30	1.7465		302	0.0530	696.6760	8.59
	35	2.0376		352	0.0455	819.0907	9.91
	40	2.3287		402	0.0398	943.3059	11.26
50	25	1.4554	345	355	0.0450	414.2351	5.54
	30	1.7465		426	0.0375	502.4838	6.49
	35	2.0376		497	0.0322	592.5330	7.47
	40	2.3287		568	0.0281	684.3829	8.46
55	25	1.4554	252	486	0.0329	309.0131	4.40
	30	1.7465		583	0.0274	376.2174	5.13
	35	2.0376		680	0.0235	445.2223	5.87
	40	2.3287		777	0.0206	516.0277	6.64
60	25	1.4554	190	646	0.0248	237.8406	3.63
	30	1.7465		776	0.0206	290.8104	4.20
	35	2.0376		905	0.0177	345.5808	4.80
	40	2.3287		1034	0.0155	402.1518	5.41
65	25	1.4554	146	841	0.0190	188.0926	3.09
	30	1.7465		1009	0.0159	231.1129	3.56
	35	2.0376		1177	0.0136	275.9336	4.04
	40	2.3287		1345	0.0119	322.5550	4.55
70	25	1.4554	114	1072	0.0149	152.3422	2.71
	30	1.7465		1286	0.0124	188.2124	3.10
	35	2.0376		1501	0.0107	225.8831	3.50
	40	2.3287		1715	0.0093	265.3543	3.93
75	25	1.4554	91	1344	0.0119	126.0339	2.42
	30	1.7465		1613	0.0099	156.6424	2.75
	35	2.0376		1882	0.0085	189.0514	3.10
	40	2.3287		2151	0.0074	223.2610	3.47
80	25	1.4554	74	1662	0.0096	106.2721	2.21
	30	1.7465		1994	0.0080	132.9282	2.50
	35	2.0376		2326	0.0069	161.3849	2.81
	40	2.3287		2658	0.0060	191.6421	3.13

Table C.5 Pump Discharge Pressure of Voranol RN482

Temp (°C)	Flow (m^3/h)	Velocity (m/s)	Visc. (cP)	Pressure Drop (bar)	Pump Discharge Pressure (barg)
40	**25**	0.8495	5581	25.88	26.38
	30	1.0194		30.86	31.36
	35	1.1893		35.85	36.35
	40	1.3592		40.84	41.34
45	**25**	0.8495	3298	15.77	16.27
	30	1.0194		18.73	19.23
	35	1.1893		21.69	22.19
	40	1.3592		24.66	25.16
50	**25**	0.8495	2060	10.28	10.78
	30	1.0194		12.15	12.65
	35	1.1893		14.01	14.51
	40	1.3592		15.89	16.39
55	**25**	0.8495	1346	7.12	7.62
	30	1.0194		8.35	8.85
	35	1.1893		9.59	10.09
	40	1.3592		10.83	11.33
60	**25**	0.8495	912	5.20	5.70
	30	1.0194		6.05	6.55
	35	1.1893		6.90	7.40
	40	1.3592		7.76	8.26
65	**25**	0.8495	638	3.99	4.49
	30	1.0194		4.59	5.09
	35	1.1893		5.20	5.70
	40	1.3592		5.81	6.31
70	**25**	0.8495	458	3.19	3.69
	30	1.0194		3.63	4.13
	35	1.1893		4.08	4.58
	40	1.3592		4.54	5.04
75	**25**	0.8495	337	2.65	3.15
	30	1.0194		2.99	3.49
	35	1.1893		3.33	3.83
	40	1.3592		3.68	4.18
80	**25**	0.8495	252	2.28	2.78
	30	1.0194		2.54	3.04
	35	1.1893		2.81	3.31
	40	1.3592		3.08	3.58

Table C.6 Pump Discharge Pressure of Voranol RA440

Temp (°C)	Flow (m³/h)	Velocity (m/s)	Visc (cP)	Pressure Drop (bar)	Pump Discharge Pressure (barg)
40	**25**	1.4554	28998	363.79	364.29
	30	1.7465		436.38	436.88
	35	2.0376		508.99	509.49
	40	2.3287		581.61	582.11
45	**25**	1.4554	14140	178.04	178.54
	30	1.7465		213.49	213.99
	35	2.0376		248.94	249.44
	40	2.3287		284.42	284.92
50	**25**	1.4554	7437	94.26	94.76
	30	1.7465		112.94	113.44
	35	2.0376		131.64	132.14
	40	2.3287		150.36	150.86
55	**25**	1.4554	4159	53.28	53.78
	30	1.7465		63.76	64.26
	35	2.0376		74.27	74.77
	40	2.3287		84.79	85.29
60	**25**	1.4554	2447	31.87	32.37
	30	1.7465		38.07	38.57
	35	2.0376		44.30	44.80
	40	2.3287		50.54	51.04
65	**25**	1.4554	1502	20.06	20.56
	30	1.7465		23.90	24.40
	35	2.0376		27.76	28.26
	40	2.3287		31.64	32.14
70	**25**	1.4554	956	13.23	13.73
	30	1.7465		15.71	16.21
	35	2.0376		18.20	18.70
	40	2.3287		20.71	21.21
75	**25**	1.4554	627	9.13	9.63
	30	1.7465		10.78	11.28
	35	2.0376		12.46	12.96
	40	2.3287		14.15	14.65
80	**25**	1.4554	423	6.57	7.07
	30	1.7465		7.72	8.22
	35	2.0376		8.89	9.39
	40	2.3287		10.07	10.57

Table C.7 Pump Discharge Pressure of Voranol RN490

Temp (°C)	Flow (m³/h)	Velocity (m/s)	Visc (cP)	Pressure Drop (bar)	Pump Discharge Pressure (barg)
40	**25**	1.4554	1327	14.41	14.91
	30	1.7465		17.13	17.63
	35	2.0376		19.88	20.38
	40	2.3287		22.64	23.14
45	**25**	1.4554	864	9.85	10.35
	30	1.7465		11.66	12.16
	35	2.0376		13.49	13.99
	40	2.3287		15.35	15.85
50	**25**	1.4554	589	7.13	7.63
	30	1.7465		8.41	8.91
	35	2.0376		9.70	10.20
	40	2.3287		11.01	11.51
55	**25**	1.4554	416	5.43	5.93
	30	1.7465		6.36	6.86
	35	2.0376		7.32	7.82
	40	2.3287		8.29	8.79
60	**25**	1.4554	303	4.32	4.82
	30	1.7465		5.03	5.53
	35	2.0376		5.76	6.26
	40	2.3287		6.51	7.01
65	**25**	1.4554	227	3.56	4.06
	30	1.7465		4.12	4.62
	35	2.0376		4.70	5.20
	40	2.3287		5.30	5.80
70	**25**	1.4554	173	3.04	3.54
	30	1.7465		3.49	3.99
	35	2.0376		3.96	4.46
	40	2.3287		4.45	4.95
75	**25**	1.4554	135	2.66	3.16
	30	1.7465		3.03	3.53
	35	2.0376		3.43	3.93
	40	2.3287		3.85	4.35
80	**25**	1.4554	106	2.38	2.88
	30	1.7465		2.70	3.20
	35	2.0376		3.04	3.54
	40	2.3287		3.40	3.90

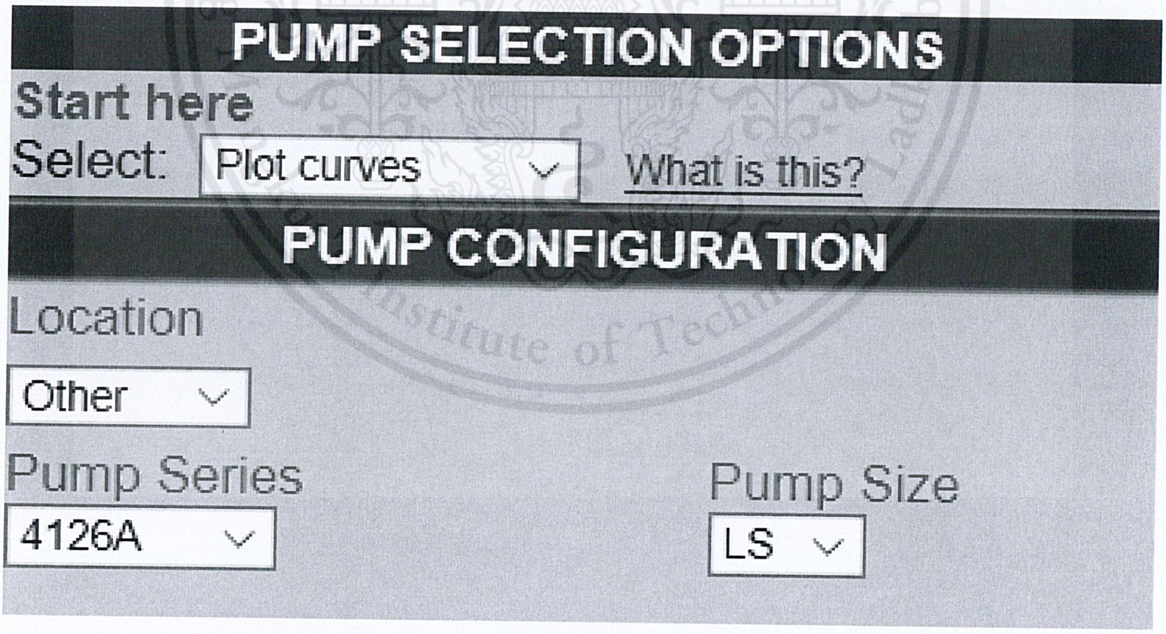
Table C.8 Pump Discharge Pressure of Voranol RH360

Temp (°C)	Flow (m^3/h)	Velocity (m/s)	Visc (cP)	Pressure Drop (bar)	Pump Discharge Pressure (barg)
40	25	1.4554	718	10.11	10.61
	30	1.7465		11.98	12.48
	35	2.0376		13.87	14.37
	40	2.3287		15.78	16.28
45	25	1.4554	488	7.29	7.79
	30	1.7465		8.59	9.09
	35	2.0376		9.91	10.41
	40	2.3287		11.26	11.76
50	25	1.4554	345	5.54	6.04
	30	1.7465		6.49	6.99
	35	2.0376		7.47	7.97
	40	2.3287		8.46	8.96
55	25	1.4554	252	4.40	4.90
	30	1.7465		5.13	5.63
	35	2.0376		5.87	6.37
	40	2.3287		6.64	7.14
60	25	1.4554	190	3.63	4.13
	30	1.7465		4.20	4.70
	35	2.0376		4.80	5.30
	40	2.3287		5.41	5.91
65	25	1.4554	146	3.09	3.59
	30	1.7465		3.56	4.06
	35	2.0376		4.04	4.54
	40	2.3287		4.55	5.05
70	25	1.4554	114	2.71	3.21
	30	1.7465		3.10	3.60
	35	2.0376		3.50	4.00
	40	2.3287		3.93	4.43
75	25	1.4554	91	2.42	2.92
	30	1.7465		2.75	3.25
	35	2.0376		3.10	3.60
	40	2.3287		3.47	3.97
80	25	1.4554	74	2.21	2.71
	30	1.7465		2.50	3.00
	35	2.0376		2.81	3.31
	40	2.3287		3.13	3.63

APPENDIX D
SELECTION TOOL OF VIKING PUMP AND GEAR RATIO CALCULATION

Gear pump performance curve of polyol pump presents on the pump selection tool of Viking pump. Pump performance curve is the relation of pump speed, flow rate, pressure and power. The tool of Viking pump is used to read pump curve and estimate the parameter of pump when some of the parameter is unknown.

1. Select plot curves in pump selection tool of Viking pump.
2. Select location, size and pump series from pump specification of Viking pump as shown in Figure D.1. In this case, pump serie is 4126A and size of pump is LS.
3. Input the operating conditions of Viking gear pump as shown in Figure D.2. The required conditions consist of viscosity, differential pressure, temperature, specific gravity, and flow rate or pump speed. Differential pressure is assumed to be pump discharge pressure. The conditions are plotted on pump curve. The other conditions including with power are estimated by pump performance curve.


PUMP SELECTION OPTIONS

Start here

Select: Plot curves

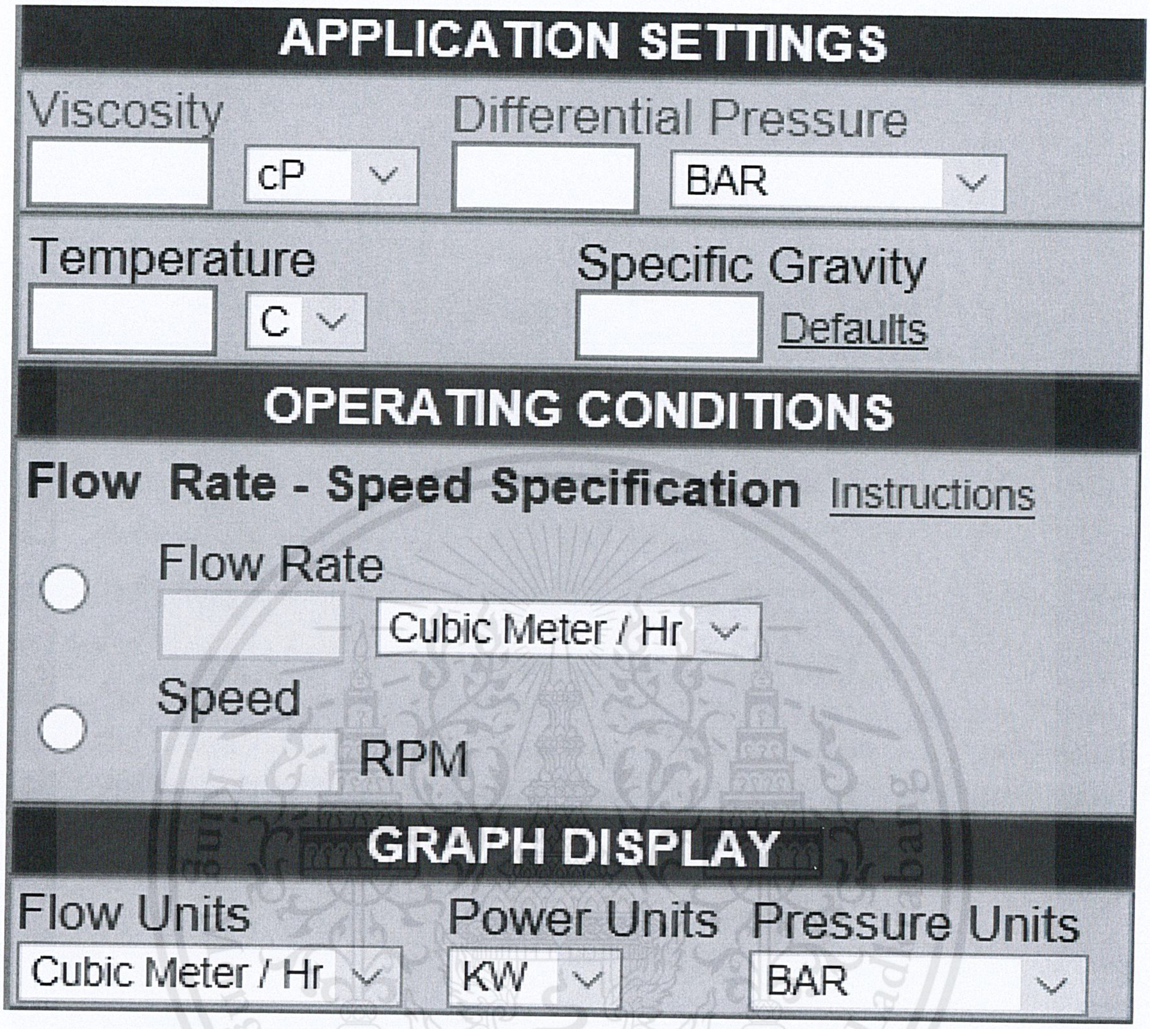
PUMP CONFIGURATION

Location: Other

Pump Series: 4126A

Pump Size: LS

Figure D.1 Pump Information Input [Viking Pump Inc., 2006]



APPLICATION SETTINGS

Viscosity cP

Differential Pressure BAR

Temperature C

Specific Gravity

Defaults

OPERATING CONDITIONS

Flow Rate - Speed Specification

Instructions

○ Flow Rate Cubic Meter / Hr

○ Speed RPM

GRAPH DISPLAY

Flow Units Cubic Meter / Hr

Power Units KW

Pressure Units BAR

Figure D.2 Operating Conditions Input [Viking Pump Inc., 2006]

Example of Gear Ratio Calculation

1. Calculate gear ratio from equation 3.7.

$$Gear\ Ratio = \frac{Motor\ Speed}{Pump\ Speed} \tag{3.7}$$

$$= \frac{1460\ RPM}{391.19\ RPM}$$

$$= 3.732$$

2. Compare calculated gear ratio with gear reducer specification sheet of the Dorris company as shown in Table A.8. 3.630 is the nearest gear ratio from Table A.8.

APPENDIX E

BASED POLYOL MASS FLOW RATE AND TRANSFER TIME CALCULATION

Example of Calculation

1. Calculate mass flow rate of polyol transfer process by equation 3.8.

$$\dot{M} = \rho\dot{V} \tag{3.8}$$

$$= 1100\ {}^{\mathrm{kg}}/_{\mathrm{m}^3} \times 30.85\ {}^{\mathrm{m}^3}/_{\mathrm{h}}$$

$$= 33{,}935\ {}^{kg}/_{\mathrm{h}}$$

2. Consider limiting mass flow rate of blender which from ventilation system design. Mass flow rate is not greater than 35,000 kg/h for each grade of polyol.

3. Calculate maximum volume of each grade of based polyol used by maximum percent of composition of each grade and equation 3.9. Maximum amount of based polyols to blender are shown in Table E.1.

Table E.1 Maximum Amount of Based Polyol to the Blender (% of Blender Volume) [Dow Chemical Thailand, 2016]

Based Product Grades	**Maximum Amount of Based Polyol to the Blender V_{max} (% of Blender Volume)**
Voranol RN482	64.7
Voranol RA440	62.7
Voranol RN490	45.0
Voranol RH360	84.2

$$V_a = \frac{V_{max}}{100} \times V \tag{3.9}$$

$$= \frac{84.7}{100} \times 20\ \mathrm{m}^3$$

$$= 12.94\ \mathrm{m}^3$$

4. Calculate transfer time by volume flow rate and maximum volume of each grade by equation 3.10.

$$t = \frac{V_a}{\dot{V}} \tag{3.10}$$

$$= \frac{12.94\ \text{m}^3}{30.85\ \text{m}^3/\text{h}} \times 60\ \text{min}/\text{h}$$

$$= 25\ \text{min}$$

The results of based polyol mass flow rate and transfer time are shown on Table E.2 and Table E.3, respectively.

Table E.2 Mass Flow Rate of Based Polyol

Grades	Temperature (°C)	Based Polyol Flow Rate (m^3/h)	Based Polyol Mass Flow Rate (kg/h)
Voranol RN482	55	30.85	33,935
Voranol RA440	75	27.53	30,558
Voranol RN490	50	30.63	33,693
Voranol RH360	45	30.30	32,754

Table E.3 Based Polyol Transfer Time

Grades	V_{max} (% of Blender Volume)	Maximum Volume (m^3)	Transfer Time (min)
Voranol RN482	64.7	12.9400	25
Voranol RA440	62.7	12.4270	27
Voranol RN490	45.0	9.0000	18
Voranol RH360	84.2	17.1360	34

APPENDIX F
SET PRESSURE ESTIMATION OF INTERNAL RELIEF VALVE
[VIKING PUMP INC., 2010]

1. The following charts show the performance of Viking pressure relief valves. These charts show the relationship between the capacity, cracking pressure, and full bypass pressure. Consider operating condition at 9.06 barg and 30.85 m^3/h.

2. Convert operating condition to 131 psig and 137 GPM.

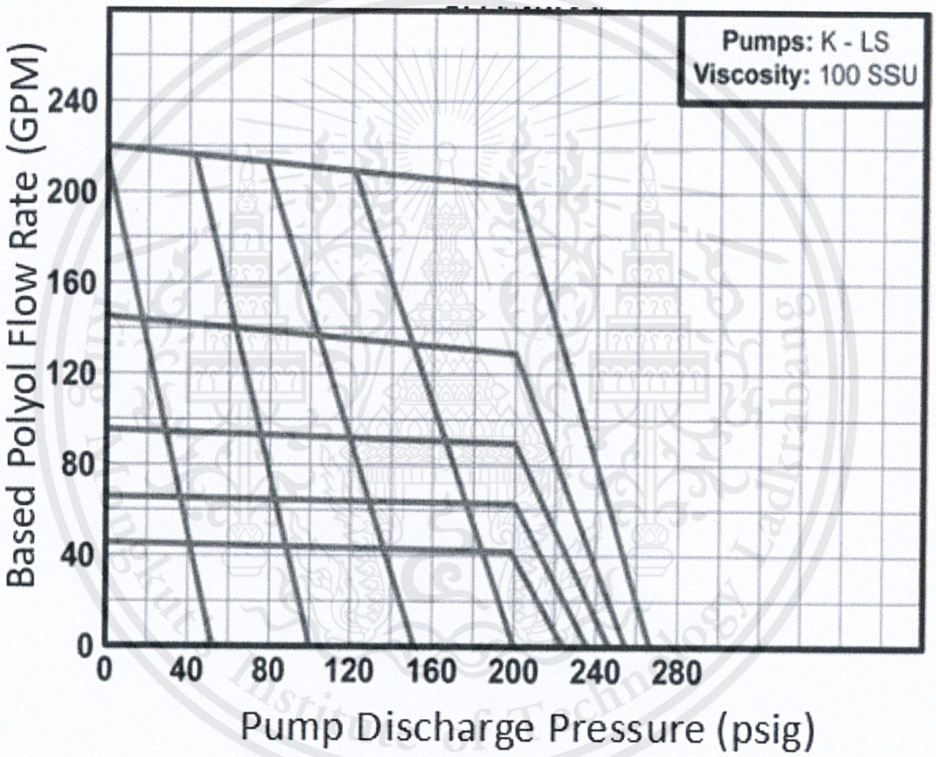


Figure F.1 Pressure Relief Valve Performance Chart [Viking Pump Inc. 2010]

3. On the relief valve chart for LS size pumps, draw a horizontal line at 137 GPM and draw a vertical line of pressure at 131 psig as shown in Figure F.2.

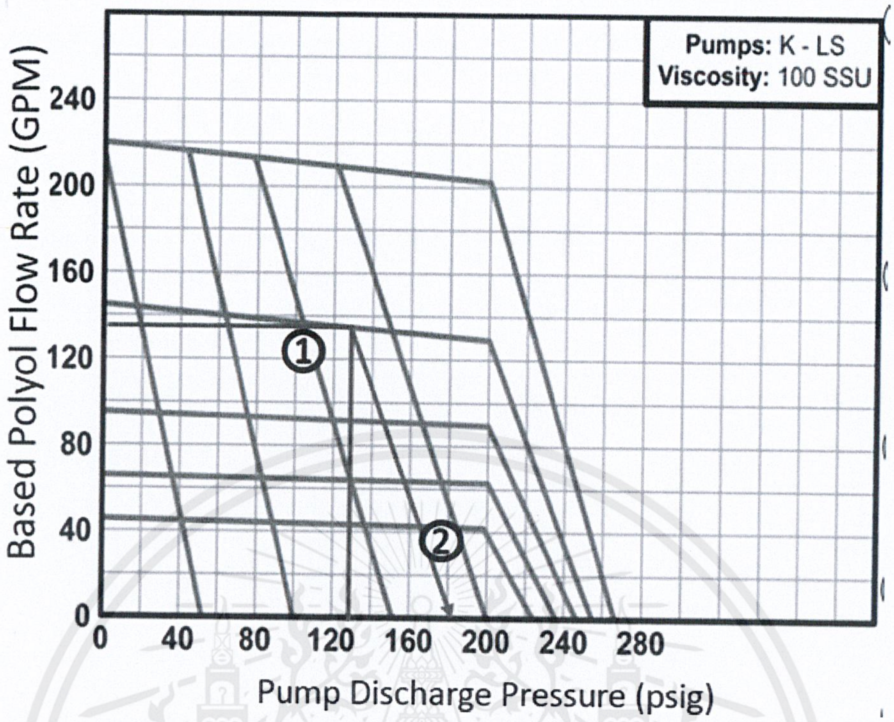


Figure F.2 Operating Conditions on Relief Valve Performance Chart [Viking Pump Inc. 2010]

4. Through the point of intersection of these two lines, draw a line parallel to the nearest diagonal relief valve line directly to the right of the point.

5. Read the full bypass relief valve setting at the intersection with the horizontal axis at 180 psig.

6. The relief valve charts are plotted for a viscosity of 100 SSU. For viscosities mor than 100 SSU, add 5 psig to the pressure between cracking and full bypass become 185 psig.

7. Multiply value by safety factor 10%. Viking recommends a relief valve setting which is 10% greater than what is shown in the charts to account for any variations in the spring rate of the spring. 110% is 204 psig.

8. Relief valve settings are usually rounded up to the nearest 25 psig increment. The nearest 25 psig from 204 psig is 225 psig or 15.5 barg which is the relief valve set point.

APPENDIX G
COOLING TIME CALCULATION AND ADDITIONAL PRODUCTIVITY ESTIMATION

Cooling Time Calculation

Assumptions

- U is constant for the process and over the entire surface.
- Liquid flow rates are constant.
- Specific heats are constant for the process.
- The heating or cooling medium has a constant inlet temperature.
- Agitation produces a uniform batch fluid temperature.
- No partial phase changes occur.
- Heat losses are negligible.

Example of Calculation

1. Calculate Prandtl number of polyol by equation 3.11.

$$\mathrm{Pr} = \frac{c_p \mu}{k} \tag{3.11}$$

$$= \frac{1164.32 \frac{J}{kg \cdot ^\circ C} \times 8452.18\ cP}{0.1259 \frac{W}{m \cdot k} \times 1000}$$

$$= 78{,}181$$

Inside Film Calculation

2. Calculate Reynolds number by equation 3.12.

$$\mathrm{Re} = \frac{\rho {D_a}^2 N}{\mu} \tag{3.12}$$

$$= \frac{1100 \frac{kg}{m^3} \times 1.067^2 \times 56}{8452.18\ cP}$$

$$= 138$$

3. Calculate Nusselt number by Reynolds number and Prandtl Number by equation 3.13.

$$\begin{aligned} \mathrm{Nu} &= 0.54Re^{0.67}Pr^{0.33} \\ &= 0.54 \times 138^{0.67} \times 78181^{0.33} \\ &= 274.47 \end{aligned} \tag{3.13}$$

4. Calculate heat transfer coefficient of convection by equation 3.14.

$$\begin{aligned} \mathrm{h}_i &= \frac{Nu{\cdot}k}{D} \\ &= \frac{274.47\times 0.1259\,\frac{W}{m\cdot k}}{3} \\ &= 13.17\,\frac{W}{m^2\cdot K} \end{aligned} \tag{3.14}$$

Outside Film Calculation

5. Calculate Prandtl number of cooling water by equation 3.11.

$$\begin{aligned} \mathrm{Pr} &= \frac{c_p\mu}{k} \\ &= \frac{3265.7\,\frac{J}{kg\cdot ^\circ C}\times 6.9\ cP}{0.415\,\frac{W}{m\cdot k}\times 1000} \\ &= 54.29 \end{aligned} \tag{3.11}$$

6. Calculate cross sectional area which is used to calculate velocity of fluid by equation 3.15.

$$\begin{aligned} A_c &= W_a p \\ &= 0.12\ m\ \times 0.5\ m \\ &= 0.6\ m^2 \end{aligned} \tag{3.15}$$

7. Calculate equivalent length by equation 3.16.

$$\begin{aligned} D_e &= 4W_a \\ &= 4 \times 0.12\ m \end{aligned} \tag{3.16}$$

$$= 0.48\ m$$

8. Calculate Reynolds number by equation 3.17.

$$\mathrm{Re} = \frac{\rho \overline{V_e} D_e}{\mu} \qquad (3.17)$$

$$= \frac{1100\frac{kg}{m^3} \times 0.0278\,\frac{m}{s} \times 0.48\ m}{6.9\ cP}$$

$$= 2{,}125$$

9. Calculate Nusselt number by Reynolds number, Prandtl number and equivalent length by equation 3.18.

$$\mathrm{Nu} = 1.86 Re^{0.33} Pr^{0.33} \times \left(\frac{D_e}{H}\right)^{0.33} \qquad (3.18)$$

$$= 1.86 \times 2125^{0.33} \times 54.3^{0.33} \times \left(\frac{0.48\ m}{2.67\ m}\right)^{0.33}$$

$$= 49.44$$

10. Calculate heat transfer coefficient of convection by equation 3.19.

$$\mathrm{h}_o = \frac{Nu \cdot k}{D} \qquad (3.19)$$

$$= \frac{49.44 \times 0.42\,\frac{W}{m \cdot k}}{0.48\ m}$$

$$= 13.17\ \frac{W}{m^2 \cdot K}$$

Heat Transfer Calculation

11. Calculate overall heat transfer coefficient from heat transfer coefficient of convection in vessel and jacket by using equation of thermal resistance (equation 3.20).

$$\frac{1}{U} = \frac{1}{h_o} + \frac{x}{k} + \frac{1}{h_i} \qquad (3.20)$$

$$= \frac{1}{13.17\,\frac{W}{m^2 \cdot K}} + \frac{0.033\ m}{48\,\frac{W}{m \cdot K}} + \frac{1}{13.17\,\frac{W}{m^2 \cdot K}}$$

$$= 0.153\ \frac{m^2 \cdot K}{W}$$

12. Calculate K with overall heat transfer coefficient which is used to calculated cooling time.

$$K = e^{\frac{UA}{\dot{M}_J c_{pj}}} \tag{E.1}$$

$$= e^{\frac{9.99\frac{W}{m\cdot K}\times 25.18\,m^2}{11000\frac{kg}{h}\times 3265.7\frac{J}{kg\cdot ℃}}}$$

$$= 1.05$$

13. Calculate cooling time of cooling by equation 3.21.

$$\ln\frac{T(t)-T_\infty}{T_i-T_\infty} = -\frac{\dot{M}_O c_{po}}{Mc_{pi}}\left(\frac{K-1}{K}\right)t \tag{3.21}$$

$$\mathrm{t} = \left(\ln\frac{T(t)-T_\infty}{T_i-T_\infty}\right)\left(-\frac{\dot{M}_O c_{po}}{Mc_{pi}}\right)\left(\frac{K}{K-1}\right)\left(\frac{1.05}{1.05-1}\right)$$

$$= \left(\ln\frac{30-2}{55-2}\right)\left(-\frac{11000\frac{kg}{h}\times 3265.7\frac{J}{kg\cdot ℃}}{23000\,kg \times 1164.32\frac{J}{kg\cdot ℃}}\right)\left(\frac{1.05}{1.05-1}\right)$$

$$= 16.64\,h$$

Estimation of Additional Productivity

Current blending time is 20.14 h from 80 – 30 °C. Design blending time is 18.64 h from 55 – 30 °C. Time is reduced 3.5 h/batch for propose operation. 2,000 tons of formulated polyol are produced annually. Production time of current operation is 1751 h/year. For proposed operation, production time can be reduced. Productivity is increased 161 MT/year or 7 batchs/year. The benefit of this project is additional productivity from cooling time reduction.

BIBLIOGRAHPY

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- 2013 – Present: Bachelor of Petrochemical Engineering
  Faculty of Engineering, King Mongkut's Institute of Technology Ladkrabang

Working Experiences

- June 2016 – July 2016: PTT Exploration and Production Plc.
  PTTEP Internship 2016, S1 Project PTTEP
  Drilling & Well Engineering Internship Program, Well Operation Devision
- August 2016 – November 2016: The Dow Chemical Thailand Company
  Co-operative Education 2016, MTP Operation
  Polyol and Latex Production Team