Chapter 1. Introduction

1.1 Background

Due to economic growth and increasing of demand, the addition of the production line is a quick solution employed by many industries including Ampol Food Processing Ltd. They had installed many chillers over the years for supporting the demand for ice water in the production line. For this reason, the existing design has become insufficient for the rising of workload. To illustrate, the pipe size that was designed to support the flow rate of the initial design may not be able to operate with the low head loss as before. To support our hypothesis, we have decided to employ the ASHRAE 90.1 standard to evaluate the existing design. If the design does not meet the standard, we shall suggest the changes to be made.

1.2 Objectives

1. Analyse existing chilled water piping system and find the shortcoming of system and Improve by using ASHRAE 90.1 standard
2. Simulate the existing system by using computer aided software in order to create virtual situation for maintenance advantages.

1.3 Scope of work

The existing chilled water pipe distribution system of Ampol food processing ltd. only SABROE and MYCOM1, MYCOM2 distribution loop

Chapter 2. Theories and Principles

2.1 Chilled Water System

A chilled water is cold water which be provided by water-cooled chillers. Its temperature is normally controlled below 10°C to be able to absorb heat from cooling load of the plant. This system is widely used in several circumstances. Not only, HVAC for large buildings but also many foods processing industries which needed high demand of chilled water to control desirable temperature for their production processes.

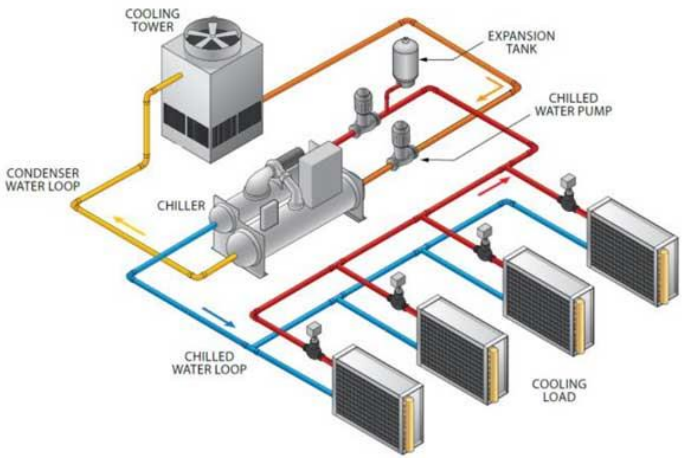


Figure 2-1 General Chilled Water System

A typical water-cooled chiller uses recirculating condenser water from a cooling tower to condense the refrigerant. A water-cooled chiller contains a refrigerant dependent on the entering condenser water temperature and flow rate, which functions in relation to the ambient wet-bulb temperature. The water-cooled chiller system is a combination of three refrigeration systems consist of the recirculating condenser water system, the chiller and chilled-water distribution system.

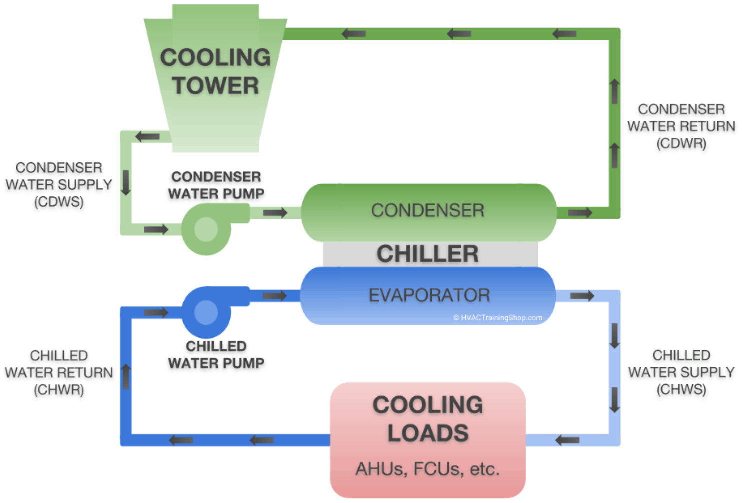


Figure 2-2 A Chilled Water System using Water-cooled Chiller

2.1.1 Recirculating condenser water system (Open-loop)

From figure 2-2, In order to cool the water that absorbed heat from a condenser, the cooling tower sprays the water over the tower media surface. The conversion of liquid water to gaseous phase required the latent heat of vaporization. Cooling towers use the internal heat frow water to vaporize the water in an adiabatic saturation process. A cooling tower’s purpose is to expose as much water surface area to air as possible to promote the evaporation of the water. Then, the cooled water collected into the tower basin, pumped by the condenser water pump, circulated though the condenser and send back to the cooling tower.

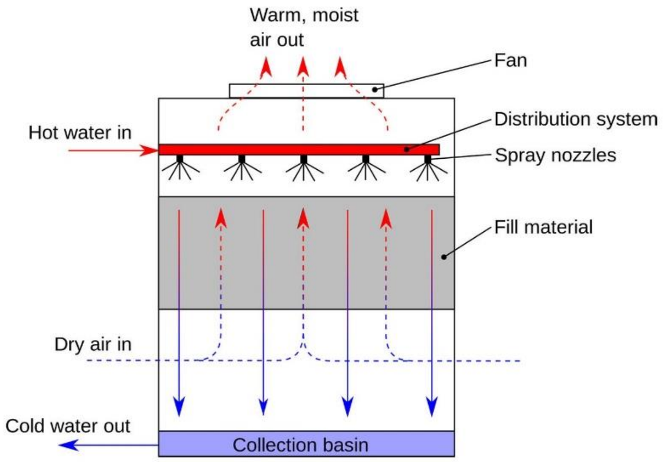


Figure 2-3 Spray Cooling Tower

2.1.2 Chiller

A general chiller works on the principle of vapor compression or vapor absorption. Chillers provide a continuous flow of coolant to the cold side of a process water system at a desired temperature of about 50°F (10°C). The coolant is then pumped through the process, extract heat out of one area of a facility (e.g., machinery, process equipment, etc.) as it flows back to the return side of the process water system.

A chiller uses a vapor compression mechanical refrigeration system that connects to the process water system through a device called an evaporator. Refrigerant circulates through an evaporator, compressor, condenser and expansion device of a chiller. A thermodynamic process occurs in each of above components of a chiller. The evaporator functions as a heat exchanger such that heat captured by the process coolant flow transfers to the refrigerant. As the heat-transfer takes place, the refrigerant evaporates, changing from a low-pressure liquid into vapor, while the temperature of the process coolant reduces.

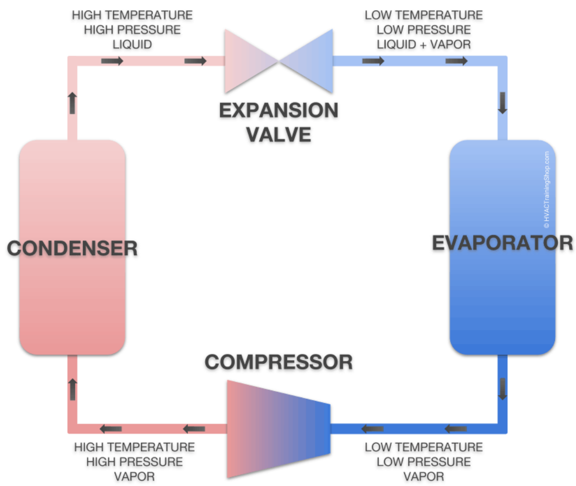


Figure 2-4 A Chiller Operation Diagram

The refrigerant then flows to a compressor, which performs multiple functions. First, it removes refrigerant from the evaporator and ensures that the pressure in the evaporator remains low enough to absorb heat at the correct rate. Second, it raises the pressure in outgoing refrigerant vapor to ensure that its temperature remains high enough to release heat when it reaches the condenser. The refrigerant returns to a liquid state at the condenser. The latent heat given up as the refrigerant changes from vapor to liquid is carried away from the environment by a cooling medium (air or water).

2.1.3 Chilled-water distribution system

Because most chilled-water distribution system is the one of a closed hydronic system. The fundamental difference between a closed and an open water system is the interface of the water with compressible gas such as air

A closed hydronic system is defined as one with no more than one point of interface with a compressible gas or surface. The definition is fundamental to understanding the hydraulic dynamics of these systems. Earlier literature referred to the system with an open or vented expansion tank as an open system, but such a system is actually a closed system; the atmospheric interface of the tank simply establishes the system pressure.

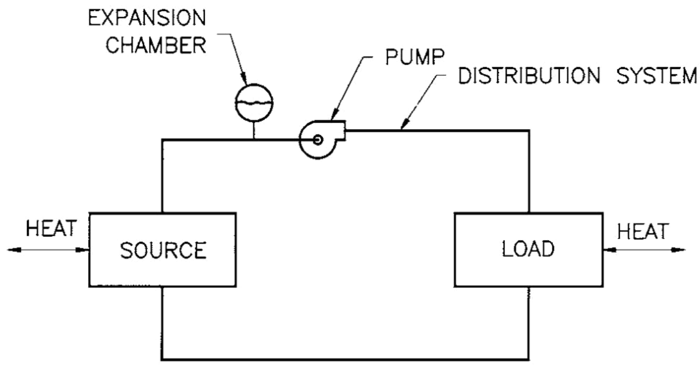


Figure 2-5 Hydronic system – Fundamental Components

A chiller operation can control temperature of water which circulated in chilled water distribution system. The chilled water flow into expansion tank, pumped through distribution system for extract heat from many difference types of loads and then send back to the source such as water-cooled chiller.

The components are subdivided into two groups: thermal components and hydraulic components. The thermal components consist of the load, the source, and the expansion chamber. The hydraulic components consist of the pipe distribution system, the chilled- water pump, and the expansion chamber. The expansion chamber is the only component that serves both a thermal and a hydraulic function.

2.1.3.1 Thermal components

2.1.3.1.1 Loads

The load is the device that causes heat to flow out of or into the system to or from the space or process, it is the independent variable to which the reminder of the system must respond. Outward heat flow characterizes a heating system, and inward heat flow characterizes a cooling system.

Gasketed plate heat exchanger (GPHE)

A plate heat exchanger is most common in the dairy, juice, beverage, alcoholic drink,
general food processing, and pharmaceutical industries, where their ease of cleaning and the thermal control required for sterilization or pasteurization make them ideal.

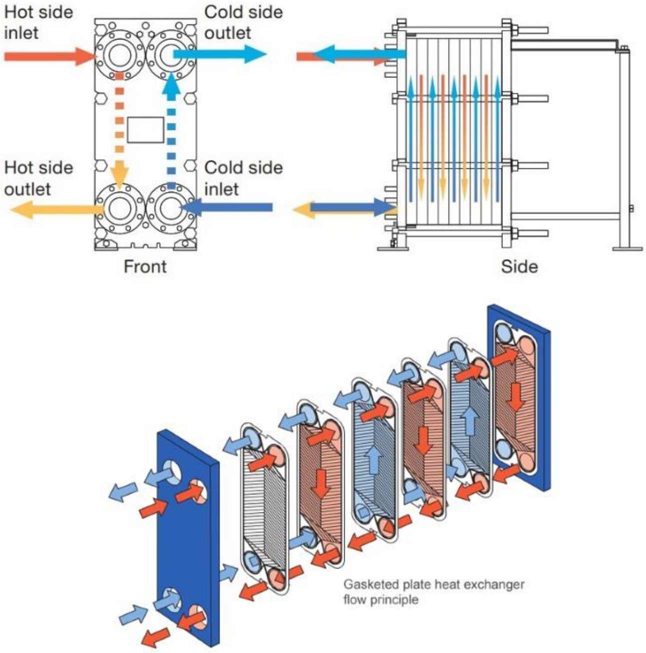
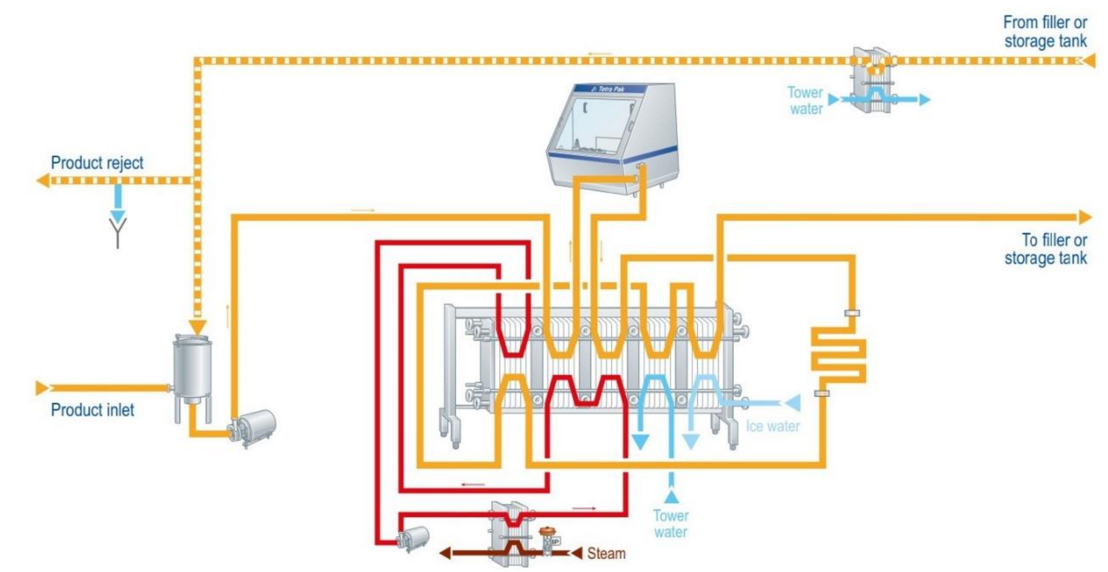


Figure 2-6 Gasketed Plate Heat Exchanger Flow Principle

As the fluids pass through the heat exchanger, heat is transferred from the hot media to the cold media. Counter current flow enables maximum heat recovery possibilities and very close temperature approach can be achieved. Temperature cross is also possible, meaning that the hot outlet can reach a lower temperature than the cold outlet. This can only be achieved to a limited extent with tubular heat exchangers making plate-and-frame heat exchangers more thermally efficient.

PHE-base Pasteurizer

Before production can start it is necessary to sterilize the aseptic area of the unit by circulating pressurized hot water. An internal sterilizing loop minimizes the energy consumption and start-up time. After sterilization, the unit is cooled down step by step as by using tower water or softener water and ice water (CHW) crossflow with product through plate heat exchanger to production temperature shown in figure 2-7. Finally, sterile water is circulated through the production unit.



Media	Design temperature	Design pressure	Consumption Pre-sterilization	Consumption Production	Consumption CIP
Steam	–	6 bar	1,065 kg/h *	762 kg/h	593 kg/h *
Instrument air	–	6 bar	50 Nl/min	50 Nl/min	200 Nl/min *
Potable water	15°C	3 bar	5,000 l/h *	600 l/h	11,290 l/h *
Ice water	2°C	3 bar	30,000 l/h **	30,000 l/h	–
Tower water	30°C	3 bar	–	30,000 l/h	–

* No or low consumption during circulation. ** During pre-sterilization above 100°C.

Figure 2-7 Plate Heat Exchanger based Pasturizer

Mixing Tank

In the mixing process, The temperature is the importance one of factor to mix the product with other substances. Cooling jacket is used to control the temperature in some desirable point for the perfect mixing of product. Chilled water flow through the cooling jacket and drain out to return line at the bottom of tank.

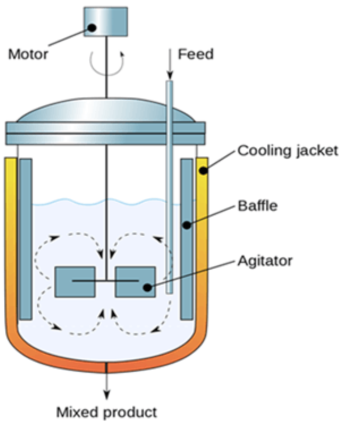


Figure 2-8 Basic Jacketed Mixing Tank

2.1.3.1.2 Source

The source is the point where heat is removed from (cooling) the system. Ideally, the amount of energy entering or leaving the source equals the amount entering or leaving through the load. Under steady-state conditions, the load energy and source energy are equal and opposite. For chilled water system, the source is water-cooled chiller.

2.1.3.1.3 Expansion Chamber

The expansion chamber (also called an expansion tank) serves both thermal function and a hydraulic function. In its thermal function the tank provides a space into which the noncompressible liquid can expand or from which it can contract as the liquid undergoes volumetric changes with changes in temperature. To allow for this expansion or contraction, the expansion tank provides an interface point between the system fluid and a compression gas. By definition, a closed system can have only one such interface; thus, a system designed to function as a closed system can have only one expansion chamber.

2.1.3.2 Hydraulic components

2.1.3.2.1 Expansion Chamber

As a hydraulic device, the expansion tank serves as the reference pressure point in the system. Where the tank connects to the piping, the pressure equals the pressure of the air in the tank plus or minus any fluid pressure due to the elevation difference between the tank liquid surface and the pipe

2.1.3.2.2 Pump

Pump is a device that moves fluids (liquids or gases), or sometimes slurries, by mechanical action, typically converted from electrical energy into Hydraulic energy. Pumps operate by some mechanism (typically reciprocating or rotary), and consume energy to perform mechanical work moving the fluid. Pumps operate via many energy sources, including manual operation, electricity, engines, or wind power, and come in many sizes, from microscopic for use in medical applications, to large industrial pumps. Pump operating characteristics must be carefully matched to system operating requirements.

2.1.3.2.3 Distribution system

The distribution system is the piping connecting the various other components of the system. The primary considerations in designing this system are the sizing the piping to handle the cooling capacity required and arranging the pipe to ensure flow in the quantities required at design conditions and at all other loads. For the design of distribution system is explained in a topic 2.2 Chilled Water Distribution System Design.

2.2 Chilled Water Distribution System Design

2.2.1 Variable flow chilled-water system

In variable-flow hydronic systems, reducing pump speed or staging of pumps with chillers to suit part load conditions is an energy efficient method of control. These systems were developed as an alternative to constant volume systems because of the potential pump energy savings to be derived by varying the flows to match the diversity on load requirements. There is also the additional benefit from reduced pipe heat losses due to low return water temperatures that two-way valve systems give on part load compared to the higher return temperatures with three-way valve control.

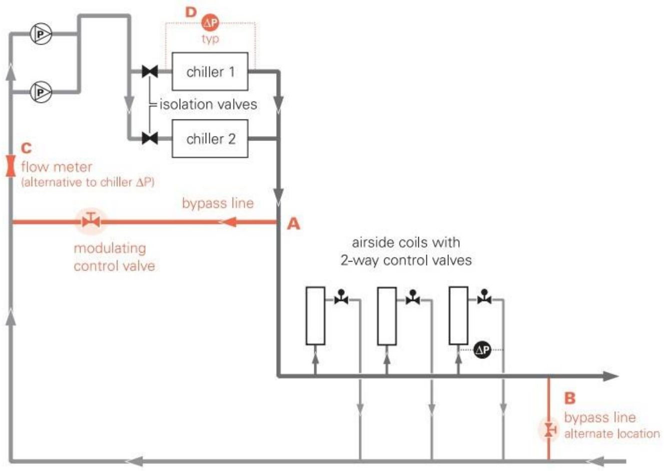


Figure 2-9 Variable Flow System

2.2.2 2-pipe system

The 2-pipe system is widely used for heating or cooling purposes, which carry chilled or hot water from a plant by the supply and return mains are separate pipes and water leaving the supply main goes into the return main. As water leaves the supply main and goes to the terminal unit, the quantity of water flowing in the main is reduced, so the pipe diameter can be reduced. The advantages of a 2-pipe system are the temperature entering each zone terminal will be the same in temperature because the return water from each terminal unit does not mix with the supply water in the supply main.

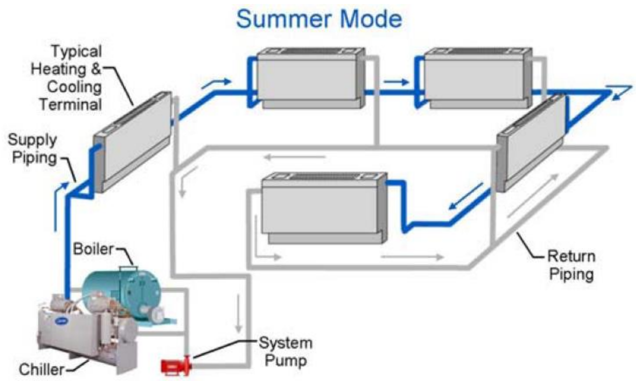


Figure 2-10 2-Pipe Reverse Return Distribution System

2.2.3 Constant Primary Flow/Variable Secondary Flow Chilled Water System

The constant primary flow and variable secondary flow chilled water system is one kind of system for water cooling application, which provides chilled water to collect and reject heat from air handling units, industrial processes, etc. The system consists of primary loop and secondary loop, which are production loop and consuming loop, respectively. The primary loop or chilled water production loop provides chilled water to collect heat from cooling loads in the system and reject the heat out by condenser.

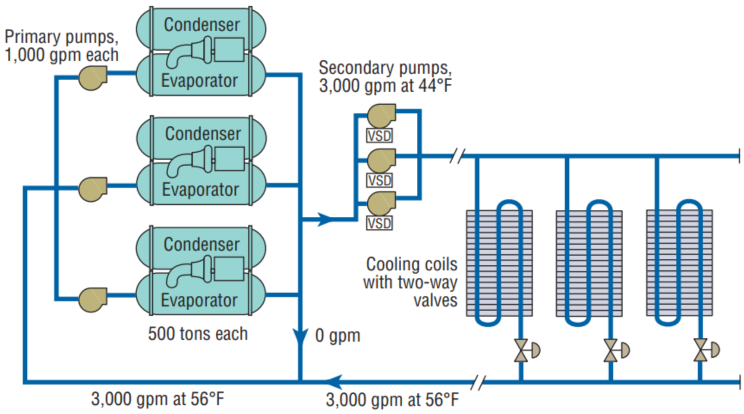


Figure 2-11 Constant Primary Flow/Variable Secondary Flow Chilled Water System

2.2.4 Direct Return

The direct return system allows piping to be run in the most direct path to optimize piping costs. From the figure 2-8, The first unit supplied is the first returned, which has the shortest water flow path of the system. In the otherwise, the last unit supplied is also the last return that will make the Unit-5 is the longest flow path of the system. So, the disadvantage is that the flow at each coil load unit usually needs to be balanced using a balancing valve because the circuit pressure drop of the system is varied as shown in the figure 2-12.

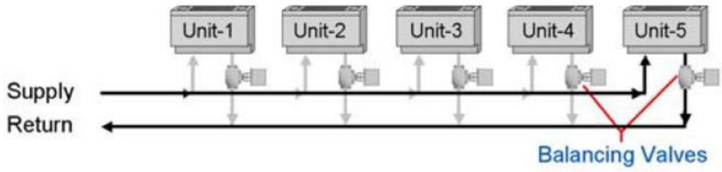


Figure 2-12 Direct Return Horizontal System Layout

- Water enter Unit-1 from supply
- Water leaves Unit-1 and returns directly to source
- The first unit supplied is the first returned
- Unequal circuit pressure drops result
- Circuit pressures drop through Unit-1 < Unit-2 < Unit-3 < Unit-4 < Unit-5
- Balancing valves are a necessity

2.3 Pipe Selection

2.3.1 Dimensional analysis of pipe flow

It is often necessary to determine the head loss that occurs in a pipe flow so that the energy equation can be used in the analysis of pipe flow problems. A typical pipe system usually consists of various lengths of straight pipe interspersed with various types of components (valves, elbows, etc.). The overall head loss for the pipe system consists of the head loss due to viscous effects in the straight pipes, termed the major loss (h_L,major) and the head loss in the various pipe components, termed the minor loss (h_L,minor). So, the total head loss can be determined by the following equation.

$$h_L = h_{L,major} + h_{L,minor}$$

In dimensional analysis, the external forces on the pipe from velocity, density, and pressure must take into account. To understand the creation of these forces, it is important to know the behavior detail of the flow. There are three kinds of fluid flow; laminar, turbulent, and transition flow; which have different characteristics.

2.3.1.1 Characteristic of the flow

2.3.1.1.1 Laminar flow

(Ghani R., 2017) When the flow rate in the pipe becomes slow, all the molecules travel parallel to the axes of the pipe. This kind of flow is called laminar flow. In the laminar flow, molecules near the wall move a bit slower as compared to molecules in the center. Due to this reason, flow becomes parabolic. Pipe internal roughness also affects the flow. Therefore, we can say rougher the pipe from inside, causes the friction and increases the pressure drop. The laminar flow is kind of critical to solve any problem in fluid dynamics.

When the fluid particles flow in the straight line parallel to pipeline wall with low velocities without any distance between the layers, this kind of flow is also known as streamline flow. Reynolds number helps us to recognize the type of flow. When the Reynolds number is less than 2300, the flow is considered as laminar so we can say that Reynolds number is used as parameter to determine the type of flow. The velocity profile of laminar flow is shown in figure 2-13

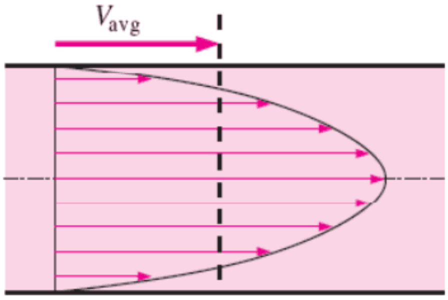


Figure 2-13 Velocity Profile of Laminar Flow in Pipe

2.3.1.1.2 Transition flow

Transition flow is the flow which is between laminar and turbulent flow. In the transitional flow Reynolds number is greater than 2300 but less than 4000. In that type of flow viscous and Reynolds stresses are equal, that is why it is called transitional flow.

2.3.1.1.3 Turbulent flow

Because of his fluctuation complexity, it is very difficult to find the exact theory regarding turbulent flow in pipes. To understand the phenomena of turbulent flow is important because it creates shear stresses on the wall of the pipes. The velocity profile of turbulent flow is shown figure 2-14

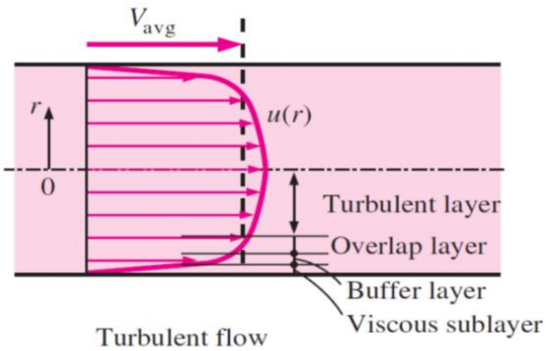


Figure 2-14 Velocity Profile of Turbulent Flow in Pipe

2.3.1.2 Major losses

White Frank M. (2010) Major losses, which are associated with frictional energy loss per length of pipe depends on the flow velocity, pipe length, pipe diameter, and a friction factor based on the roughness of the pipe, and whether the flow is laminar or turbulent (i.e. the Reynolds number of the flow). Although the head loss represents a loss of energy, it does not represent a loss of total energy of the fluid. The total energy of the fluid conserves as a consequence of the law of conservation of energy. In reality, the head loss due to friction results in an equivalent increase in the internal energy (increase in temperature) of the fluid. By observation, the major head loss is roughly proportional to the square of the flow rate in most engineering flows (fully developed, turbulent pipe flow).

In fluid dynamics, the Darcy–Weisbach equation is a phenomenological equation, which relates the major head loss, or pressure loss, due to fluid friction along a given length of pipe to the average velocity.

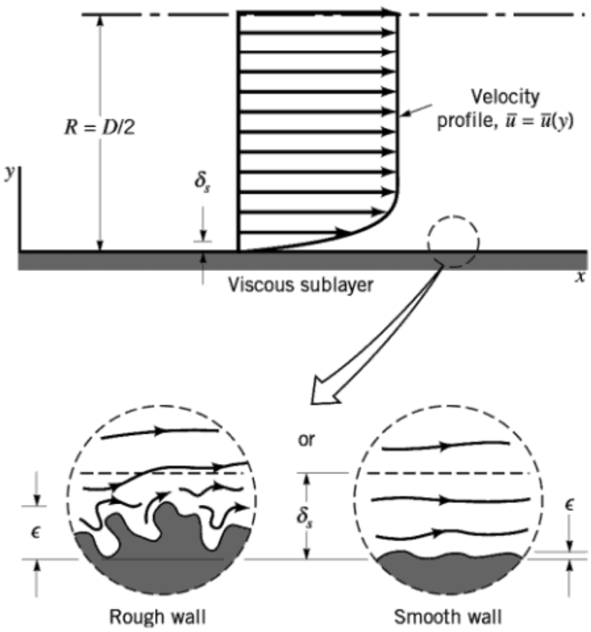


Figure 2-15 Flow in Viscous Sublayer near Rough and Smooth Walls

This equation is valid for fully developed, steady, incompressible single-phase flow. The Darcy–Weisbach equation can be written in two forms (pressure loss form or head loss form). In the head loss can be written as

$$\Delta h_f = f_D \frac{L}{D} \frac{V^2}{2g}$$

Where f_D is the Darcy friction factor that can be found in Appendix-1 Moody chart.

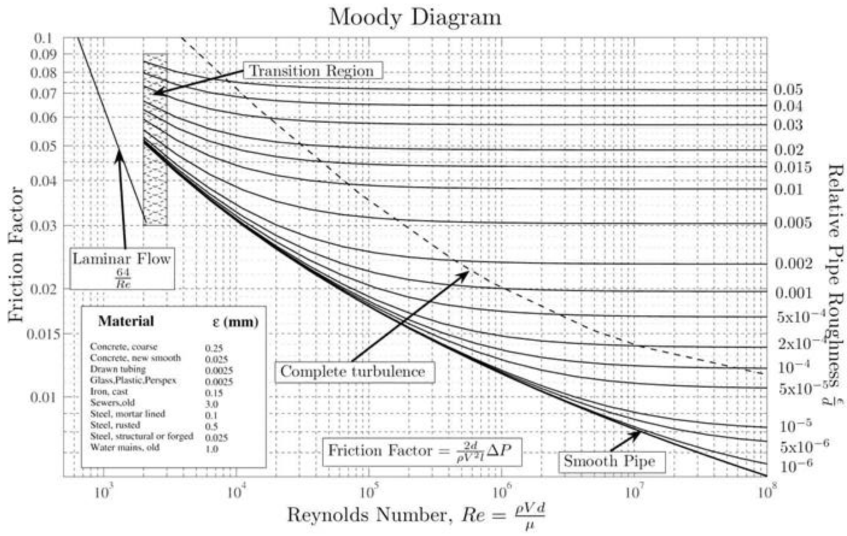


Figure 2-16 Moody Chart

Friction factor dependence on the Reynold number and the relative roughness. Typical roughness values for various pipe surfaces are given in Table 2-1.

<u>**Table 2.1 Equivalent Roughness of Pipes**</u>

	Equivalent Roughness, ε	
Pipe	**Feet**	**Millimeters**
Riveted steel	0.003–0.03	0.9–9.0
Concrete	0.001–0.01	0.3–3.0
Wood stave	0.0006–0.003	0.18–0.9
Cast iron	0.00085	0.26
Galvanized iron	0.0005	0.15
Commercial steel or wrought iron	0.00015	0.045
Drawn tubing	0.000005	0.0015
Plastic, glass	0.0 (smooth)	0.0 (smooth)

2.3.1.3 Minor losses

These additional components (valves, bends, tees, and the like) add to the overall head loss of the system. Such losses are generally termed minor losses, with the corresponding head loss denoted $h_{L,minor}$ (Munson, 2009)

$$h_L = K_L \frac{V^2}{2g}$$

Where K_L is loss coefficient. The actual value of K_L is strongly dependent on the geometry of the component and fluid property.

$$K_L = \phi(\text{Geometry, Reynold number})$$

Loss coefficient can occur at the entrance of pipe, the exit of the pipe and also flow through pipe components such as elbows, tees, and valves. And K_L can be found from Appendix-2 Loss coefficient (K_L) of Fittings and Valves

2.3.2 Stainless steel schedule 10 pipe

(Elin M. Westin, 2010) Stainless steels are alloyed with at least 12% chromium and become corrosion resistant by formation of a passive film on the surface. By varying the composition of the steel with chromium, nickel, molybdenum, nitrogen, etc., it is possible to achieve different properties suitable for various applications. Stainless steels may be divided into different groups on the basis of their microstructure. Of these austenitic, ferritic and ferritic-austenitic (duplex) are the most commonly used.

There are several grades of stainless steel and SUS 304 steel is one of the common uses including in this project. This grade of steel is Chromium-Nickel austenitic stainless steels. As a Chromium-Nickel carbon steel, it can be higher corrosion resistant austenitic stainless steel. This is the chemical composition of this grade.

- Maximum percentage of Carbon (C) is 0.08%
- Maximum percentage of Manganese (Mn) is 2%
- Maximum percentage of Phosphorous (P) is 0.045%
- Maximum percentage of Sulphur (S) is 0.03%
- Minimum percentage of Chromium (Cr) is 18% and a maximum of 20%
- Maximum percentage of Silicon (Si) is 1%

- Minimum percentage of Nickel (Ni) is 8% and a maximum of 10.5%

2.3.2.1 Stainless steel schedule 10 pipe characteristic

Dimension, weight, and pipe wall thickness of stainless-steel pipes Schedule10 can be determined by the following table.

<u>Table 2.2 Stainless Steel Pipe Schedule 10</u>

Nominal size [inches]	Outside diameter [inches]	Outside diameter [mm]	Wall thickness [inches]	Wall thickness [mm]	Weight [lb/ft]	Weight [kg/m]
1/2	0.840	21.3	0.083	2.11	0.68	1.00
3/4	1.050	26.7	0.083	2.11	0.87	1.29
1	1.315	33.4	0.109	2.77	1.41	2.11
1 1/4	1.660	42.2	0.109	2.77	1.82	2.71
1 1/2	1.900	48.3	0.109	2.77	2.1	3.13
2	2.375	60.3	0.109	2.77	2.66	3.96
2 1/2	2.875	73.0	0.120	3.05	3.56	5.29
3	3.500	88.9	0.120	3.05	4.37	6.50
3 1/2	4.000	101.6	0.120	3.05	5.01	7.46
4	4.500	114.3	0.120	3.05	5.66	8.42
5	5.563	141.3	0.134	3.40	7.82	11.64
6	6.625	168.3	0.134	3.40	9.35	13.91
8	8.625	219.1	0.148	3.76	13.50	20.10
10	10.750	273.1	0.165	4.19	18.79	27.96
12	12.750	323.9	0.180	4.57	24.34	36.22
14	14.000	355.6	0.188	4.78	27.97	41.62
16	16.000	406.4	0.188	4.78	32.02	47.65
18	18.000	457.0	0.188	4.78	36.05	53.65
20	20.000	508.0	0.218	5.54	46.42	69.09
22	22.000	559.0	0.218	5.54	51.14	76.10
24	24.000	610.0	0.250	6.35	63.93	95.13
30	30.000	762.0	0.312	7.92	99.60	148.22

Pipe friction chart is one of the basic tools to determine friction loss of the specific pipe at different diameter and flow rate. There is no published information for schedule 10 steel pipe. But schedule 40 steel pipe chart can be used instead because the only difference is wall thickness. So we can use Appendix-3 Pipe friction chart of SCH 40 pipe

The allowable working pressure is the pipe characteristic that needs to be considered as piping selection criteria. The values vary with different temperature as shown in the table in Appendix-4 Allowable working pressure at temperature.

2.3.3 ASHRAE 90.1 Standard

The ASHRAE Standard 90.1 is published by the American Society of Heating, Refrigerating and Air-Conditioning Engineer.

The information about the creation of this table is mentioned in the article of the ASHRAE journal of October 2008 "Sizing Pipe Using Life-Cycle Costs" by Steven T. Taylor, P.E., Fellow ASHRAE; and Molly McGuire, P.E., Member ASHRAE. In it you can see the details of how they developed this table. To summarize, the authors used their specialized spreadsheet to determine the flowrate limits with best 'life-cycle cost'.

2.3.3.1 Purpose

ASHRAE Standard 90.1 provides minimum requirements for the energy-efficient design of buildings and building systems except the low-rise residential building. The standard is created and intended to be the basis of enforceable code for government agencies.

This standard has also been discussed in the united states congress, The Energy Policy and Conservation Act of 2005 and it also requires state and local governments to base their commercial building energy efficiency codes to be at least as strict as ASHRAE Standard 90.1.

2.3.3.2 Application

Although the standard is concerned mostly about the water-chiller system for the air conditioning aspect in buildings, it should be possible to use it as a guideline to design the chiller system for manufacturing processes application. That is, because the operations of water chillers are similar and the operating hours at the plant are accounted for in our pipe sizing table in the standard.

2.3.3.3 Limitation

Although ASHRAE 90.1 can be used as a guideline to create/make the buildings operate efficiently, it may not consider another aspect of the design. For example, it has been noted explicitly in the cold water insulation table 6.8.3B of the ASHRAE 90.1 that the table acts as only the guideline for creating the energy efficient system but it doesn't account for another aspect such as water vapor permeability.

Likewise, ASHRAE 90.1 standard for pipe sizing (TABLE 6.5.4.5) mostly just concerns energy conservation economics. It doesn't consider about noise requirement, water hammering in the pipes.

2.3.3.4 Other Limitation for Certain types of building

The standard is not supposed to be used on the 'low-rise residential building'. According to the ASHRAE 90.1 standard, Low-rise residential buildings are defined as single-family houses, multi-family structures of three stories or fewer above grade.

2.3.3.5 ASHRAE 90.1 standard for pipe sizing

Pipe diameter affects head loss in the system which consequently affects the energy use in pumps. The bigger pipe size may reduce head loss significantly, however the extra material cost of the bigger design also rises which may make it economically infeasible.

The pipe sizing guideline according to ASHRAE 90.1 standard is based on the energy conservation aspect. As for acoustics and water hammering issues, the larger pipe may be considered to decrease the velocity of fluid inside.

Based on the TABLE 6.5.4.5 (Piping System Design Maximum Flow Rate of ASHRAE 90.1) standard, the pipe size is selected per the requirement. (operating hours per year, variability of the flowrate and speed).

In the table, we got the inputs which are operating hours (in our case is we will use 7200 hours ,assuming that the factory operates every week with only holiday being Sunday) .And for the nature of the flow, it could be stationary or variable (for our flow, it should be variable since production line is dynamics).

<u>Table 2.3 Piping System Design Maximum Flow Rate in GPM</u>

Operating Hours/Year	≤2000 Hours/Year		>2000 and ≤ 4400 Hours/Year		>4400 Hours/Year	
Nominal Pipe Size, in.	**Other**	**Variable Flow/ Variable Speed**	**Other**	**Variable Flow/ Variable Speed**	**Other**	**Variable Flow/ Variable Speed**
2 1/2	120	180	85	130	68	110
3	180	270	140	210	110	170
4	350	530	260	400	210	320
5	410	620	310	470	250	370
6	740	1100	570	860	440	680
8	1200	1800	900	1400	700	1100
10	1800	2700	1300	2000	1000	1600
12	2500	3800	1900	2900	1500	2300
Maximum Velocity for Pipes over 12 in. Size	8.5 fps	13.0 fps	6.5 fps	9.5 fps	5.0 fps	7.5 fps

2.4 Pump Characteristic

2.4.1 Pump Curve

The pump curve shows the relationship between H (differential head) and Q (volumetric flow rate) as well as brake horsepower (power required from motor to drive a pump). The graph is used to adjust the operating point of the pump. NPSH (Net positive suction head) indicates the minimum inlet pressure required to prevent cavitation. The point where the pump operates with the best efficiency is called BEP (best efficient point), which is the optimum point at a given impeller diameter.

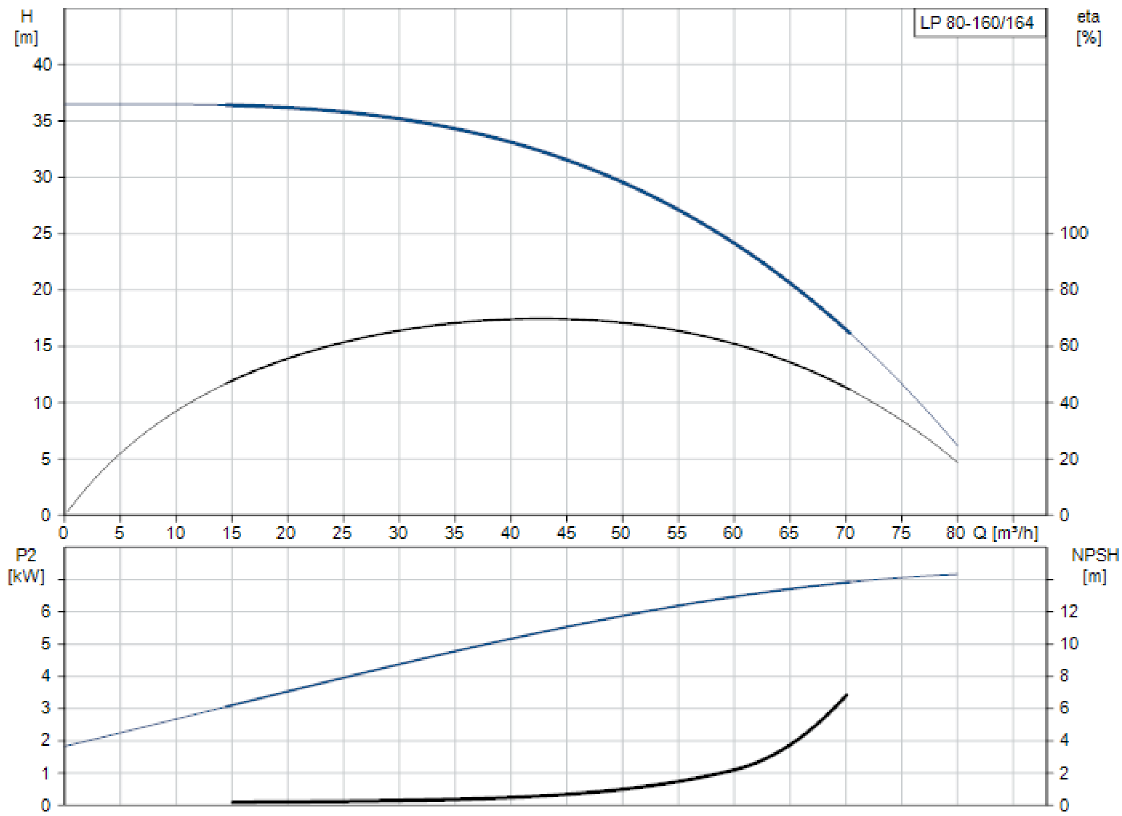


Figure 2-17 Grundfos LP 80-160/164 that uses in SABROE chiller system

2.4.2 System Curve

The system characteristic curve represents the relationship between the system head and the flow rate. It is often parabola-shaped and does not generally pass through the origin of the H/Q coordinate system. The curve becomes progressively steeper as throttling increases. Figure 2.4.x shows the system characteristic curve intersect with the pump performance curve that gives an operating point, which is the operating point of the pump.

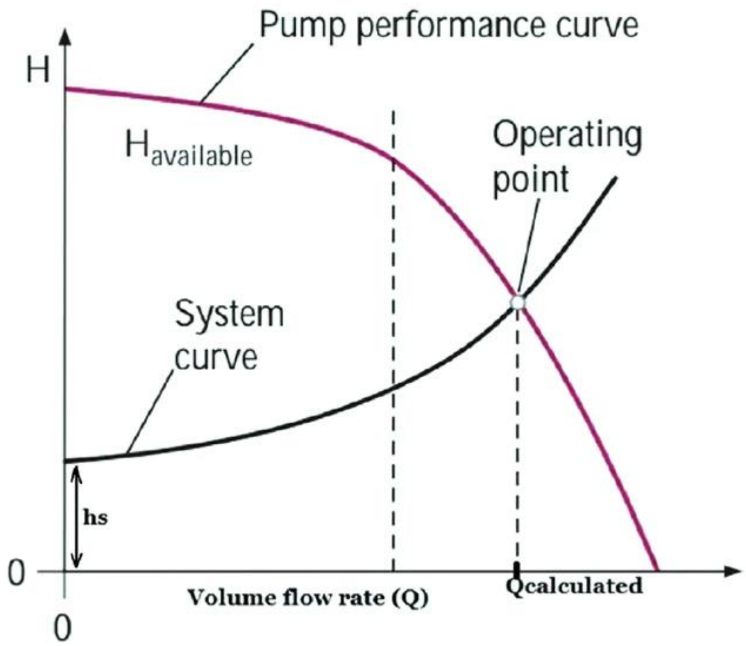


Figure 2-18 System curve versus pump performance curve give an operating point

2.5 EPANET 2.2

EPANET is the public domain computer program designed by the United States government's agency 'Environmental Protection Agency (EPA)'.

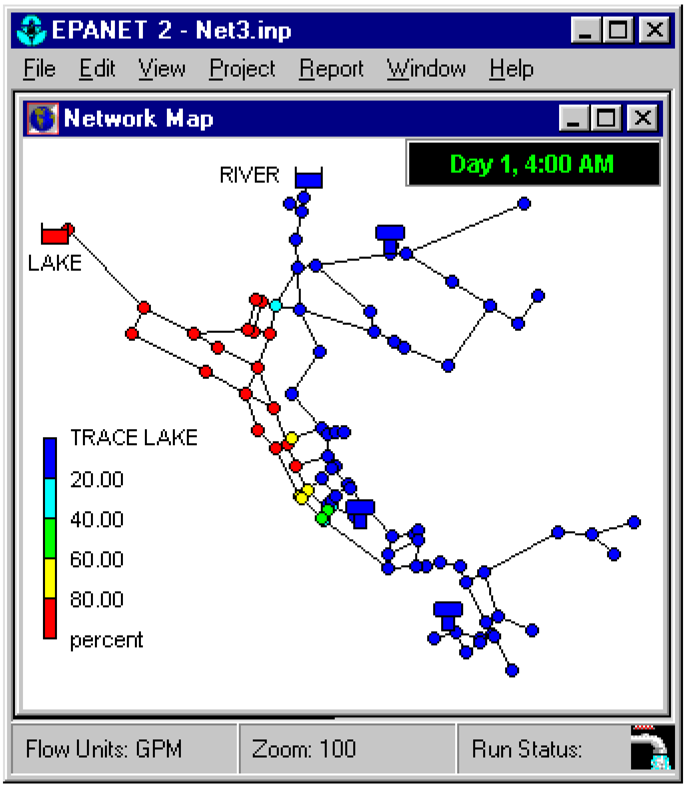


Figure 2-19 EPANET software's window

Figure 2-20 EPA logo

2.5.1 Calculation principle

Consider a pipe network with N junction nodes and NF fixed grade nodes (tanks and reservoirs). Let q_{ij} be the flow in the pipe connecting nodes i and j which is positive if water flows from i to j and negative if it flows in the opposite direction. The relation between the frictional head loss and the flow in the pipe can be expressed as

$$h_{Lij} = r\, q_{ij}\, |q_{ij}|^{n-1} + m\, q_{ij}\, |q_{ij}| \quad (1.1)$$

where h_{Lij} is head loss, r is a resistance coefficient, n is a flow exponent, and m is a minor loss coefficient. The value of the resistance coefficient will depend on which friction head loss formula is being used (see table in topic 2.5.2).

For a pump between nodes i and j, the head loss (negative of the head gain) can be represented by a power law of the form

$$h_{Lij} = -\omega^2 \left(\mathrm{h_0} - \mathrm{r}\, (q_{\mathrm{ij}}/\omega)^{\mathrm{n}} \right) \quad (1.2)$$

where h_0 is the shutoff head for the pump, ω is a relative speed setting, r and n are the pump curve coefficients, and q_{ij} is required to be positive.

Conservation of energy across a link between nodes i and j requires that

$$h_{\mathrm{i}} - h_{\mathrm{j}} = h_{L\mathrm{ij}}(q_{ij}) \quad (1.3)$$

where h_i and h_j are the hydraulic heads at each node, respectively.

Conservation of mass at a node i requires that total inflow equal total outflow:

$$_{\mathrm{j}}q_{\mathrm{ij}} - D_{\mathrm{i}} = 0 \quad (1.4)$$

where the summation is made over all nodes j connected to node i, and by convention flow into a node is positive.

D_i as a known demand flow required to be delivered at node i. For a set of known heads at the fixed grade nodes, a solution is sought for the head h at each node and the flow q in each link that satisfy Equations (1.3) and (1.4).

EPANET uses Todini's Global Gradient Algorithm (GGA) (Todini and Pilati, 1988) to solve this system of equations. The GGA uses a linearization of the conservation equations within an iterative Newton-Raphson scheme that results in a two-step solution procedure at each iteration. The first step solves a ($N \times N$) sparse system of linear equations for nodal heads while the second step applies a scaler updating formula to each link to compute its new flow. Todini and Rossman (2013) provide a full derivation of the GGA and discuss the advantages it has over other network solution methods.

2.5.2 Hydraulic option

Head loss formula options are three equations which are Darcy-Weisbach, Hazen-Williams and Chezy-Manning equation.

Formula	*Resistance Coefficient* (A)	*Flow Exponent* (B)
Hazen-Williams	$4.727\, C^{-1.852}\, d^{-4.871}\, L$	1.852
Darcy-Weisbach	$0.0252\, f(\epsilon, d, q)\, d^{-5}\, L$	2
Chezy-Manning	$4.66\, n^2\, d^{-5.33}\, L$	2

Notes:

C = Hazen-Williams roughness coefficient
ϵ = Darcy-Weisbach roughness coefficient (ft)
f = friction factor (dependent on ϵ, d, and q)
n = Manning roughness coefficient
d = pipe diameter (ft)
L = pipe length (ft)
q = flow rate (cfs)

Demand driven analysis (DDA), or pressure driven analysis (PDA)

In DDA mode, demand must be met even if it means that the result pressure is below zero.

In PDA mode, nodes with demands may get less water than based demand specified, but the pressure always stays positive.

Minimum Pressure

(For PDA analysis only): minimum pressure: below this pressure, no demand can be supplied at all at the node with demand.

Required pressure

(For PDA analysis only): required pressure at nodes with demand where the full demand is supplied.

2.5.3 Object properties

Junctions

Junctions are points in the network where links join together and where water enters or leaves the network. The basic input data required for junctions are:

- elevation above some reference (usually mean sea level)
- water demand (rate of withdrawal from the network)
- initial water quality

Tanks

Tanks are nodes with storage capacity, where the volume of stored water can vary with time during a simulation. The primary input properties for tanks are:

- bottom elevation (where water level is zero)
- diameter (or shape if non-cylindrical)
- initial, minimum and maximum water levels
- initial water quality.

Pipes

Pipes are links that convey water from one point in the network to another. EPANET assumes that all pipes are full at all times. Flow direction is from the end at higher hydraulic head (internal energy per weight of water) to that at lower head. The principal hydraulic input parameters for pipes are:

- start and end nodes
- diameter
- length
- roughness coefficient (for determining head loss)
- status (open, closed, or contains a check valve).

Pumps

Pumps are links that impart energy to a fluid thereby raising its hydraulic head. The principal input parameters for a pump are its start and end nodes and its pump curve (the combination of heads and flows that the pump can produce).

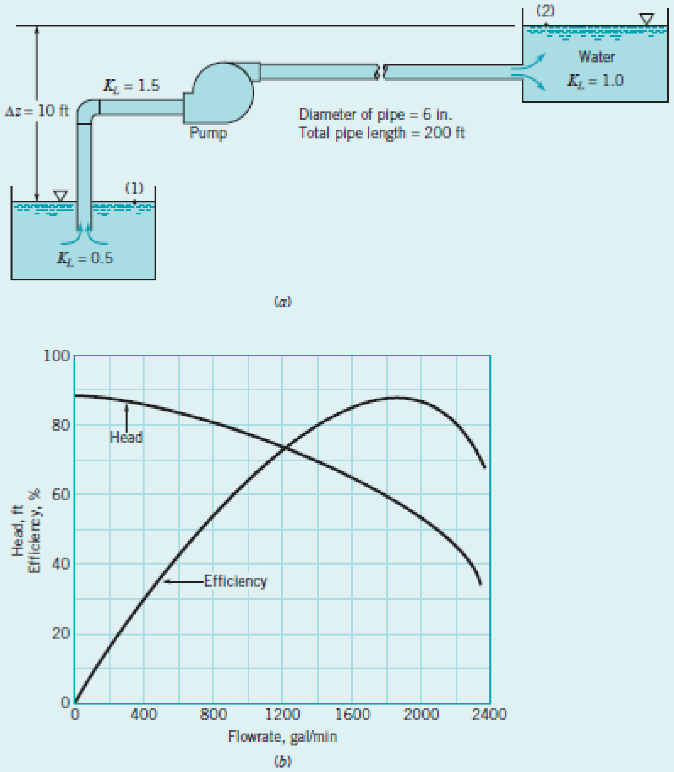
2.5.4 Test Example on EPANET

In this example we are going to demonstrate the system containing pipes, pumps, and water tanks. We will use the example from the chapter 12.4 of *Munson, Bruce R., Young, Donald F., Okiishi, Theodore H., Huebsch, Wade W. "Fundamentals of Fluid Mechanics, Sixth Edition"".*

EXAMPLE 12.4 Use of Pump Performance Curves

GIVEN Water is to be pumped from one large, open tank to a second large, open tank as shown in Fig. E12.4*a*. The pipe diameter throughout is 6 in. and the total length of the pipe between the pipe entrance and exit is 200 ft. Minor loss coefficients for the entrance, exit, and the elbow are shown, and the friction factor for the pipe can be assumed constant and equal to 0.02. A certain centrifugal pump having the performance characteristics shown in Fig. E12.4*b* is suggested as a good pump for this flow system.

FIND With this pump, what would be the flowrate between the tanks? Do you think this pump would be a good choice?

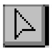


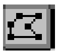
■ FIGURE E12.4a, b

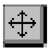
2.5.4.1 Map Toolbar

The Map Toolber contains buttons of working with the Network Map.

 Selects an object on the map (Edit >> Select Object)

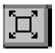
 Selects link vertex points (Edit >> Select Vertex)

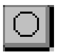
 Selects a region on the map (Edit >> Select Region)

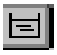
 Pans across the map (View >> Pan)

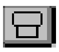
 Zooms in on the map (View >> Zoom In)

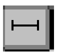
 Zooms out on the map (View >> Zoom Out)

 Draws map at full extent (View >> Zoom out)

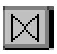
 Adds a junction to the map

 Adds reservoir to the map

 Adds a tank to the map

 Adds a pipe to the map

 Adds a pump to the map

 Adds a valve to the map

Adds a label to the map

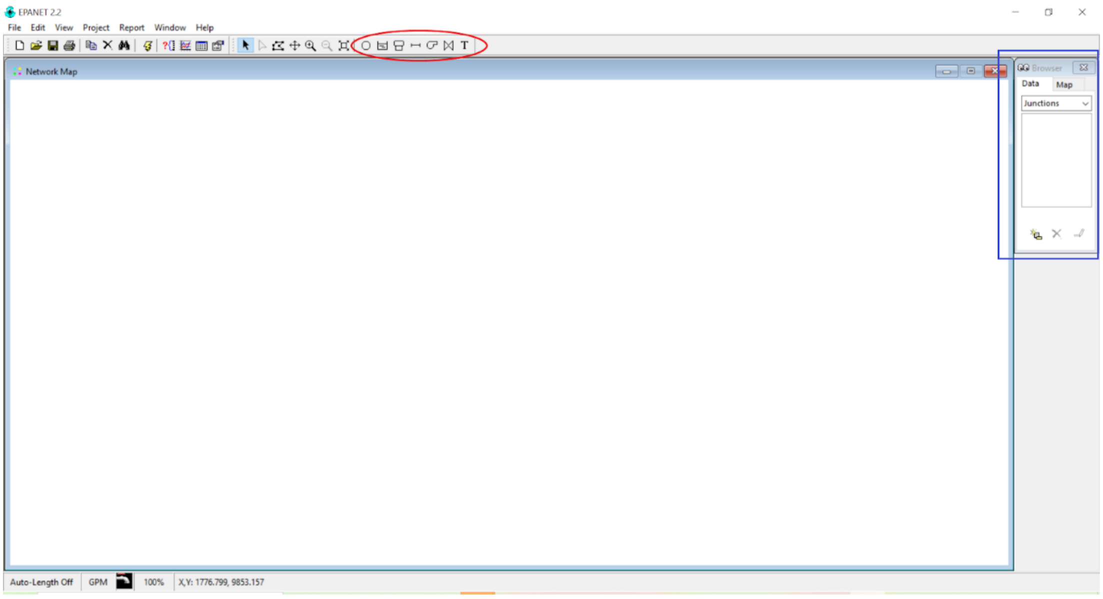
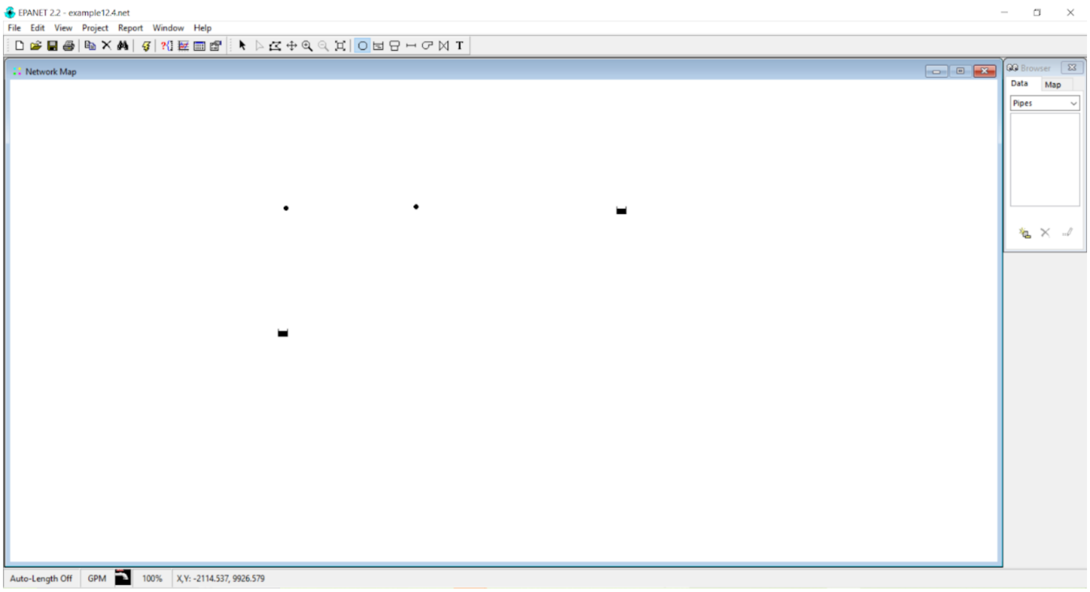


Figure 2-21 EPANET 2.2 Window

The user may choose the objects preferred from the toolbox in the red circle and visualize the existing objects in the window in the right in the blue square.

2.5.4.2 Step of system modeling on EPANET

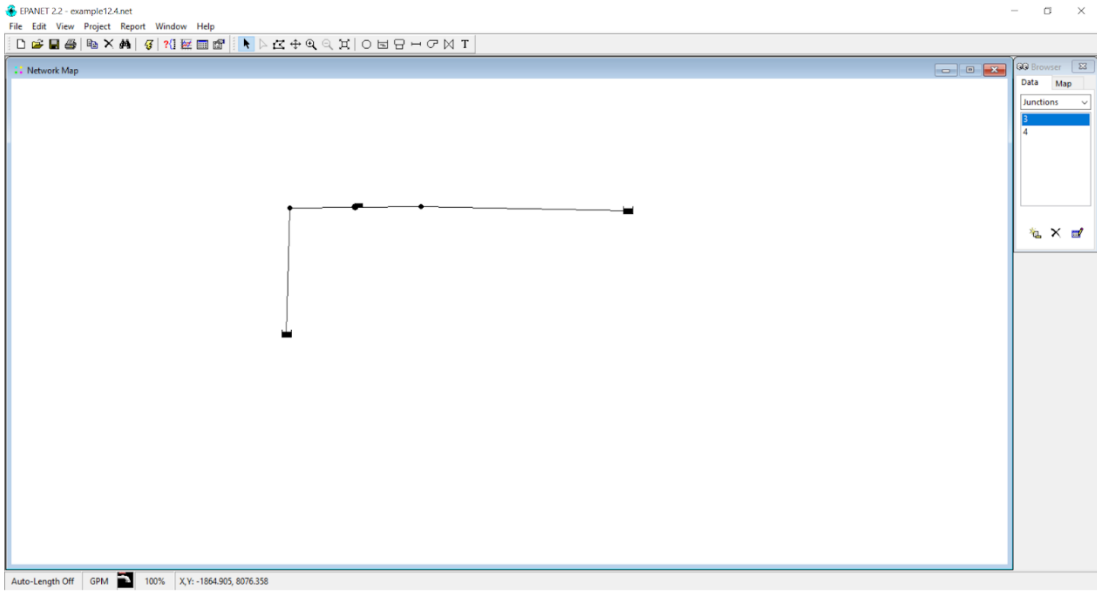
Step 1: Create 2 junctions and 2 tanks.



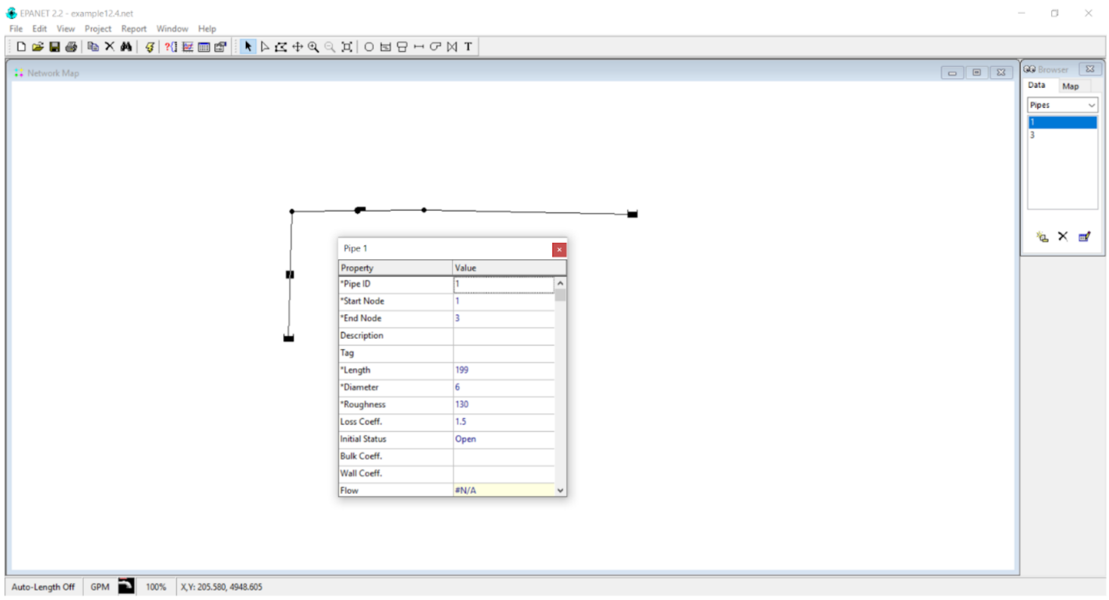
Step 2: Connect them with pipes. And a pump.

Note I: that the pump must be place with the right direction.

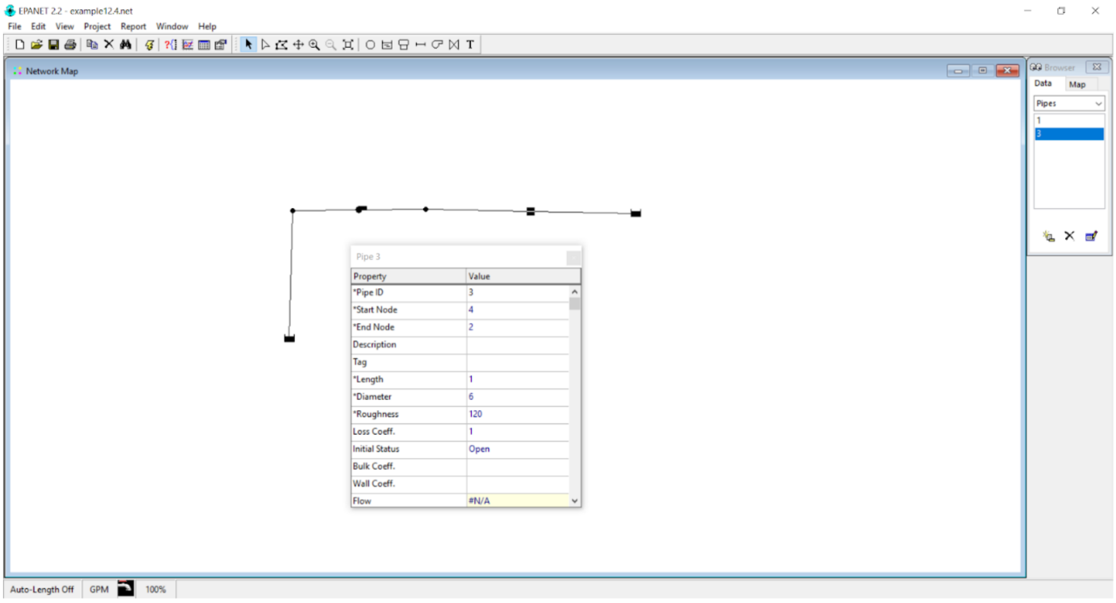
Note II: the length of pipes shown in this window does not necessarily reflect the real length of the system.



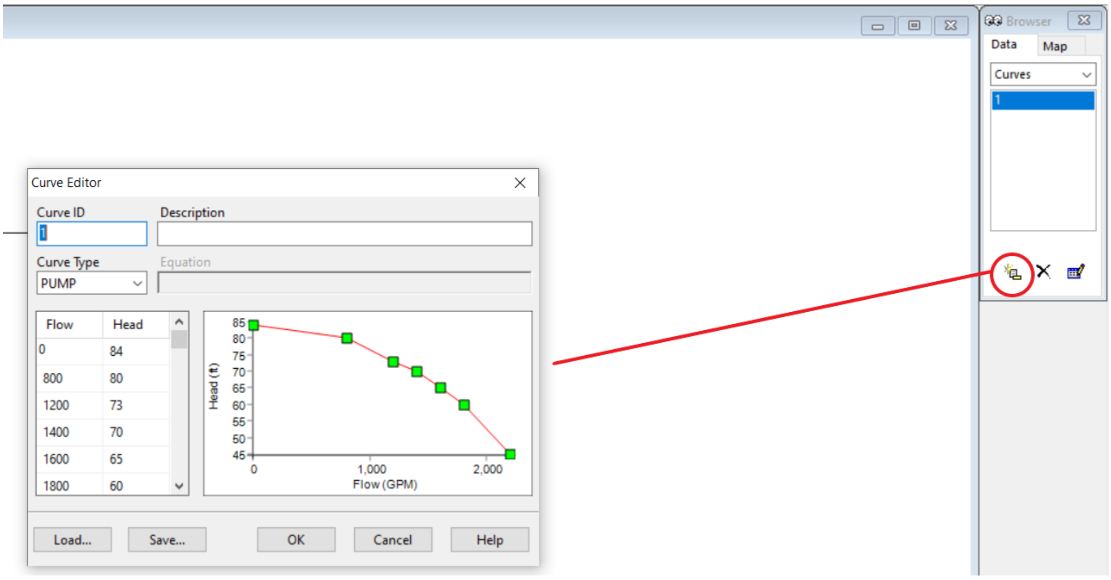
Step 3: We input parameters of the pipe connecting to the lower tank.

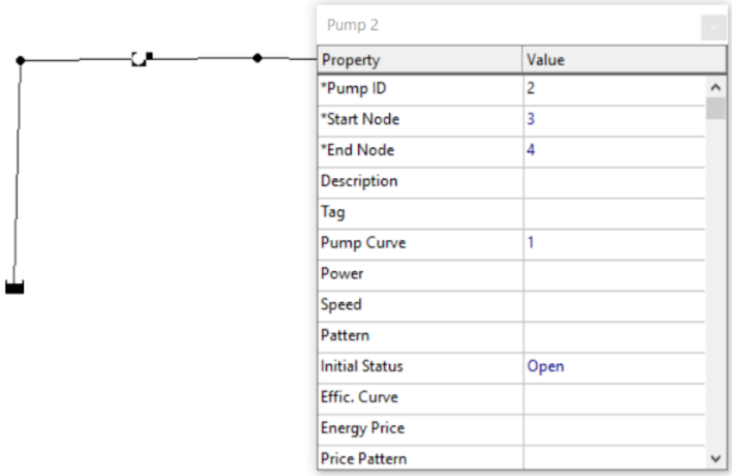


Step 4: We input parameters of the pipe connecting to the upper tank.

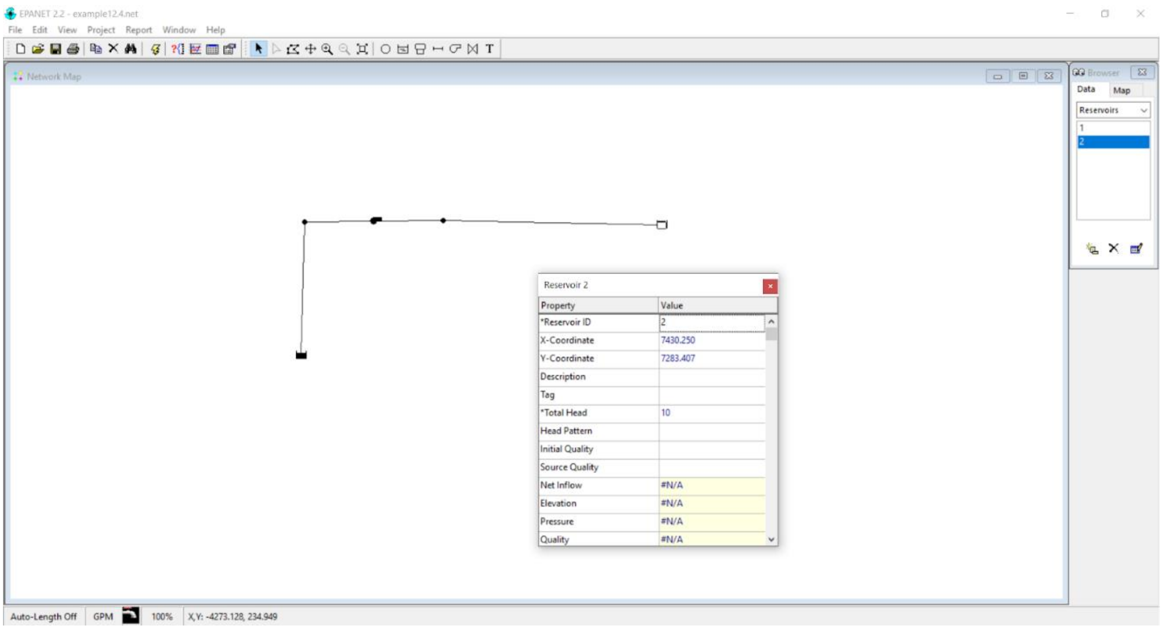


Step 5: Create the pump curve and input the properties of the pump.

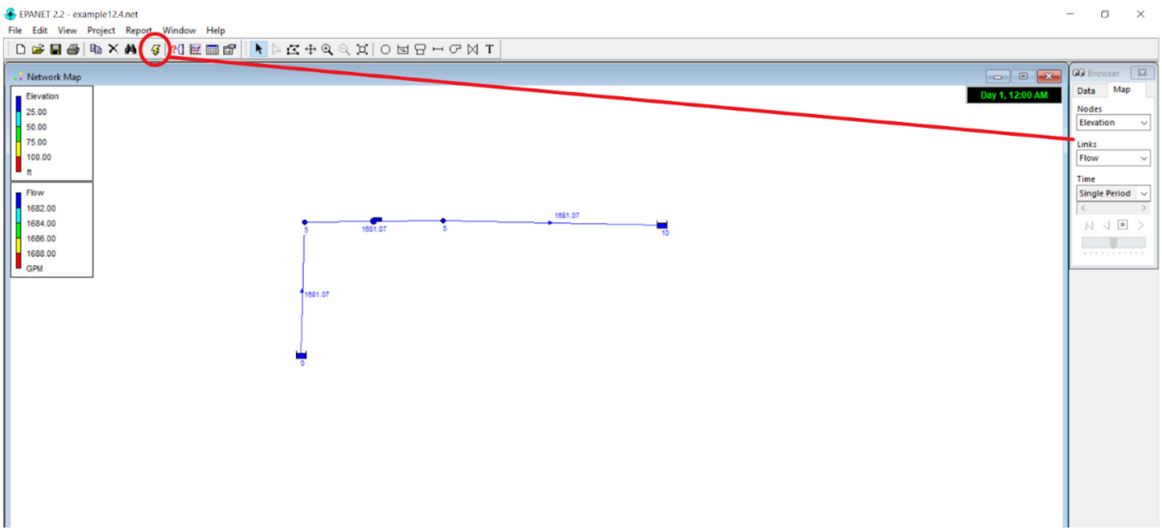


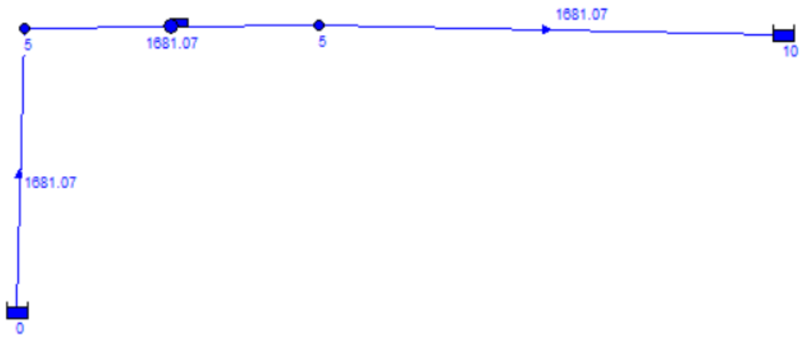


Step 6: Input the height of the second tank into the box.



Step 7: after running the program, we obtain the gpm of the pipe.





SOLUTION

Application of the energy equation between the two free surfaces, points (1) and (2) as indicated, gives

$$\frac{p_1}{\gamma} + \frac{V_1^2}{2g} + z_1 + h_a = \frac{p_2}{\gamma} + \frac{V_2^2}{2g} + z_2 + f\frac{\ell}{D}\frac{V^2}{2g} + \sum K_L \frac{V^2}{2g} \quad (1)$$

Thus, with $p_1 = p_2 = 0$, $V_1 = V_2 = 0$, $\Delta z = z_2 - z_1 = 10$ ft, $f = 0.02$, $D = 6/12$ ft, and $\ell = 200$ ft, Eq. 1 becomes

$$h_a = 10 + \left[0.02\frac{(200 \text{ ft})}{(6/12 \text{ ft})} + (0.5 + 1.5 + 1.0)\right]\frac{V^2}{2(32.2 \text{ ft/s}^2)} \quad (2)$$

where the given minor loss coefficients have been used. Since

$$V = \frac{Q}{A} = \frac{Q(\text{ft}^3/\text{s})}{(\pi/4)(6/12 \text{ ft})^2}$$

Eq. 2 can be expressed as

$$h_a = 10 + 4.43\, Q^2 \quad (3)$$

where Q is in ft^3/s, or with Q in gallons per minute

$$h_a = 10 + 2.20 \times 10^{-5} Q^2 \quad (4)$$

Equation 3 or 4 represents the system equation for this particular flow system and reveals how much actual head the fluid will need to gain from the pump to maintain a certain flowrate. Performance data shown in Fig. E12.4*b* indicate the actual head the fluid will gain from this particular pump when it operates at a certain flowrate. Thus, when Eq. 4 is plotted on the same graph with performance data, the intersection of the two curves represents the operating point for the pump and the system. This combination is shown in Fig. E12.4*c* with the intersection (as obtained graphically) occurring at

$$Q = 1600 \text{ gal/min} \quad \textbf{(Ans)}$$

with the corresponding actual head gained equal to 66.5 ft.

Another concern is whether the pump is operating efficiently at the operating point. As can be seen from Fig. E12.4*c*, although this is not peak efficiency, which is about 86%, it is close (about 84%). Thus, this pump would be a satisfactory choice, assuming the 1600 gal/min flowrate is at or near the desired flowrate.

We got a quite accurate result compared to the exact hand calculation.

The percentage error: (|1681.07 gpm-1600 gpm|/1600 gpm) * 100 = 5.067 %

Chapter 3. Data Collecting

3.1 Planning and Categorizing the group of pipes

3.1.1 Survey

At Ampol Food processing ltd., The production lines have many systems combined and work together such as steam boiler, softener water, cold water and chilled water. These systems have their own pipelines and they all overlapped. This is a cause of difficulty to indicate our interest pipeline which is the chilled water distribution system. After we can separate the chilled water pipeline from others, we found that there are many branch lines from main supply pipes and look very complex to clearly understand and memorize so that we considered to separate branch lines by coloring those pipes from CAD file.

3.1.2 Categorizing the groups of pipes

To make the plant's pipeline diagram easier to understand, we classify water pipes into 'lines' then we marked them differently from each other by using different color, and also each of them contains supply and return lines. These lines are:

Red line

The red line is composed of the 4” main pipes of the entire system which is connected to the supply part equipment which are Chillers Sabroe, Mycom1. The main line(red) is connected to the northern branch lines: yellow, blue, green and pink; and the western line which is solely orange. The western line is also tapped to supply the various equipment: 4 mixing tanks, Herring Plus Plate heat exchanger, Old squeezing Plate heat exchanger, Chill coconut juice Plate heat exchanger, and the new Almix.

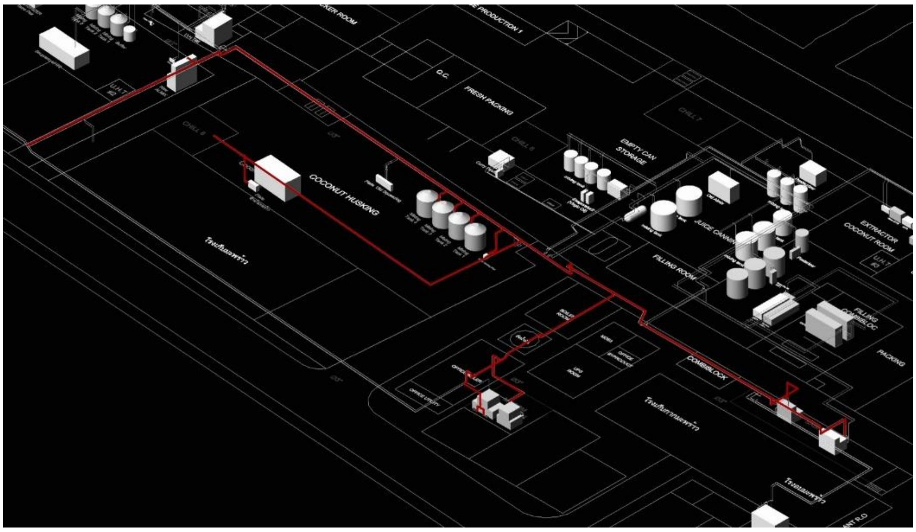


Figure 3-1 Isometric view of Red pipe

Figure 3-2 Top view of Red pipe

Purple line

The purple color represents the pipe with the diameter of 3”. The pipe can be seen at the outside of the factory heading along the wall of the building, and the function of it is to supply the chilled water from Mycom2 to the western pipe (orange).

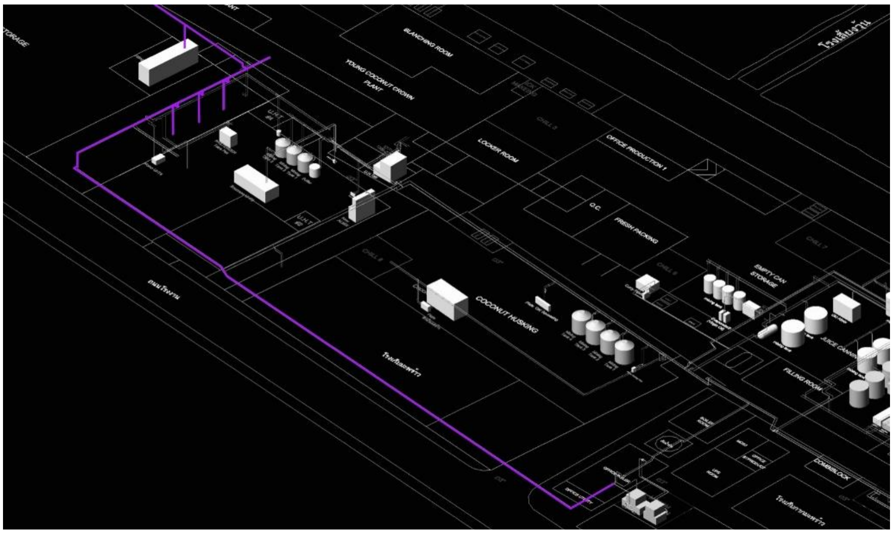


Figure 3-3 Isometric view of Purple pipe

Figure 3-4 Top view of Purple pipe

Yellow line

The pipes painted with the yellow color have diameter of 2.5”. The pipe is the branch of the red main line, heading through the wall of the northern building (Juice canning zone). The devices which are connected to the yellow lines are 8 mixers, TetraPak Plate, and Almix.

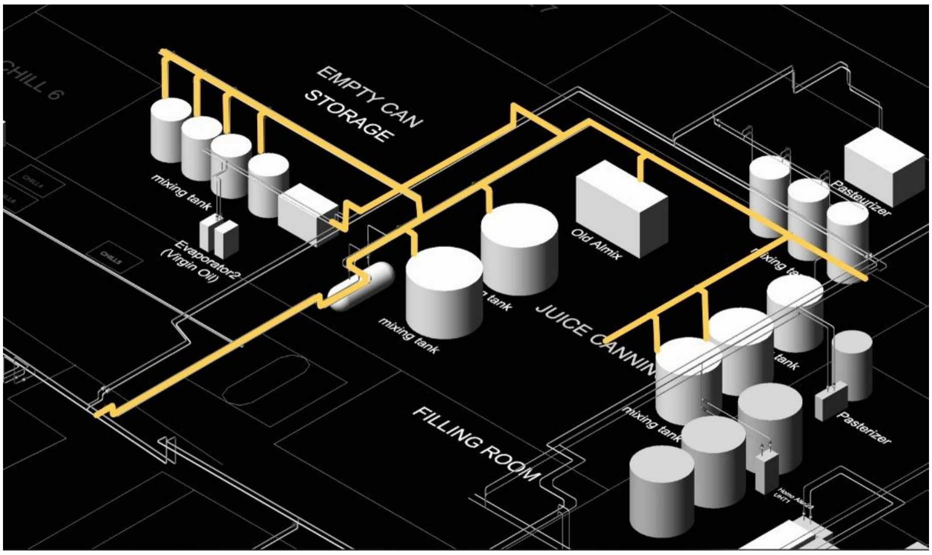


Figure 3-5 Isometric view of Yellow pipe

Figure 3-6 Top view of Yellow pipe

<u>Blue line</u>

The pipes represented by blue color have diameter of 2.5 inches. The pipes connect to and supply water to the pasteurizer and 3 mixers of the new juice extraction zone in the Juice canning room.

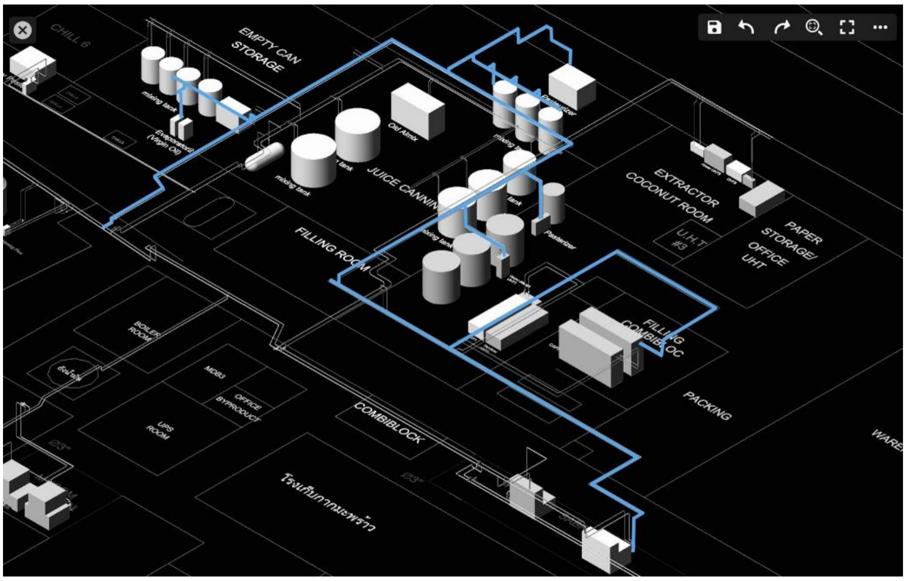


Figure 3-7 Isometric view of Blue pipe

Figure 3-8 Top view of Blue pipe

Green line

The pipes painted with the green color are those with diameter of 2.5”. They are the branch that connected with the main line (red). On another side of the pipes, they travel through the northern building’s wall to supply water to UHT3 and Homogenous UHT3 in the UHT3 room as well as the UHT1 in the UHT1 room.

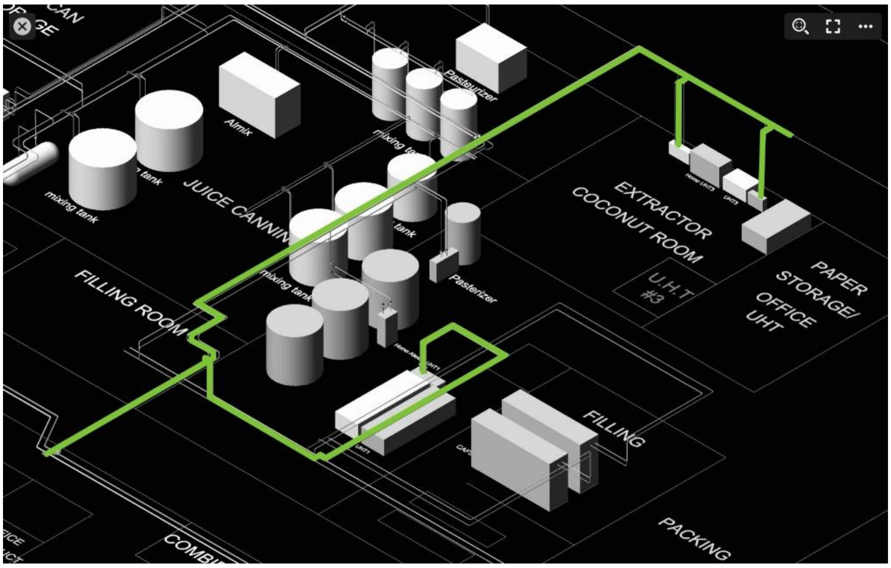


Figure 3-9 Isometric view of Green pipe


Figure 3-10 Top view of Green pipe

Pink line

The pipes marked with pink color have diameter of 0.5”, it supplies water from the Sabroe device into CAF505 in the filling Combibloc room

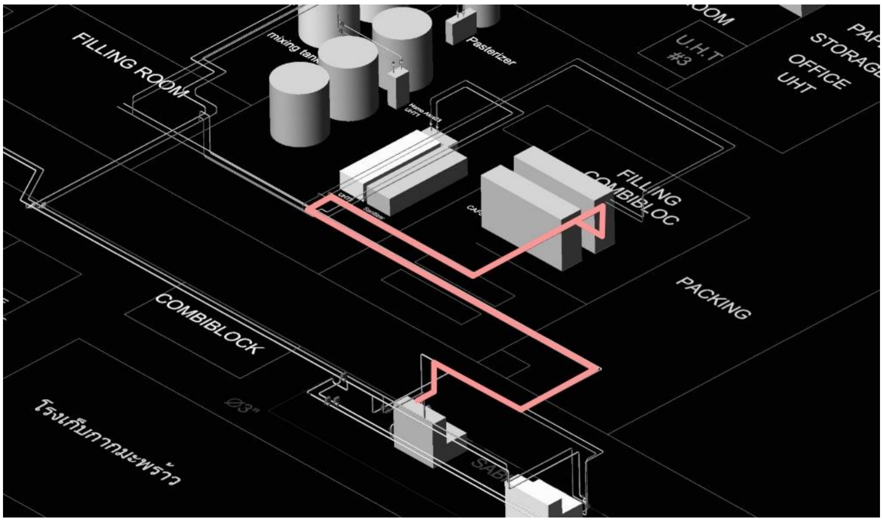


Figure 3-11 Isometric view of Pink pipe

Figure 3-12 Top view of Pink pipe

Orange line

The pipes colored by orange have diameter of 2.5” the pipes are connected from 2 set of pipes (red and purple) which supply water to UHT5, including other machine in UHT2 room which are Plate Alfa Laval CB110, Plate Past UHT2, Pasteurizer TetraPak.

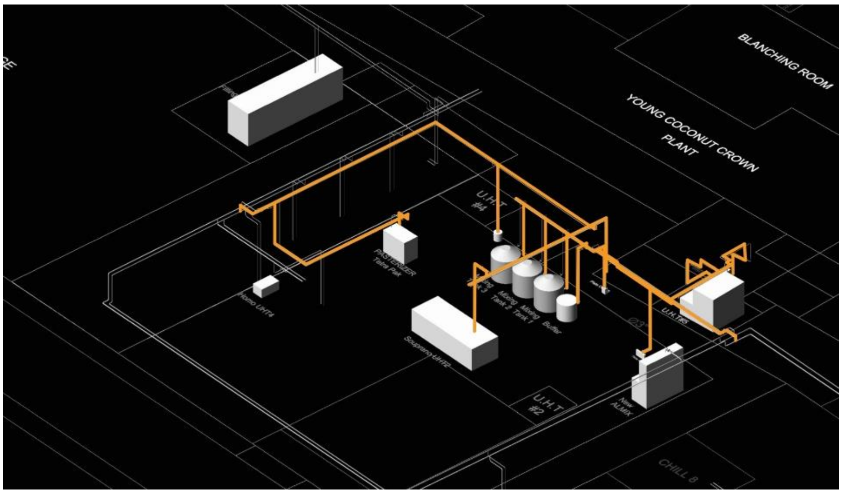


Figure 3-13 Isometric view of Orange pipe

Figure 3-14 Top view of Orange pipe

3.2 Length of pipes

Figure 3-15 Measuring wheel

For the measurement of the length of the pipes, we realized that the measuring tape would be virtually impossible to be used to measure the complicated surfaces of the worksite. Therefore, after consulting with an AF engineer, we decided to use the measuring wheel.

Generally, we can use this piece of equipment to measure the horizontal distance on the pipes. It's to be noted however, that the vertical distance of the pipes are estimated to be the same dimensions as those in the CAD file due to the difficulty in measuring the extreme high pipes.

Figure 3-16 Measure the length of a pipe.

And the measurer must sure that the path of the wheel aligns correctly alongside the pipes to ensure that the measurements are accurate.

3.3 Nominal diameter of pipes

There are three methods that we employed to determine the diameter of pipes:
1). We inquired the APT engineers for the existing record about the diameter.
2). If the engineers did not have the data that we needed, we would inspect around the pipes ourselves, looking for valves and fitting and take note of the dimension.
3). If the second method failed, we would measure them. As the diameters of the pipes are not very large, we decided to use the vernier caliper to measure the diameters of the pipes.

3.4 Collect pressure and temperature data

According to the calculation method in chapter 2, it states that flow rate is needed to take into account and pressure is relative to the flow rate. Moreover, temperature and pressure also affect fluid characteristics. So, we need to determine the value of those values.

In the manufacturing line in the factory, there is the equipment that shows the temperature and pressure value which are pressure gauge and thermometer. So, we can obtain them from that equipment but not all the machines attach the gauge and thermometer. Therefore, we can determine the values for just some of them.

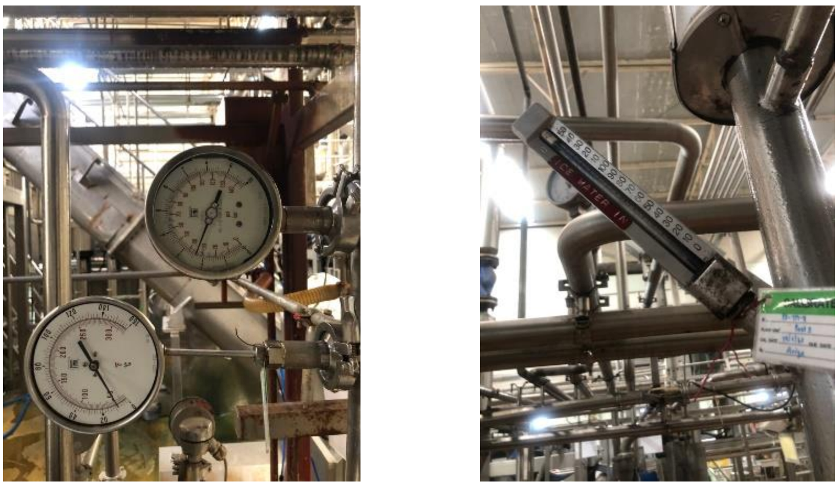


Figure 3-17 Pressure gauge and Thermometer that attach to the machine

3.5 Collecting pressure, temperature, and flow rate data

For selecting the proper pipe size of the system, we need a water flow rate in pipe to calculate the proper size of the pipe followed by ASHRAE 90.1 Standard. We have visited Ampol Foods Processing's production office to request for pressure, temperature, and water flow rate of the chilled water system. Unfortunately, we have got only inlet pressure and one-side inlet and outlet temperature of chilled water. Due to the limitation of information and time, estimating the required value by engineering knowledge is needed to fulfill the project objectives. In chapter 4, the estimating value calculation will be explained.

3.6 Collecting nameplate data from the machine

Due to the difficulty of measuring required value, collecting the required value from a datasheet is an option to complete the pipe size selection calculation. By taking photos of the nameplate of the process machine, we can search on the internet for the datasheet from the manufacturer website to get the datasheet and get the required value.

3.7 Data source

3.7.1 Pump information

3.7.1.1 SABROE's pumps

- TP 80-330/2 A-F-B-BAQE

Pump speed on which pump data are based:	2930 rpm
Rated flow:	102 m^3/h
Rated head:	27.4 m
Actual impeller diameter:	157 mm

- LP 80-160/164 AFA-BBUE

Pump speed on which pump data are based:	2920 rpm
Rated flow:	43 m^3/h
Rated head:	32 m
Actual impeller diameter:	164 mm

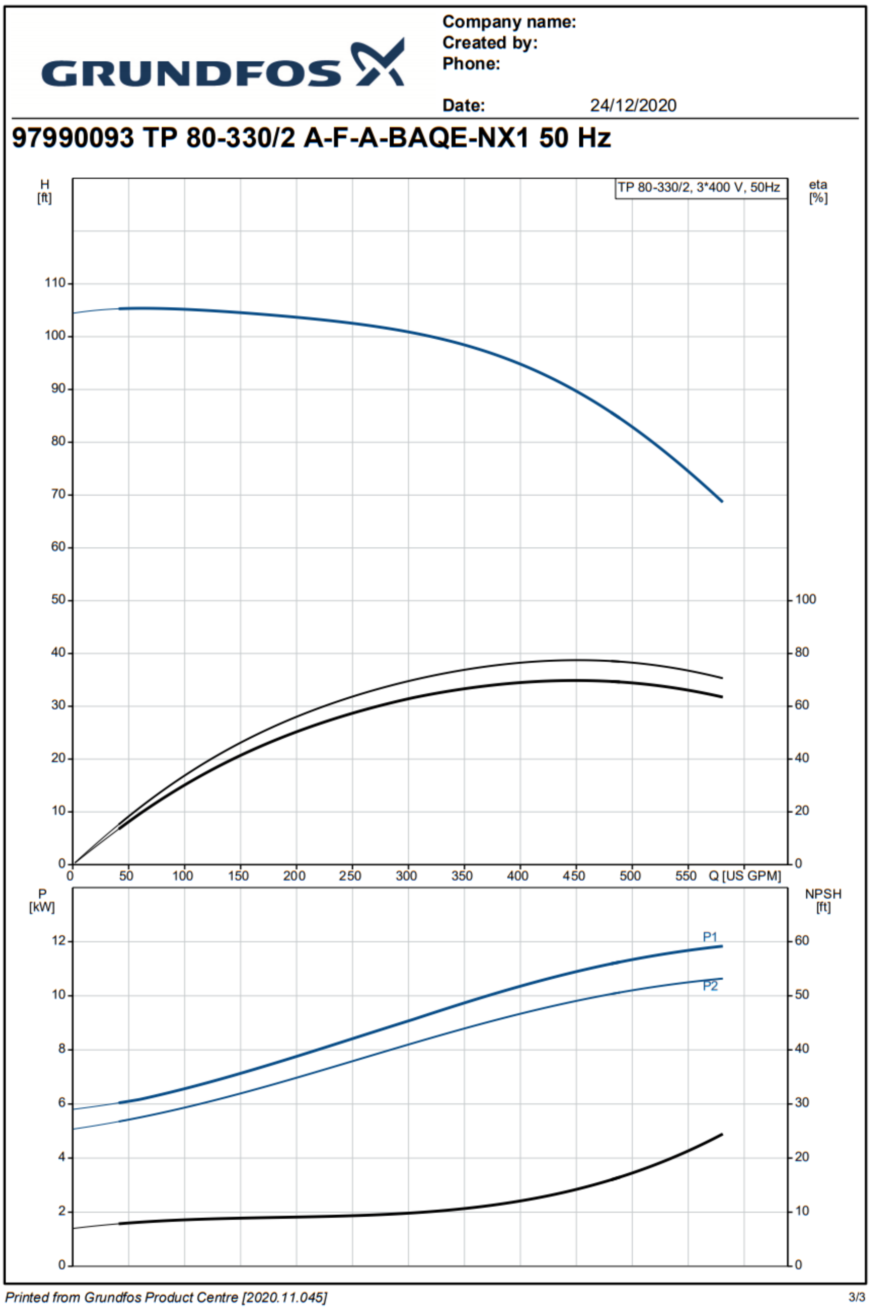


Figure 3-18 Pump curve of TP 80-330/2 A-F-B-BAQE

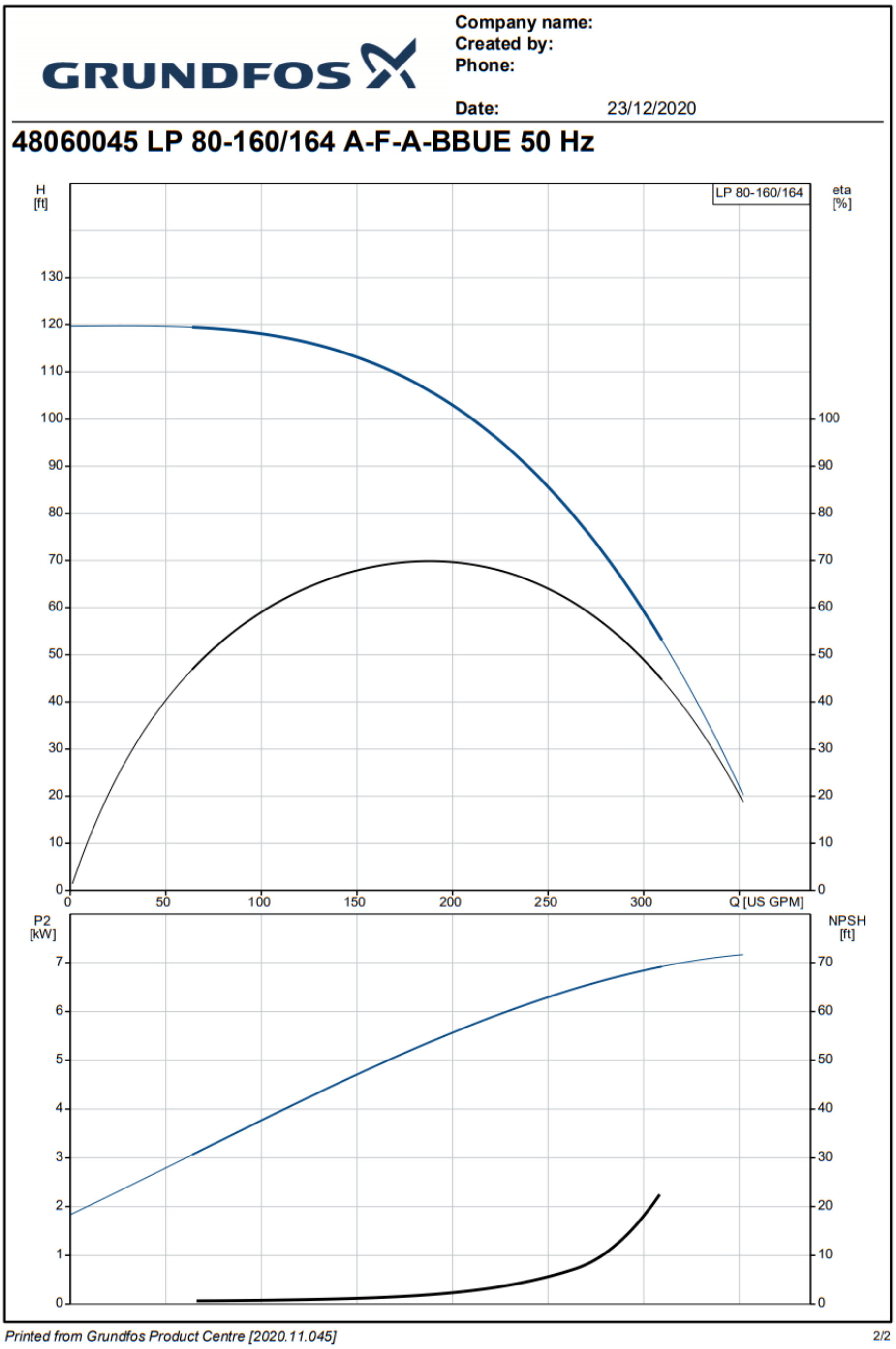


Figure 3-19 Pump curve of LP 80-160/164 AFA-BBUE

3.7.1.2 MYCOM1's pumps

- 2x NBG 80-65-160/177 A-F-B-BAQE

Pump speed on which pump data are based:	2940 rpm
Rated flow:	94.98 m^3/h
Rated head:	38.92 m
Actual impeller diameter:	177 mm

For MYCOM1's pumps, we assume these two pumps are similar with MYCOM2's pumps.

3.7.1.3 MYCOM2's pumps

- 2x NBG 80-65-160/177 A-F-B-BAQE

Pump speed on which pump data are based:	2940 rpm
Rated flow:	94.98 m^3/h
Rated head:	38.92 m
Actual impeller diameter:	177 mm

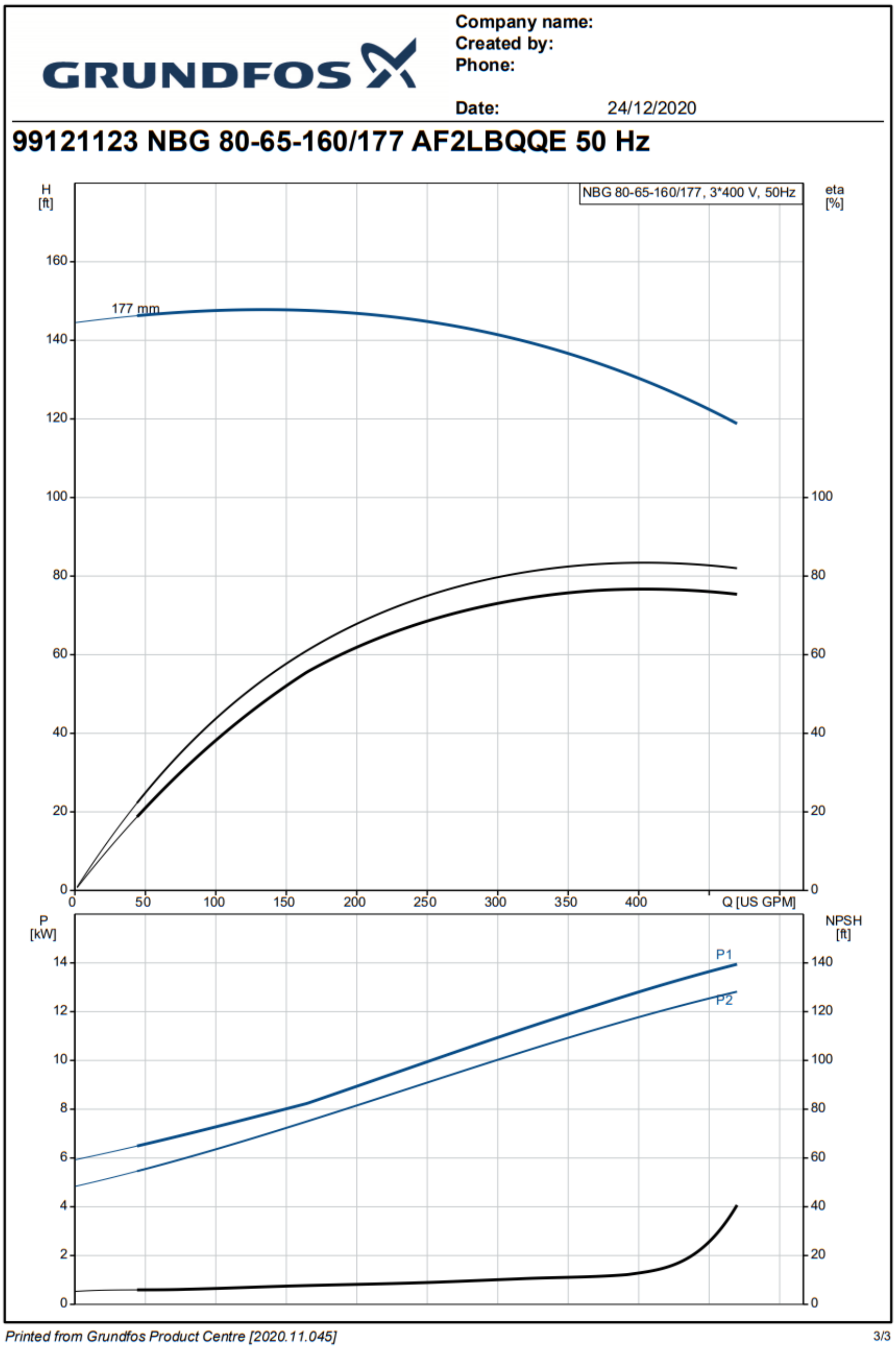


Figure 3-20 Pump curve of NBG 80-65-160/177 A-F-B-BAQE

3.7.2 Pipe information

Table 3.1 Red line

Total length = 407.7 m

No.	Zone	Equipment	NPS	P_{in} (bar)	Q (gpm)	NOTE
1	Coconut Husking	Coconut Cleaning Machine	2		75	Estimation from sch40 pipe chart
2		Plate Herring Plus	1.5	1.6	47	Estimation from sch40 pipe chart
3		Mixing tank 10	2	2.6	13.208	Measured data by operator (file: CHW-cost.xlsx)
4		Mixing tank 11	2	2.6	13.208	
5		Mixing tank 12	2	2.6	13.208	
6		Mixing tank 13	2	2.6	13.208	
7		Plate Old Squeezing	2	3	75	Estimation from sch40 pipe chart
8	UHT2	New All mix	2		35.22	Measured data by operator (file: CHW-cost.xlsx)

Fittings and Valves

Size		1/2	3/4	1	1.25	1.5	2	2.5	3	3.5	4
Fitting	90deg	0	0	0	0	0	74	0	0	0	6
	T-Joint	0	0	0	0	0	9	0	0	0	7
	45deg	0	0	0	0	0	2	0	0	0	2
Valve	Ball valve	0	0	0	0	0	10	0	0	0	0
	Check valve	0	0	0	0	0	0	0	0	0	0
	Butterfly valve	N/A	N/A	N/A	N/A	N/A	0	0	0	0	0
	Globe valve	0	0	0	0	0	0	0	0	0	0
Strainer		N/A	N/A	0	0	N/A	0	0	N/A	N/A	N/A

Table 3.2 Purple line

Total length = 229.4 m

No.	Zone	Equipment	NPS	P_{in} (bar)	Q (gpm)	NOTE
1	Storage	Filling Tetra Pak	1.5		0.44	Measured data by operator (file: CHW-cost.xlsx)

Fittings and Valves

Size		1/2	3/4	1	1.25	1.5	2	2.5	3	3.5	4
Fitting	90deg	0	0	0	0	0	2	20	0	0	0
	T-Joint	0	0	0	0	0	1	7	0	0	0
	45deg	0	0	0	0	0	0	2	0	0	0
Valve	Ball valve	0	0	0	0	0	0	2	0	0	0
	Check valve	0	0	0	0	0	0	0	0	0	0
	Butterfly valve	N/A	N/A	N/A	N/A	N/A	0	0	0	0	0
	Globe valve	0	0	0	0	0	0	0	0	0	0
Strainer		N/A	N/A	0	0	N/A	0	0	N/A	N/A	N/A

Table 3.3 Yellow line

Total length = 153.06 m

No.	Zone	Equipment	NPS	P_{in} (bar)	Q (gpm)	NOTE
1	Old Squeezing (คั้นเก่า)	mixing tank 1	2	2.5	13.208	Measured data by operator (file: CHW-cost.xlsx)
2		mixing tank 2	2	2.5	13.208	
3		mixing tank 3	2	2.5	13.208	
4		mixing tank 4	2	2.5	13.208	
5		Plate Past Tetra Pak	1 1/4	1	35	Estimation from sch40 pipe chart
6		mixing tank 5	2	2.2	13.208	Measured data by operator (file: CHW-cost.xlsx)
7		mixing tank 6	2	2.2	13.208	
8		Almix	1 1/2		35.22	
9		Plate mixing tank	1 1/2		8.8058	
10		Plate mixing tank	1 1/2		8.8058	

Fittings and Valves

Size		1/2	3/4	1	1.25	1.5	2	2.5	3	3.5	4
Fitting	90deg	0	0	0	0	0	0	17	0	0	0
	T-Joint	0	0	0	0	0	0	2	0	0	0
	45deg	0	0	0	0	0	0	0	0	0	0
Valve	Ball valve	0	0	0	3	0	11	0	0	0	0
	Check valve	0	0	0	0	0	5	0	0	0	0
	Butterfly valve	N/A	N/A	N/A	N/A	N/A	0	0	0	0	0
	Globe valve	0	0	0	0	0	2	0	0	0	0
Strainer		N/A	N/A	0	0	N/A	2	0	N/A	N/A	N/A

Table 3.4 Blue line

Total length = 190.75 m

No.	Zone	Equipment	NPS	P_{in} (bar)	Q (gpm)	NOTE
1	Old Squeezing	Evaporator2	2		13.208	Measured data by operator (file: CHW-cost.xlsx)
2		mixing tank 7	2	2	13.208	
3		mixing tank 8	2	2	13.208	
4		mixing tank 9	2	2	13.208	
5		Pasteurizer	2	2.4	8.8058	
6	UHT1	Pasteurizer	2	2.6	10.127	
7		Homo UHT1	2		4.403	
8		Sterilizer UHT1	2		75	Estimation from pipe chart
9	Filling	CAF 712C Combibloc	1/2		0.44	Measured data by operator (file: CHW-cost.xlsx)

Fittings and Valves

Size		1/2	3/4	1	1.25	1.5	2	2.5	3	3.5	4
Fittings	90deg	0	0	0	0	0	18	14	0	0	0
	T-Joint	0	0	0	0	0	5	4	0	0	0
	45deg	0	0	0	0	0	2	5	0	0	0
Valves	Ball valve	0	0	0	0	0	16	0	0	0	0
	Check valve	0	0	0	0	0	3	0	0	0	0
	Butterfly valve	N/A	N/A	N/A	N/A	N/A	0	0	0	0	0
	Globe valve	0	0	0	0	0	0	0	0	0	0
Strainer		N/A	N/A	0	0	N/A	0	0	N/A	N/A	N/A

Table 3.5 Green line

Total length = 98.4 m

No.	Zone	Equipment	NPS	P_{in} (bar)	Q (gpm)	NOTE
1	UHT 3	Homo UHT3	2		17.616	Measured data by operator (file: CHW-cost.xlsx)
2		UHT3	2		15.410	
3	UHT 1	UHT1	2		17.611	

Fittings and Valves

Size		1/2	3/4	1	1.25	1.5	2	2.5	3	3.5	4
Fitting	90deg	0	0	0	0	0	17	0	0	0	0
	T-Joint	0	0	0	0	0	3	0	0	0	0
	45deg	0	0	0	0	0	1	0	0	0	0
Valve	Ball valve	0	0	0	0	0	4	0	0	0	0
	Check valve	0	0	0	0	0	0	0	0	0	0
	Butterfly valve	N/A	N/A	N/A	N/A	N/A	0	0	0	0	0
	Globe valve	0	0	0	0	0	0	0	0	0	0
Strainer		N/A	N/A	0	0	N/A	0	0	N/A	N/A	N/A

Table 3.6 Pink line

Total length = 69.8 m

No.	Zone	Equipment	NPS	P_{in} (bar)	Q (gpm)	NOTE
1	Filling	CAF 505 Combibloc	0.5		0.44	Measured data by operator (file: CHW-cost.xlsx)

Fittings and Valves

Size		1/2	3/4	1	1.25	1.5	2	2.5	3	3.5	4
Fitting	90deg	11	0	0	0	0	0	0	0	0	0
	T-Joint	2	0	0	0	0	0	0	0	0	0
	45deg	0	0	0	0	0	0	0	0	0	0
Valve	Ball valve	0	0	0	0	0	0	0	0	0	0
	Check valve	0	0	0	0	0	0	0	0	0	0
	Butterfly valve	N/A	N/A	N/A	N/A	N/A	0	0	0	0	0
	Globe valve	0	0	0	0	0	0	0	0	0	0
Strainer		N/A	N/A	0	0	N/A	0	0	N/A	N/A	N/A

Table 3.7 Orange line

Total length = 93.7 m

No.	Zone	Equipment	NPS	P_{in} (bar)	Q (gpm)	NOTE
1	UHT 5	UHT5	1.5		17.61	Measured data by operator (file: CHW-cost.xlsx)
2		Filling A1	1.5		0.44	
3	UHT 2	Plate CB1 10	3		90.5	From Alfa-Laval
4		mixing tank 14	2	2.4	13.2	Measured data by operator (file: CHW-cost.xlsx)
5		mixing tank 15	2	2.4	13.2	
6		mixing tank 16	2	2.4	13.2	
7		Plate Past UHT2	2		24.21	
8		Souprano UHT2	2 1/2		88.05	From production department
9		Pasteurizer Tetra Pak	2		6.6	Measured data by operator (file: CHW-cost.xlsx)

Fittings and Valves

Size		1/2	3/4	1	1.25	1.5	2	2.5	3	3.5	4
Fitting	90deg	0	0	0	0	0	0	37	0	0	0
	T-Joint	0	0	0	0	0	0	9	0	0	0
	45deg	0	0	0	0	0	0	0	0	0	0
Valve	Ball valve	0	0	0	0	6	2	3	0	0	0
	Check valve	0	0	0	0	0	0	0	0	0	0
	Butterfly valve	N/A	N/A	N/A	N/A	N/A	0	0	0	0	0
	Globe valve	0	0	0	0	0	0	0	0	0	0
Strainer		N/A	N/A	0	0	N/A	0	0	N/A	N/A	N/A

Chapter 4. Analysis and Calculation

4.1 Analyze the existing system

After we collected all data needed as shown in chapter 3 and can understood the chilled water piping system of this industry. Next thing is presumption of possible problems which can be happened or defect in case of piping design standard as ASHRAE 90.1.
and the presumption are

4.1.1 Pressure gauge at the front of the machines lower than required pressure of them ($P_g < P_{req}$)

Ampol Food installed several chilled waters used machines to support their increasing of production through decade. Therefore, the branched pipes and fittings was added for send chilled water to the new installed machines so that demand of chilled water was increasing, and their chillers must work more also.

In the side of piping system, the original pipe network was designed to provide appropriate required flow rate and pressure of all machines in the past. At present the flow rate in main pipes are increased while the diameter of pipes are the same as the original design. Consequently, the pressure drop in these pipes will be increased as this equation

$$\Delta p = \lambda \times \frac{L}{D} \times \frac{\rho}{2} \times \omega^2$$

Δp	=	Pressure Drop (Pa)
λ	=	Pipe Friction Coefficient
L	=	Length of Pipe (m)
D	=	Pipe Diameter (m)
ρ	=	Density of fluid (kg/m^3)
ω	=	Flow Velocity (m/s)

4.1.2 Chilled water from SABROE is tapped to green line before mixing with chilled water from MYCOM

Figure 4-1 Presumption 4.1.2

Generally, the piping design which has pumping from two reservoirs. Piping engineering mostly route main pipes from two sources of water and confluent before branching into the branch pipes. In this case, along the way from SABROE to T-junctions in yellow circle, there is one branching to green line. If pressure from SABORE is not enough to exceed the pressure from MYCOM, the chilled water which pumped from MYCOM would push CHW from SABROE and flow to green line only. So that the pumps of SABORE must work more than usual.

4.2 Simplification of the existing system

The actual chilled water system in this paper is quite complicate due to an unplanned expansion of the system that could cause several problems and poor energy saving. Figure 4-2 represents the current chilled water system in 3D software called AutoCAD, which shows the water pipeline in the system. From the figure, the green line and orange line are water supply line and water return line respectively. The red circle A and B are chiller systems that provide chilled water to fulfill the demand from the system. By considering the system, Chiller A provides 2 ways of chilled water to the left and upward of the figure, Chiller B provides 2 ways of chilled water to upward and downward of the figure.

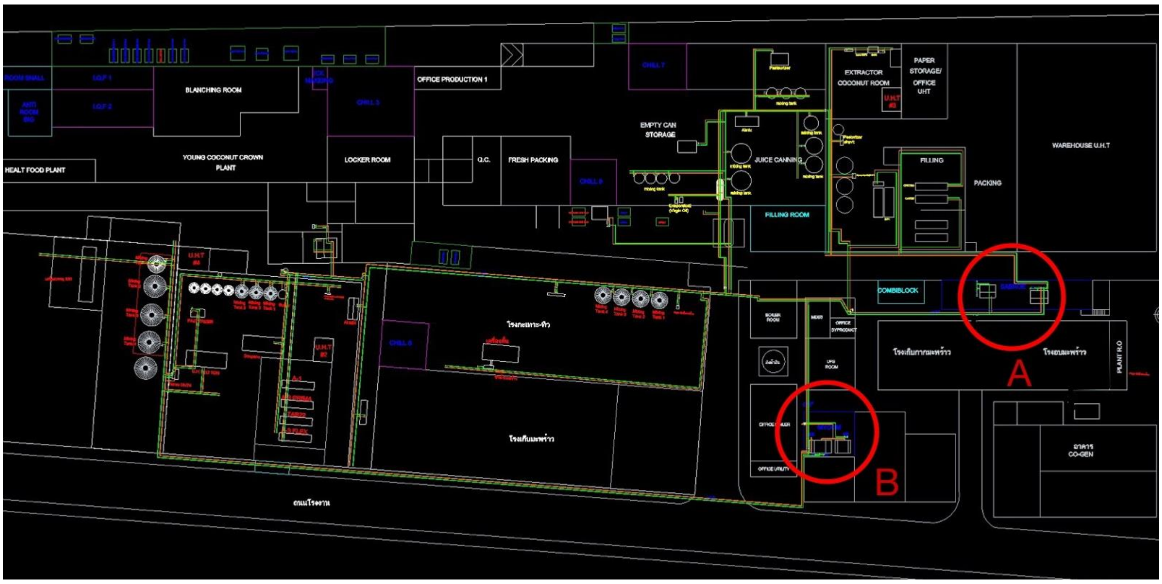


Figure 4-2 The current chilled water system represents in AutoCAD

From Figure 4-2, it is difficult to determine how much water is distributed to each pipe. The simplification is applied for this chilled water system by separating the branch pipes by colors as shown in the Figure 4-3. The red and purple lines are main chilled water distribution pipes of the yellow, blue, green, orange, and pink lines.

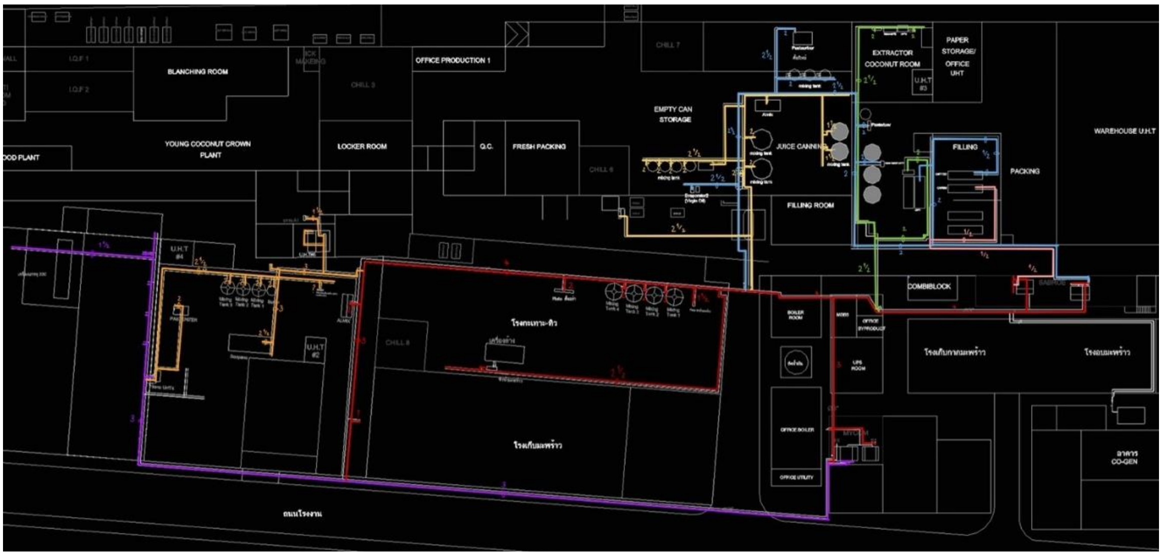


Figure 4-3 Cooling loads in the system categorized by different colors

Figure 4-4 Isometric view of the system

Figure 4-5 shows the devices that use chilled water in the production process. The devices are categorized by colors for simplified calculation. The chiller systems that provide chilled water for the system is SABROE 2, MYCOM 1 and MYCOM 2, which fulfill the demand of production machines such as mixing tank, pasteurizer, UHT, heat exchanger plate, etc. as shown in Figure 4-5.

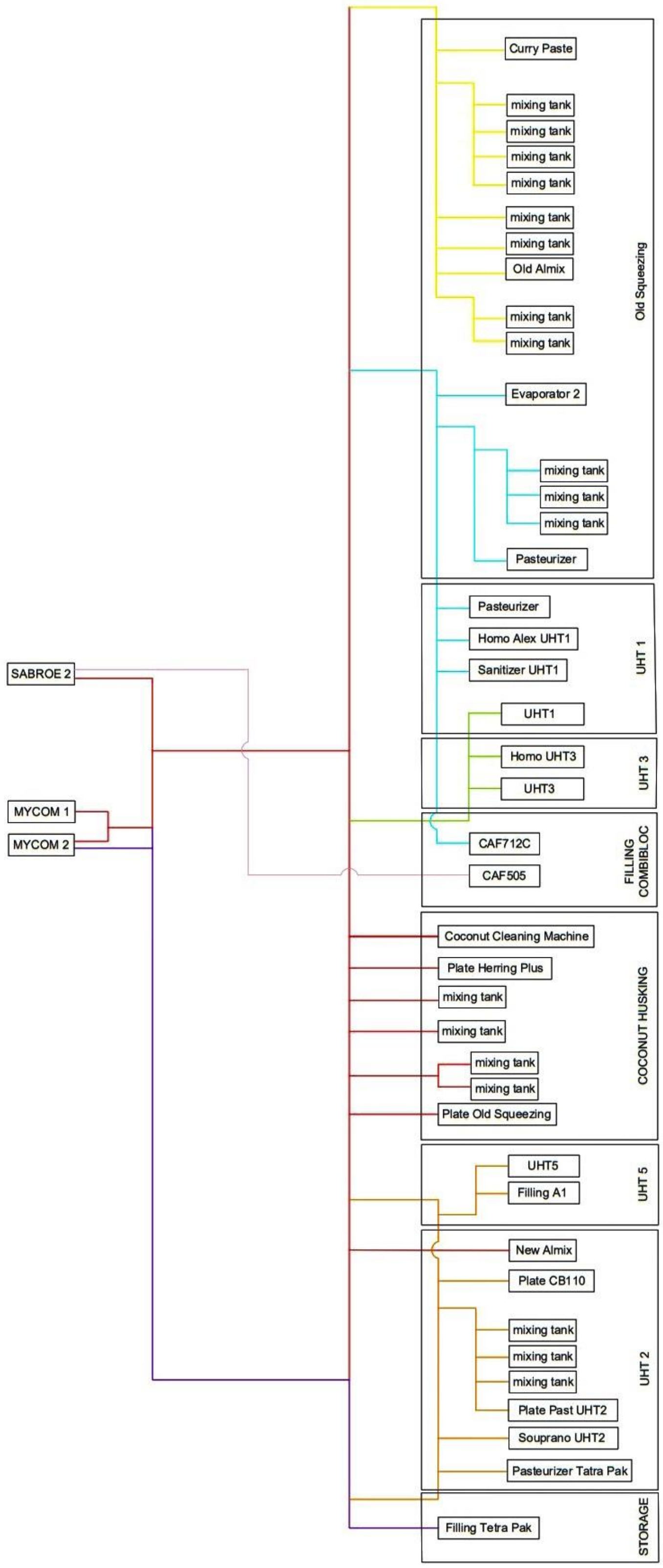


Figure 4-5 Single line shows cooling load of the system

By including all the information, the simplified system is shown in Figure 4-. The letter P with numbers represent pipe, fitting, and valve in the system. The letter N with numbers represents the junction of chilled water pipes. The color nodes are chilled water loads of the system.

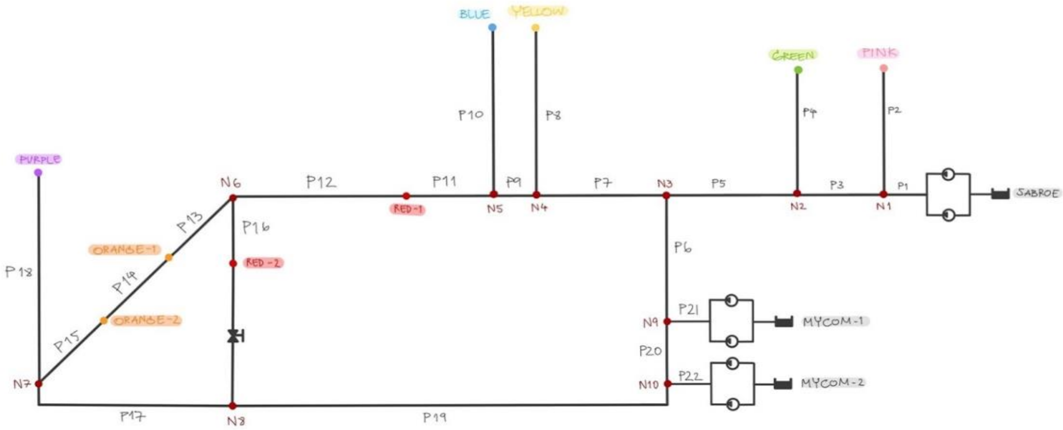


Figure 4-6 Simplified system with names and different color of loads

4.3 Supporting data for EPANET simulation

According to topics 4.2 and 4.3, there are many values which need to be substituted for the software. Moreover, we define pipe P1 to P22 for simplification. So, this topic will define that information for future use.

4.3.1 Pipe information

The pipe information that is necessary for the software is equivalent length. This topic will discuss methods to determine the equivalent length.

- Step 1: Specify pipe length and number of fittings and valves in specific pipe (P1 to P22) from CAD software. Also consider the diameter of the pipe that connects to fittings and valves.
- Step 2: Define the equivalent length of single fitting and valve from Figure 4-6 and Figure 4-7. Then sum all the values to get the total equivalent length of fittings and valves.
- Step 3: Lastly, sum the actual length and total equivalent length of fittings and valves to get the equivalent of specific pipe.

lominal Pipe or Tube Size	Actual ID Steel Pipe, inches	Friction Factor, f	Screwed and flanged gate valves β=1, θ=0	Screwed and flanged globe valves, β =1	45 Swing check valve, β =1	90 deg swing check valve, β =1	90 deg flanged angle valve, β =1	90 deg weld angle valve β=1	45 deg weld angle valve β=1	45 deg weld lift check valve β=1	Plug valve striaght way β=1	3 way plug valves β=1		Ball Valve β=1, θ=0	Butterfly Valve, centered disc
												thru	branch		
3/8	0.493	0.028	0.33	13.97	4.11	2.05	6.16	2.26	2.26	2.26	0.74	1.23	3.70	0.12	-
1/2	0.622	0.027	0.41	17.62	5.18	2.59	7.78	2.85	2.85	2.85	0.93	1.56	4.67	0.16	-
3/4	0.824	0.025	0.55	23.35	6.87	3.43	10.30	3.78	3.78	3.78	1.24	2.06	6.18	0.21	-
1	1.049	0.023	0.70	29.72	8.74	4.37	13.11	4.81	4.81	4.81	1.57	2.62	7.87	0.26	-
1 1/4	1.380	0.022	0.92	39.10	11.50	5.75	17.25	6.33	6.33	6.33	2.07	3.45	10.35	0.35	-
1 1/2	1.610	0.021	1.07	45.62	13.42	6.71	20.13	7.38	7.38	7.38	2.42	4.03	12.08	0.40	-
2	2.067	0.019	1.38	58.57	17.23	8.61	25.84	9.47	9.47	9.47	3.10	5.17	15.50	0.52	7.75
2 1/2	2.469	0.018	1.65	69.96	20.58	10.29	30.86	11.32	11.32	11.32	3.70	6.17	18.52	0.62	9.26
3	3.068	0.018	2.05	86.93	25.57	12.78	38.35	14.06	14.06	14.06	4.60	7.67	23.01	0.77	11.51
3 1/2	3.548	0.018	2.37	100.53	29.57	14.78	44.35	16.26	16.26	16.26	5.32	8.87	26.61	0.89	13.31
4	4.026	0.017	2.68	114.07	33.55	16.78	50.33	18.45	18.45	18.45	6.04	10.07	30.20	1.01	15.10
5	5.047	0.016	3.36	143.00	42.06	21.03	63.09	23.13	23.13	23.13	7.57	12.62	37.85	1.26	18.93
6	6.065	0.015	4.04	171.84	50.54	25.27	75.81	27.80	27.80	27.80	9.10	15.16	45.49	1.52	22.74
8	7.981	0.014	5.32	226.13	66.51	33.25	99.76	36.58	36.58	36.58	11.97	19.95	59.86	2.00	29.93
10	10.020	0.014	6.68	283.90	83.50	41.75	125.25	45.93	45.93	45.93	15.03	25.05	75.15	2.51	29.23
12	11.938	0.013	7.96	338.24	99.48	49.74	149.23	54.72	54.72	54.72	17.91	29.85	89.54	2.98	34.82
14	13.124	0.013	8.75	371.85	109.37	54.68	164.05	60.15	60.15	60.15	19.69	32.81	98.43	3.28	38.28
16	15.000	0.013	10.00	425.00	125.00	62.50	187.50	68.75	68.75	68.75	22.50	37.50	112.50	3.75	31.25
18	16.876	0.012	11.25	478.15	140.63	70.32	210.95	77.35	77.35	77.35	25.31	42.19	126.57	4.22	35.16
20	18.814	0.012	12.54	533.06	156.78	78.39	235.18	86.23	86.23	86.23	28.22	47.04	141.11	4.70	39.20
24	22.628	0.012	15.09	641.13	188.57	94.28	282.85	103.71	103.71	103.71	33.94	56.57	169.71	5.66	47.14

Figure 4-7 Equivalent of valve in straight pipe (feet)

Nominal Pipe or Tube Size, inches	Actual ID Steel Pipe, inches	Friction Factor f	45 deg std elbow	90 Deg Std elbow	Long radius 90 deg elbow	Std tee thru flow	Std tee branch flow	Reducing tee thru flow		90 deg weld elbow		Mitre Bend	
								1/4	1/2	r/d=1	r/d=2	45 deg	90 deg
3/8	0.493	0.028	0.66	1.23	0.66	0.82	2.47	1.09	1.27	-	-	-	-
1/2	0.622	0.027	0.83	1.56	0.83	1.04	3.11	1.38	1.60	-	-	-	-
3/4	0.824	0.025	1.10	2.06	1.10	1.37	4.12	1.83	2.12	-	-	-	-
1	1.049	0.023	1.40	2.62	1.40	1.75	5.25	2.33	2.70	-	-	-	-
1 1/4	1.380	0.022	1.84	3.45	1.84	2.30	6.90	3.06	3.55	-	-	-	-
1 1/2	1.610	0.021	2.15	4.03	2.15	2.68	8.05	3.57	4.14	-	-	-	-
2	2.067	0.019	2.76	5.17	2.76	3.45	10.34	4.58	5.31	3.45	2.07	2.58	10.34
2 1/2	2.469	0.018	3.29	6.17	3.29	4.12	12.35	5.47	6.35	4.12	2.47	3.09	12.35
3	3.068	0.018	4.09	7.67	4.09	5.11	15.34	6.80	7.89	5.11	3.07	3.84	15.34
3 1/2	3.548	0.018	4.73	8.87	4.73	5.91	17.74	7.86	9.12	5.91	3.55	4.44	17.74
4	4.026	0.017	5.37	10.07	5.37	6.71	20.13	8.92	10.35	6.71	4.03	5.03	20.13
5	5.047	0.016	6.73	12.62	6.73	8.41	25.24	11.19	12.98	8.41	5.05	6.31	25.24
6	6.065	0.015	8.09	15.16	8.09	10.11	30.33	13.44	15.60	10.11	6.07	7.58	30.33
8	7.981	0.014	10.64	19.95	10.64	13.30	39.91	17.69	20.52	13.30	7.98	9.98	39.91
10	10.020	0.014	13.36	25.05	13.36	16.70	50.10	22.21	25.76	16.70	10.02	12.53	50.10
12	11.938	0.013	15.92	29.85	15.92	19.90	59.69	26.46	30.70	19.90	11.94	14.92	59.69
14	13.124	0.013	17.50	32.81	17.50	21.87	65.62	29.09	33.75	21.87	13.12	16.41	65.62
16	15.000	0.013	20.00	37.50	20.00	25.00	75.00	33.25	38.57	25.00	15.00	18.75	75.00
18	16.876	0.012	22.50	42.19	22.50	28.13	84.38	37.41	43.39	28.13	16.88	21.10	84.38
20	18.814	0.012	25.09	47.04	25.09	31.36	94.07	41.70	48.38	31.36	18.81	23.52	94.07
24	22.628	0.012	30.17	56.57	30.17	37.71	113.14	50.16	58.18	37.71	22.63	28.29	113.14

Figure 4-8 Equivalent of fitting in straight pipe (feet)

Table 4.1 P1 information

Length = 369.984 feet

Diameter = 4 inch

Fitting and valve

Size		½	3/4	1	1.25	1.5	2	2.5	3	3.5	4
Fittings	90deg	0	0	0	0	0	0	0	0	0	24
	T-Joint	0	0	0	0	0	0	0	0	0	6
	45deg	0	0	0	0	0	0	0	0	0	0
Valves	Ball valve	0	0	0	0	0	0	0	0	0	2
	Check valve	0	0	0	0	0	0	0	0	0	0
	Butterfly valve	N/A	N/A	N/A	N/A	N/A	0	0	0	0	0
	Globe valve	0	0	0	0	0	0	0	0	0	0
	Strainer	N/A	N/A	0	0	N/A	0	0	N/A	N/A	N/A

Equivalent length	Size	1/2	3/4	1	1.25	1.5	2	2.5	3	3.5	4
Fittings	90deg	0	0	0	0	0	0	0	0	0	241.68
	T-Joint	0	0	0	0	0	0	0	0	0	40.26
	45deg	0	0	0	0	0	0	0	0	0	0
Valves	Ball valve	0	0	0	0	0	0	0	0	0	2.02
	Check valve	0	0	0	0	0	0	0	0	0	0
	Butterfly valve	N/A	N/A	N/A	N/A	N/A	0	0	0	0	0
	Globe valve	0	0	0	0	0	0	0	0	0	0
	Strainer	N/A	N/A	0	0	N/A	0	0	N/A	N/A	N/A
										sum	283.960

Total equivalent length = 653.944 feet

Table 4.2 P2 information

Length = 228.944 feet

Diameter = 1/2 inch

Fitting and valve

Size		1/2	3/4	1	1.25	1.5	2	2.5	3	3.5	4
Fittings	90deg	11	0	0	0	0	0	0	0	0	0
	T-Joint	2	0	0	0	0	0	0	0	0	0
	45deg	0	0	0	0	0	0	0	0	0	0
Valves	Ball valve	0	0	0	0	0	0	0	0	0	0
	Check valve	0	0	0	0	0	0	0	0	0	0
	Butterfly valve	N/A	N/A	N/A	N/A	N/A	0	0	0	0	0
	Globe valve	0	0	0	0	0	0	0	0	0	0
	Strainer	N/A	N/A	0	0	N/A	0	0	N/A	N/A	N/A

Equivalent length	Size	1/2	3/4	1	1.25	1.5	2	2.5	3	3.5	4
Fittings	90deg	17.16	0	0	0	0	0	0	0	0	0
	T-Joint	2.08	0	0	0	0	0	0	0	0	0
	45deg	0	0	0	0	0	0	0	0	0	0
Valves	Ball valve	0	0	0	0	0	0	0	0	0	0
	Check valve	0	0	0	0	0	0	0	0	0	0
	Butterfly valve	N/A	N/A	N/A	N/A	N/A	0	0	0	0	0
	Globe valve	0	0	0	0	0	0	0	0	0	0
	Strainer	N/A	N/A	0	0	N/A	0	0	N/A	N/A	N/A
										sum	19.240

Total equivalent length = 248.184 feet

Table 4.3 P3 information

Length = 70.52 feet

Diameter = 4 inch

Fitting and valve

Size		1/2	3/4	1	1.25	1.5	2	2.5	3	3.5	4
Fittings	90deg	0	0	0	0	0	0	0	0	0	0
	T-Joint	0	0	0	0	0	0	0	0	0	1
	45deg	0	0	0	0	0	0	0	0	0	0
Valves	Ball valve	0	0	0	0	0	0	0	0	0	0
	Check valve	0	0	0	0	0	0	0	0	0	0
	Butterfly valve	N/A	N/A	N/A	N/A	N/A	0	0	0	0	0
	Globe valve	0	0	0	0	0	0	0	0	0	0
	Strainer	N/A	N/A	0	0	N/A	0	0	N/A	N/A	N/A

Eq length	Size	1/2	3/4	1	1.25	1.5	2	2.5	3	3.5	4
Fittings	90deg	0	0	0	0	0	0	0	0	0	0
	T-Joint	0	0	0	0	0	0	0	0	0	6.71
	45deg	0	0	0	0	0	0	0	0	0	0
Valves	Ball valve	0	0	0	0	0	0	0	0	0	0
	Check valve	0	0	0	0	0	0	0	0	0	0
	Butterfly valve	N/A	N/A	N/A	N/A	N/A	0	0	0	0	0
	Globe valve	0	0	0	0	0	0	0	0	0	0
	Strainer	N/A	N/A	0	0	N/A	0	0	N/A	N/A	N/A
										sum	6.710

Total equivalent length = 77.23 feet

Table 4.4 P4 information

Length = 322.752 feet

Diameter = 2 1/2 inch

Fitting and valve

Size		1/2	3/4	1	1.25	1.5	2	2.5	3	3.5	4
Fittings	90deg	0	0	0	0	0	17	0	0	0	0
	T-Joint	0	0	0	0	0	3	0	0	0	0
	45deg	0	0	0	0	0	1	0	0	0	0
Valves	Ball valve	0	0	0	0	0	4	0	0	0	0
	Check valve	0	0	0	0	0	0	0	0	0	0
	Butterfly valve	N/A	N/A	N/A	N/A	N/A	0	0	0	0	0
	Globe valve	0	0	0	0	0	0	0	0	0	0
	Strainer	N/A	N/A	0	0	N/A	0	0	N/A	N/A	N/A

Equivalent length	Size	1/2	3/4	1	1.25	1.5	2	2.5	3	3.5	4
Fittings	90deg	0	0	0	0	0	87.89	0	0	0	0
	T-Joint	0	0	0	0	0	10.35	0	0	0	0
	45deg	0	0	0	0	0	2.76	0	0	0	0
Valves	Ball valve	0	0	0	0	0	2.08	0	0	0	0
	Check valve	0	0	0	0	0	0	0	0	0	0
	Butterfly valve	N/A	N/A	N/A	N/A	N/A	0	0	0	0	0
	Globe valve	0	0	0	0	0	0	0	0	0	0
	Strainer	N/A	N/A	0	0	N/A	0	0	N/A	N/A	N/A
										sum	103.080

Total equivalent length = 425.823 feet

Table 4.5 P5 information

Length = 55.104 feet

Diameter = 4 inch

Fitting and valve

Size		1/2	3/4	1	1.25	1.5	2	2.5	3	3.5	4
Fittings	90deg	0	0	0	0	0	0	0	0	0	0
	T-Joint	0	0	0	0	0	0	0	0	0	1
	45deg	0	0	0	0	0	0	0	0	0	1
Valves	Ball valve	0	0	0	0	0	0	0	0	0	0
	Check valve	0	0	0	0	0	0	0	0	0	0
	Butterfly valve	N/A	N/A	N/A	N/A	N/A	0	0	0	0	0
	Globe valve	0	0	0	0	0	0	0	0	0	0
	Strainer	N/A	N/A	0	0	N/A	0	0	N/A	N/A	N/A

Equivalent length	Size	1/2	3/4	1	1.25	1.5	2	2.5	3	3.5	4
Fittings	90deg	0	0	0	0	0	0	0	0	0	0
	T-Joint	0	0	0	0	0	0	0	0	0	6.71
	45deg	0	0	0	0	0	0	0	0	0	5.37
Valves	Ball valve	0	0	0	0	0	0	0	0	0	0
	Check valve	0	0	0	0	0	0	0	0	0	0
	Butterfly valve	N/A	N/A	N/A	N/A	N/A	0	0	0	0	0
	Globe valve	0	0	0	0	0	0	0	0	0	0
	Strainer	N/A	N/A	0	0	N/A	0	0	N/A	N/A	N/A
										sum	12.080

Total equivalent length = 67.184 feet

Table 4.6 P6 information

Length = 159.08 feet

Diameter = 3 inch

Fitting and valve

Size		1/2	3/4	1	1.25	1.5	2	2.5	3	3.5	4
Fittings	90deg	0	0	0	0	0	0	0	20	0	0
	T-Joint	0	0	0	0	0	0	0	4	0	0
	45deg	0	0	0	0	0	0	0	2	0	0
Valves	Ball valve	0	0	0	0	0	0	0	4	0	0
	Check valve	0	0	0	0	0	0	0	0	0	0
	Butterfly valve	N/A	N/A	N/A	N/A	N/A	0	0	0	0	0
	Globe valve	0	0	0	0	0	0	0	0	0	0
	Strainer	N/A	N/A	0	0	N/A	0	0	N/A	N/A	N/A

Equivalent length	Size	1/2	3/4	1	1.25	1.5	2	2.5	3	3.5	4
Fittings	90deg	0	0	0	0	0	0	0	153.4	0	0
	T-Joint	0	0	0	0	0	0	0	20.44	0	0
	45deg	0	0	0	0	0	0	0	8.18	0	0
Valves	Ball valve	0	0	0	0	0	0	0	3.08	0	0
	Check valve	0	0	0	0	0	0	0	0	0	0
	Butterfly valve	N/A	N/A	N/A	N/A	N/A	0	0	0	0	0
	Globe valve	0	0	0	0	0	0	0	0	0	0
	Strainer	N/A	N/A	0	0	N/A	0	0	N/A	N/A	N/A
										sum	185.100

Total equivalent length = 344.18 feet

Table 4.7 P7 information

Length = 73.472 feet

Diameter = 4 inch

Fitting and valve

Size		1/2	3/4	1	1.25	1.5	2	2.5	3	3.5	4
Fittings	90deg	0	0	0	0	0	0	0	0	0	3
	T-Joint	0	0	0	0	0	0	0	0	0	2
	45deg	0	0	0	0	0	0	0	0	0	0
Valves	Ball valve	0	0	0	0	0	0	0	0	0	0
	Check valve	0	0	0	0	0	0	0	0	0	0
	Butterfly valve	N/A	N/A	N/A	N/A	N/A	0	0	0	0	0
	Globe valve	0	0	0	0	0	0	0	0	0	0
	Strainer	N/A	N/A	0	0	N/A	0	0	N/A	N/A	N/A

Equivalent length	Size	1/2	3/4	1	1.25	1.5	2	2.5	3	3.5	4
Fittings	90deg	0	0	0	0	0	0	0	0	0	30.21
	T-Joint	0	0	0	0	0	0	0	0	0	13.42
	45deg	0	0	0	0	0	0	0	0	0	0
Valves	Ball valve	0	0	0	0	0	0	0	0	0	0
	Check valve	0	0	0	0	0	0	0	0	0	0
	Butterfly valve	N/A	N/A	N/A	N/A	N/A	0	0	0	0	0
	Globe valve	0	0	0	0	0	0	0	0	0	0
	Strainer	N/A	N/A	0	0	N/A	0	0	N/A	N/A	N/A
										sum	43.63

Total equivalent length = 117.102 feet

Table 4.8 P8 information

Length = 307.336 feet

Diameter = 2 1/2 inch

Fitting and valve

Size		1/2	3/4	1	1.25	1.5	2	2.5	3	3.5	4
Fittings	90deg	0	0	0	0	0	0	37	0	0	0
	T-Joint	0	0	0	0	0	0	9	0	0	0
	45deg	0	0	0	0	0	0	0	0	0	0
Valves	Ball valve	0	0	0	0	6	2	3	0	0	0
	Check valve	0	0	0	0	0	0	0	0	0	0
	Butterfly valve	N/A	N/A	N/A	N/A	N/A	0	0	0	0	0
	Globe valve	0	0	0	0	0	0	0	0	0	0
	Strainer	N/A	N/A	0	0	N/A	0	0	N/A	N/A	N/A

Equivalent length	Size	1/2	3/4	1	1 .25	1.5	2	2.5	3	3.5	4
Fittings	90deg	0	0	0	0	0	0	228.29	0	0	0
	T-Joint	0	0	0	0	0	0	37.08	0	0	0
	45deg	0	0	0	0	0	0	0	0	0	0
Valves	Ball valve	0	0	0	0	2.4	1.04	1.86	0	0	0
	Check valve	0	0	0	0	0	0	0	0	0	0
	Butterfly valve	N/A	N/A	N/A	N/A	N/A	0	0	0	0	0
	Globe valve	0	0	0	0	0	0	0	0	0	0
	Strainer	N/A	N/A	0	0	N/A	0	0	N/A	N/A	N/A
										sum	270.670

Total equivalent length = 578.006 feet

Table 4.9 P9 information

Length = 2.6896 feet

Diameter = 4 inch

Fitting and valve

Size		1/2	3/4	1	1.25	1.5	2	2.5	3	3.5	4
Fittings	90deg	0	0	0	0	0	0	0	0	0	0
	T-Joint	0	0	0	0	0	0	0	0	0	0
	45deg	0	0	0	0	0	0	0	0	0	0
Valves	Ball valve	0	0	0	0	0	0	0	0	0	0
	Check valve	0	0	0	0	0	0	0	0	0	0
	Butterfly valve	N/A	N/A	N/A	N/A	N/A	0	0	0	0	0
	Globe valve	0	0	0	0	0	0	0	0	0	0
	Strainer	N/A	N/A	0	0	N/A	0	0	N/A	N/A	N/A

Equivalent length	Size	1/2	3/4	1	1 .25	1.5	2	2.5	3	3.5	4
Fittings	90deg	0	0	0	0	0	0	0	0	0	0
	T-Joint	0	0	0	0	0	0	0	0	0	0
	45deg	0	0	0	0	0	0	0	0	0	0
Valves	Ball valve	0	0	0	0	0	0	0	0	0	0
	Check valve	0	0	0	0	0	0	0	0	0	0
	Butterfly valve	N/A	N/A	N/A	N/A	N/A	0	0	0	0	0
	Globe valve	0	0	0	0	0	0	0	0	0	0
	Strainer	N/A	N/A	0	0	N/A	0	0	N/A	N/A	N/A
										sum	0.000

Total equivalent length = 2.69 feet

Table 4.10 P10 information

Length = 625.66 feet

Diameter = 2 1/2 inch

Fitting and valve

Size		1/2	3/4	1	1.25	1.5	2	2.5	3	3.5	4
Fittings	90deg	0	0	0	0	0	18	14	0	0	0
	T-Joint	0	0	0	0	0	5	4	0	0	0
	45deg	0	0	0	0	0	2	5	0	0	0
Valves	Ball valve	0	0	0	0	0	16	0	0	0	0
	Check valve	0	0	0	0	0	3	0	0	0	0
	Butterfly valve	N/A	N/A	N/A	N/A	N/A	0	0	0	0	0
	Globe valve	0	0	0	0	0	0	0	0	0	0
	Strainer	N/A	N/A	0	0	N/A	0	0	N/A	N/A	N/A

Equivalent length	Size	1/2	3/4	1	1 .25	1.5	2	2.5	3	3.5	4
Fittings	90deg	0	0	0	0	0	93.06	86.38	0	0	0
	T-Joint	0	0	0	0	0	17.25	16.48	0	0	0
	45deg	0	0	0	0	0	5.52	16.45	0	0	0
Valves	Ball valve	0	0	0	0	0	8.32	0	0	0	0
	Check valve	0	0	0	0	0	25.83	0	0	0	0
	Butterfly valve	N/A	N/A	N/A	N/A	N/A	0	0	0	0	0
	Globe valve	0	0	0	0	0	0	0	0	0	0
	Strainer	N/A	N/A	0	0	N/A	0	0	N/A	N/A	N/A
										sum	269.290

Total equivalent length = 894.95 feet

Table 4.11 P11 information

Length = 14.015 feet

Diameter = 4 inch

Fitting and valve

Size		1/2	3/4	1	1.25	1.5	2	2.5	3	3.5	4
Fittings	90deg	0	0	0	0	0	0	0	0	0	0
	T-Joint	0	0	0	0	0	0	0	0	0	0
	45deg	0	0	0	0	0	0	0	0	0	0
Valves	Ball valve	0	0	0	0	0	0	0	0	0	0
	Check valve	0	0	0	0	0	0	0	0	0	0
	Butterfly valve	N/A	N/A	N/A	N/A	N/A	0	0	0	0	0
	Globe valve	0	0	0	0	0	0	0	0	0	0
	Strainer	N/A	N/A	0	0	N/A	0	0	N/A	N/A	N/A

Equivalent length	Size	1/2	3/4	1	1.25	1.5	2	2.5	3	3.5	4
Fittings	90deg	0	0	0	0	0	0	0	0	0	0
	T-Joint	0	0	0	0	0	0	0	0	0	0
	45deg	0	0	0	0	0	0	0	0	0	0
Valves	Ball valve	0	0	0	0	0	0	0	0	0	0
	Check valve	0	0	0	0	0	0	0	0	0	0
	Butterfly valve	N/A	N/A	N/A	N/A	N/A	0	0	0	0	0
	Globe valve	0	0	0	0	0	0	0	0	0	0
	Strainer	N/A	N/A	0	0	N/A	0	0	N/A	N/A	N/A
										sum	0.000

Total equivalent length = 14.015 feet

Table 4.12 P12 information

Length = 106.206 feet

Diameter = 4 inch

Fitting and valve

Size		1/2	3/4	1	1.25	1.5	2	2.5	3	3.5	4
Fittings	90deg	0	0	0	0	0	0	0	1	0	0
	T-Joint	0	0	0	0	0	0	0	0	0	0
	45deg	0	0	0	0	0	0	0	0	0	0
Valves	Ball valve	0	0	0	0	0	0	0	0	0	0
	Check valve	0	0	0	0	0	0	0	0	0	0
	Butterfly valve	N/A	N/A	N/A	N/A	N/A	0	0	0	0	0
	Globe valve	0	0	0	0	0	0	0	0	0	0
	Strainer	N/A	N/A	0	0	N/A	0	0	N/A	N/A	N/A

Equivalent Length	Size	1/2	3/4	1	1.25	1.5	2	2.5	3	3.5	4
Fittings	90deg	0	0	0	0	0	0	0	7.67	0	0
	T-Joint	0	0	0	0	0	0	0	0	0	0
	45deg	0	0	0	0	0	0	0	0	0	0
Valves	Ball valve	0	0	0	0	0	0	0	0	0	0
	Check valve	0	0	0	0	0	0	0	0	0	0
	Butterfly valve	N/A	N/A	N/A	N/A	N/A	0	0	0	0	0
	Globe valve	0	0	0	0	0	0	0	0	0	0
	Strainer	N/A	N/A	0	0	N/A	0	0	N/A	N/A	N/A
										sum	7.670

Total equivalent length = 113.876 feet

Table 4.13 P13 information

Length = 366.526 feet

Diameter = 2 1/2 inch

Fitting and valve

Size		1/2	3/4	1	1.25	1.5	2	2.5	3	3.5	4
Fittings	90deg	0	0	0	0	20	20	3	7	0	0
	T-Joint	0	0	0	0	0	2	4	5	0	0
	45deg	0	0	0	0	0	0	0	0	0	0
Valves	Ball valve	0	0	0	0	2	5	0	0	0	0
	Check valve	0	0	0	0	0	0	0	0	0	0
	Butterfly valve	N/A	N/A	N/A	N/A	N/A	0	0	0	0	0
	Globe valve	0	0	0	0	0	0	0	0	0	0
	Strainer	N/A	N/A	0	0	N/A	0	0	N/A	N/A	N/A

Equivalent Length	Size	1/2	3/4	1	1.25	1.5	2	2.5	3	3.5	4
Fittings	90deg	0	0	0	0	80.6	103.4	18.51	53.69	0	0
	T-Joint	0	0	0	0	0	6.9	16.48	25.55	0	0
	45deg	0	0	0	0	0	0	0	0	0	0
Valves	Ball valve	0	0	0	0	0.8	2.6	0	0	0	0
	Check valve	0	0	0	0	0	0	0	0	0	0
	Butterfly valve	N/A	N/A	N/A	N/A	N/A	0	0	0	0	0
	Globe valve	0	0	0	0	0	0	0	0	0	0
	Strainer	N/A	N/A	0	0	N/A	0	0	N/A	N/A	N/A
										sum	308.530

Total equivalent length = 675.057 feet

Table 4.14 P14 information

Length = 39.547 feet

Diameter = 2 1/2 inch

Fitting and valve

Size		1/2	3/4	1	1.25	1.5	2	2.5	3	3.5	4
Fittings	90deg	0	0	0	0	0	0	0	0	0	0
	T-Joint	0	0	0	0	0	0	0	0	0	0
	45deg	0	0	0	0	0	0	0	0	0	0
Valves	Ball valve	0	0	0	0	0	0	0	0	0	0
	Check valve	0	0	0	0	0	0	0	0	0	0
	Butterfly valve	N/A	N/A	N/A	N/A	N/A	0	0	0	0	0
	Globe valve	0	0	0	0	0	0	0	0	0	0
	Strainer	N/A	N/A	0	0	N/A	0	0	N/A	N/A	N/A

Equivalent length	Size	1/2	3/4	1	1.25	1.5	2	2.5	3	3.5	4
Fittings	90deg	0	0	0	0	0	0	0	0	0	0
	T-Joint	0	0	0	0	0	0	0	0	0	0
	45deg	0	0	0	0	0	0	0	0	0	0
Valves	Ball valve	0	0	0	0	0	0	0	0	0	0
	Check valve	0	0	0	0	0	0	0	0	0	0
	Butterfly valve	N/A	N/A	N/A	N/A	N/A	0	0	0	0	0
	Globe valve	0	0	0	0	0	0	0	0	0	0
	Strainer	N/A	N/A	0	0	N/A	0	0	N/A	N/A	N/A
										sum	0.000

Total equivalent length = 39.547 feet

Table 4.15 P15 information

Length = 178.166 feet

Diameter = 2 1/2 inch

Fitting and valve

Size		1/2	3/4	1	1.25	1.5	2	2.5	3	3.5	4
Fittings	90deg	0	0	0	0	0	2	10	0	0	0
	T-Joint	0	0	0	0	0	0	2	0	0	0
	45deg	0	0	0	0	0	0	0	0	0	0
Valves	Ball valve	0	0	0	0	0	0	1	0	0	0
	Check valve	0	0	0	0	0	0	0	0	0	0
	Butterfly valve	N/A	N/A	N/A	N/A	N/A	0	0	0	0	0
	Globe valve	0	0	0	0	0	0	0	0	0	0
	Strainer	N/A	N/A	0	0	N/A	0	0	N/A	N/A	N/A

Equivalent Length	Size	1/2	3/4	1	1.25	1.5	2	2.5	3	3.5	4
Fittings	90deg	0	0	0	0	0	10.34	61.7	0	0	0
	T-Joint	0	0	0	0	0	0	8.24	0	0	0
	45deg	0	0	0	0	0	0	0	0	0	0
Valves	Ball valve	0	0	0	0	0	0	0.62	0	0	0
	Check valve	0	0	0	0	0	0	0	0	0	0
	Butterfly valve	N/A	N/A	N/A	N/A	N/A	0	0	0	0	0
	Globe valve	0	0	0	0	0	0	0	0	0	0
	Strainer	N/A	N/A	0	0	N/A	0	0	N/A	N/A	N/A
										sum	80.900

Total equivalent length = 259.066 feet

Table 4.16 P16 information

Length = 23.983 feet

Diameter = 3 inch

Fitting and valve

Size		1/2	3/4	1	1.25	1.5	2	2.5	3	3.5	4
Fittings	90deg	0	0	0	0	0	0	0	1	0	4
	T-Joint	0	0	0	0	0	0	0	1	0	0
	45deg	0	0	0	0	0	0	0	0	0	0
Valves	Ball valve	0	0	0	0	0	0	0	0	0	1
	Check valve	0	0	0	0	0	0	0	0	0	0
	Butterfly valve	N/A	N/A	N/A	N/A	N/A	0	0	0	0	0
	Globe valve	0	0	0	0	0	0	0	0	0	0
	Strainer	N/A	N/A	0	0	N/A	0	0	N/A	N/A	N/A

Equivalent Length	Size	1/2	3/4	1	1.25	1.5	2	2.5	3	3.5	4
Fittings	90deg	0	0	0	0	0	0	0	7.67	0	40.28
	T-Joint	0	0	0	0	0	0	0	5.11	0	0
	45deg	0	0	0	0	0	0	0	0	0	0
Valves	Ball valve	0	0	0	0	0	0	0	0	0	1.01
	Check valve	0	0	0	0	0	0	0	0	0	0
	Butterfly valve	N/A	N/A	N/A	N/A	N/A	0	0	0	0	0
	Globe valve	0	0	0	0	0	0	0	0	0	0
	Strainer	N/A	N/A	0	0	N/A	0	0	N/A	N/A	N/A
										sum	54.070

Total equivalent length = 78.053 feet

Table 4.17 P17 information

Length = 157.643 feet

Diameter = 3 inch

Fitting and valve

Size		1/2	3/4	1	1.25	1.5	2	2.5	3	3.5	4
Fittings	90deg	0	0	0	0	3	0	0	3	0	0
	T-Joint	0	0	0	0	1	0	0	0	0	0
	45deg	0	0	0	0	0	0	0	2	0	0
Valves	Ball valve	0	0	0	0	0	0	0	0	0	0
	Check valve	0	0	0	0	0	0	0	0	0	0
	Butterfly valve	N/A	N/A	N/A	N/A	N/A	0	0	0	0	0
	Globe valve	0	0	0	0	0	0	0	0	0	0
	Strainer	N/A	N/A	0	0	N/A	0	0	N/A	N/A	N/A

Equivalent Length	Size	1/2	3/4	1	1.25	1.5	2	2.5	3	3.5	4
Fittings	90deg	0	0	0	0	12.09	0	0	23.01	0	0
	T-Joint	0	0	0	0	2.68	0	0	0	0	0
	45deg	0	0	0	0	0	0	0	8.18	0	0
Valves	Ball valve	0	0	0	0	0	0	0	0	0	0
	Check valve	0	0	0	0	0	0	0	0	0	0
	Butterfly valve	N/A	N/A	N/A	N/A	N/A	0	0	0	0	0
	Globe valve	0	0	0	0	0	0	0	0	0	0
	Strainer	N/A	N/A	0	0	N/A	0	0	N/A	N/A	N/A
										sum	45.960

Total equivalent length = 203.603 feet

Table 4.18 P18 information

Length = 178.068 feet

Diameter = 3 inch

Fitting and valve

Size		1/2	3/4	1	1.25	1.5	2	2.5	3	3.5	4
Fittings	90deg	0	0	0	0	3	0	0	0	0	0
	T-Joint	0	0	0	0	1	0	0	0	0	0
	45deg	0	0	0	0	0	0	0	0	0	0
Valves	Ball valve	0	0	0	0	0	0	0	0	0	0
	Check valve	0	0	0	0	0	0	0	0	0	0
	Butterfly valve	N/A	N/A	N/A	N/A	N/A	0	0	0	0	0
	Globe valve	0	0	0	0	0	0	0	0	0	0
	Strainer	N/A	N/A	0	0	N/A	0	0	N/A	N/A	N/A

Equivalent length	Size	1/2	3/4	1	1.25	1.5	2	2.5	3	3.5	4
Fittings	90deg	0	0	0	0	12.09	0	0	0	0	0
	T-Joint	0	0	0	0	2.68	0	0	0	0	0
	45deg	0	0	0	0	0	0	0	0	0	0
Valves	Ball valve	0	0	0	0	0	0	0	0	0	0
	Check valve	0	0	0	0	0	0	0	0	0	0
	Butterfly valve	N/A	N/A	N/A	N/A	N/A	0	0	0	0	0
	Globe valve	0	0	0	0	0	0	0	0	0	0
	Strainer	N/A	N/A	0	0	N/A	0	0	N/A	N/A	N/A
										sum	14.770

Total equivalent length = 192.838 feet

Table 4.19 P19 information

Length = 282.795 feet

Diameter = 3 inch

Fitting and valve

Size		1/2	3/4	1	1.25	1.5	2	2.5	3	3.5	4
Fittings	90deg	0	0	0	0	0	0	0	1	0	0
	T-Joint	0	0	0	0	0	0	0	0	0	0
	45deg	0	0	0	0	0	0	0	0	0	0
Valves	Ball valve	0	0	0	0	0	0	0	0	0	0
	Check valve	0	0	0	0	0	0	0	0	0	0
	Butterfly valve	N/A	N/A	N/A	N/A	N/A	0	0	0	0	0
	Globe valve	0	0	0	0	0	0	0	0	0	0
	Strainer	N/A	N/A	0	0	N/A	0	0	N/A	N/A	N/A

Equivalent length	Size	1/2	3/4	1	1.25	1.5	2	2.5	3	3.5	4
Fittings	90deg	0	0	0	0	0	0	0	7.67	0	0
	T-Joint	0	0	0	0	0	0	0	0	0	0
	45deg	0	0	0	0	0	0	0	0	0	0
Valves	Ball valve	0	0	0	0	0	0	0	0	0	0
	Check valve	0	0	0	0	0	0	0	0	0	0
	Butterfly valve	N/A	N/A	N/A	N/A	N/A	0	0	0	0	0
	Globe valve	0	0	0	0	0	0	0	0	0	0
	Strainer	N/A	N/A	0	0	N/A	0	0	N/A	N/A	N/A
										sum	7.670

Total equivalent length = 290.465 feet

Table 4.20 P20 information

Length = 30.743 feet

Diameter = 3 inch

Fitting and valve

Size		1/2	3/4	1	1.25	1.5	2	2.5	3	3.5	4
Fittings	90deg	0	0	0	0	0	0	0	4	0	
	T-Joint	0	0	0	0	0	0	0	0	0	0
	45deg	0	0	0	0	0	0	0	0	0	0
Valves	Ball valve	0	0	0	0	0	0	0	0	0	0
	Check valve	0	0	0	0	0	0	0	0	0	0
	Butterfly valve	N/A	N/A	N/A	N/A	N/A	0	0	1	0	0
	Globe valve	0	0	0	0	0	0	0	0	0	0
	Strainer	N/A	N/A	0	0	N/A	0	0	N/A	N/A	N/A

Equivalent Length	Size	1/2	3/4	1	1.25	1.5	2	2.5	3	3.5	4
Fittings	90deg	0	0	0	0	0	0	0	30.68	0	0
	T-Joint	0	0	0	0	0	0	0	0	0	0
	45deg	0	0	0	0	0	0	0	0	0	0
Valves	Ball valve	0	0	0	0	0	0	0	0	0	0
	Check valve	0	0	0	0	0	0	0	0	0	0
	Butterfly valve	N/A	N/A	N/A	N/A	N/A	0	0	11.51	0	0
	Globe valve	0	0	0	0	0	0	0	0	0	0
	Strainer	N/A	N/A	0	0	N/A	0	0	N/A	N/A	N/A
										sum	42.190

Total equivalent length = 72.933 feet

Table 4.21 P21 information

Length = 47.09 feet

Diameter = 3 inch

Fitting and valve

Size		1/2	3/4	1	1.25	1.5	2	2.5	3	3.5	4
Fittings	90deg	0	0	0	0	0	0	0	6	0	0
	T-Joint	0	0	0	0	0	0	0	0	0	0
	45deg	0	0	0	0	0	0	0	0	0	0
Valves	Ball valve	0	0	0	0	0	0	0	0	0	0
	Check valve	0	0	0	0	0	0	0	0	0	0
	Butterfly valve	N/A	N/A	N/A	N/A	N/A	0	0	1	0	0
	Globe valve	0	0	0	0	0	0	0	0	0	0
	Strainer	N/A	N/A	0	0	N/A	0	0	N/A	N/A	N/A

Equivalent length	Size	1/2	3/4	1	1.25	1.5	2	2.5	3	3.5	4
Fittings	90deg	0	0	0	0	0	0	0	46.02	0	0
	T-Joint	0	0	0	0	0	0	0	0	0	0
	45deg	0	0	0	0	0	0	0	0	0	0
Valves	Ball valve	0	0	0	0	0	0	0	0	0	0
	Check valve	0	0	0	0	0	0	0	0	0	0
	Butterfly valve	N/A	N/A	N/A	N/A	N/A	0	0	11.51	0	0
	Globe valve	0	0	0	0	0	0	0	0	0	0
	Strainer	N/A	N/A	0	0	N/A	0	0	N/A	N/A	N/A
										sum	57.530

Total equivalent length = 104.621 feet

Table 4.22 P22 information

Length = 16.439 feet

Diameter = 3 inch

Fitting and valve

Size		1/2	3/4	1	1.25	1.5	2	2.5	3	3.5	4
Fittings	90deg	0	0	0	0	0	0	0	2	0	0
	T-Joint	0	0	0	0	0	0	0	0	0	0
	45deg	0	0	0	0	0	0	0	0	0	0
Valves	Ball valve	0	0	0	0	0	0	0	0	0	0
	Check valve	0	0	0	0	0	0	0	0	0	0
	Butterfly valve	N/A	N/A	N/A	N/A	N/A	0	0	0	0	0
	Globe valve	0	0	0	0	0	0	0	1	0	0
	Strainer	N/A	N/A	0	0	N/A	0	0	N/A	N/A	N/A

Equivalent Length	Size	1/2	¾	1	1.25	1.5	2	2.5	3	3.5	4
Fittings	90deg	0	0	0	0	0	0	0	15.34	0	0
	T-Joint	0	0	0	0	0	0	0	0	0	0
	45deg	0	0	0	0	0	0	0	0	0	0
Valves	Ball valve	0	0	0	0	0	0	0	0	0	0
	Check valve	0	0	0	0	0	0	0	0	0	0
	Butterfly valve	N/A	N/A	N/A	N/A	N/A	0	0	0	0	0
	Globe valve	0	0	0	0	0	0	0	86.93	0	0
	Strainer	N/A	N/A	0	0	N/A	0	0	N/A	N/A	N/A
										sum	102.270

Total equivalent length = 118.709 feet

4.3.2 Flow rate in each group of pipe

According to chapter 3, there is the determination of flow rate of each machine in a different group of pipes from various methods which will be shown in the following paragraph.

- Measured data by operator: Some flow rate data are collected from operator who monitor the machine at specific time which will show in CHW-cost.xlsx file
- From the production department: The production department of the factory also collects the machine operating data. This method is similar to the previous one, but more presently.
- From manufacturer data: From field survey, we can find the name plates of some machines which can indicate their model. So, we can search for the machine needed data from manufacturer website
- Estimate from schedule 40 pipe chart: For the estimation method, we use pipe chart of schedule 40 pipe to specify the flow rate.

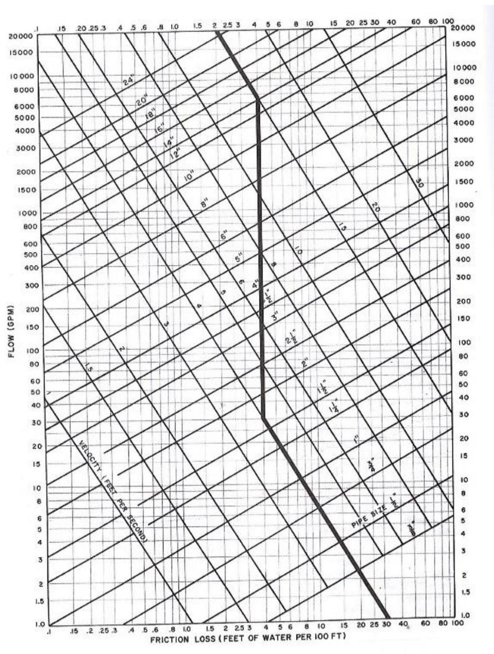


Figure 4-9 Pipe chart of schedule 40 steel pipe

From Figure 4-9, the chart is including the value of diameter of pipe and velocity. Diameter of the pipe can collect the data from the field survey and velocity can use the average value from the table below.

Table 4.23 Recommended fluid velocity in pipe (feet per second)

Services	velocity range (fps)
pump suction	8-12
pump discharge	4-7
main pipe	4-15
vertical pipe	3-10
branches and general pipe	5-10

The table mentions the velocity range of water in general pipe is 5-10 fps which will be used in our estimation and the mean of 5 fps and 10 fps is 7.5 fps. So we will use this value as an approximate value of water velocity in the factory.

After knowing water velocity, we have to match it with the pipe diameter. All the step will be explained in the following example.

Example

Table 4.24 Comparison of flow rate determination from 2 different method

Equipment	NPS	Q (gpm)	NOTE
Plate Past Tetra Pak	1 1/4	35	Estimation from pipe sch40 chart
Almix	1 1/2	35.2232	Operating data

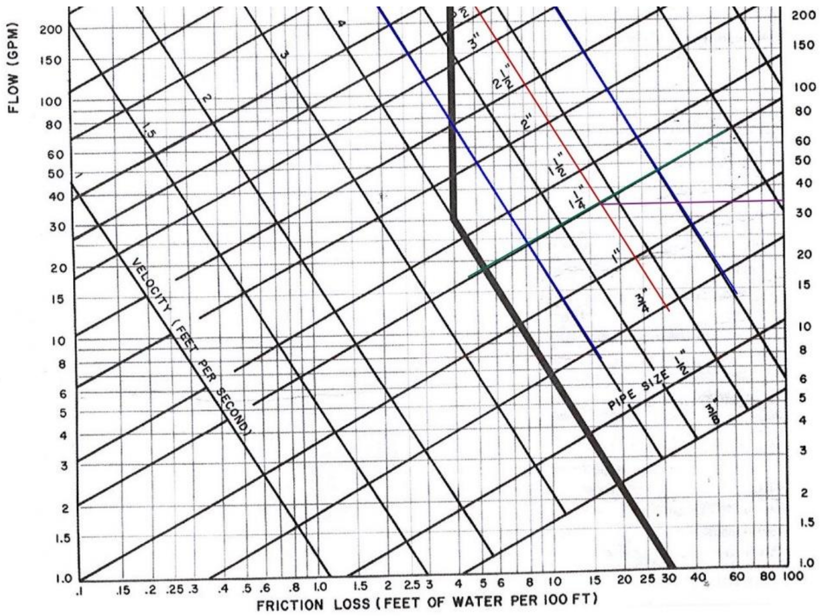


Figure 4-10 Example of determine flow rate from pipe chart

In this example, we will compare the flow rate of 2 equipment with different methods of estimate flow rate which are using pipe sch40 charts and operating data.

For pipe sch40 chart method, we know the mean velocity of water in pipe and nominal pipe size of equipment is selected. After that, we can see the intersection of lines of these values as shown in Figure 4-10. Then, if we draw a line to the right of the intersection point, we can determine the value of flow rate.

According to Table 4.24 it shows the flow rate that is considered from 2 different methods which are estimation from pipe chart and operating data. Flow rate from operation data of 1 ½ NPS pipe is 35.2232 gpm and from estimation of 1 ¼ pipe is 35 gpm.

We can see that the values are not that much different which can confirm that this method can be used.

4.3.3 Pump curve

From topic 3.2.1 Pump information, we can find the coordination in pump curves which are flow rate 'Q' in gallons per minute and Head 'H' in feet.

Table 4.25 Pump Curve of TP 80-330/2 A-F-A-BQQE-NX1

Q	H
100	104.987
300	101.706
350	98.4252
400	95.1444
450	91.8635
500	83.66142

Table 4.26 Pump Curve of LP 80-160/164 A-F-A-BBUE

Q	H
100	104.987
150	101.706
200	98.4252
200	95.1444
250	91.8635
300	83.66142

Table 4.27 Pump Curve of NBG 80-65-160/177

Q	H
48	146
100	145.8
150	145.5
200	145
250	144
300	141.5
350	136
400	130
450	120

4.3.4 Validation of Equivalent length method

According to 4.3.1, we use equivalent length as compute value in the software. But it also requires us to compute loss coefficient which already consider in term of equivalent length. Loss coefficient or K_L is the variable that use for calculating minor loss which already refer in chapter 2. This topic will discuss about the comparison of computing loss coefficient (program algorithm) and equivalent length (used method) which will use pressure drop to be checking value.

<u>Loss coefficient computing method</u>

Component	K_L
a. Elbows	
Regular 90°, flanged	0.3
Regular 90°, threaded	1.5
Long radius 90°, flanged	0.2
Long radius 90°, threaded	0.7
Long radius 45°, flanged	0.2
Regular 45°, threaded	0.4
b. 180° return bends	
180° return bend, flanged	0.2
180° return bend, threaded	1.5
c. Tees	
Line flow, flanged	0.2
Line flow, threaded	0.9
Branch flow, flanged	1.0
Branch flow, threaded	2.0
d. Union, threaded	0.08
***e. Valves**	
Globe, fully open	10
Angle, fully open	2
Gate, fully open	0.15
Gate, $\frac{1}{4}$ closed	0.26
Gate, $\frac{1}{2}$ closed	2.1
Gate, $\frac{3}{4}$ closed	17
Swing check, forward flow	2
Swing check, backward flow	∞
Ball valve, fully open	0.05
Ball valve, $\frac{1}{3}$ closed	5.5
Ball valve, $\frac{2}{3}$ closed	210

*See Fig. 8.32 for typical valve geometry.

Figure 4-11 Loss coefficient of fitting and valve

Figure 4-11 show the value loss coefficient which dependent on geometry. So, each fitting and valve have the different values. After known the total loss coefficient, we will compute the value to software and run calculation in order to get pressure drop value.

The following paragraph will be shown the comparison of two different methods which will use pipe P10 to be our case study.

- Step 1: Indicate number and type of joint and valve. Then, open loss coefficient table and find the total loss coefficient in that pipe.

Fitting and Valve	K_L	Amount	Total K_L
90-degree joint	1.5	32	48
T joint	2.0	9	18
45-degree joint	0.4	7	2.8
Ball valve	0.06	16	0.8
Check valve	2	3	6
		Total	75.6

- Step 2: Add valve in the pipe line and compute the value of loss coefficient and actual length in the software.

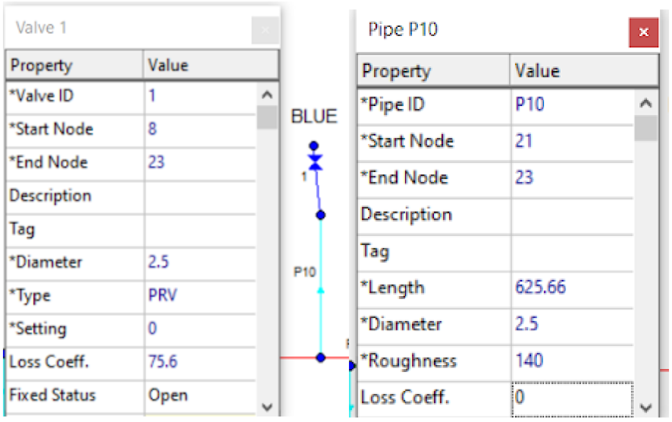


Figure 4-12 Valve adding and value computing in software

- Step 3: Run calculation and collect pressure drop value

Upstream pressure (psi)	17.94
Downstream pressure (psi)	0.05

- Step 4: Run the calculation of equivalent length method and collect pressure drop value.

Upstream pressure (psi)	19.03
Downstream pressure (psi)	0.04

- Step 5: Calculate pressure drop value of these different case and make a comparison

	Equivalent length case	Loss coefficient case
P upstream (psi)	19.03	17.94
P downstream (psi)	0.04	0.05
P drop (psi)	18.99	17.89

From the solution, we can make a conclusion that the percentage error of two different method is equal to 6.15 percent which is an acceptable amount. Moreover, the value used case is more than the method that software provided which can be consider as safety factor of designed system.

4.4 Existing system simulation on EPANET 2.2

We input the parameters which are

- Equivalent length of the pipes
- Diameter of the pipes.
- The roughness of the pipes*

*Note that the roughness is the Hazen-Williams constant of the steel pipe which is 140.

Link ID	Length ft	Diameter in	Roughness
Pipe P7	117.102	4	140
Pipe P21	104.621	3	140
Pipe P22	118.709	3	140
Pipe P1	653.944	4	140
Pipe P2	248.184	0.5	140
Pipe P6	344.180	3	140
Pipe P10	894.95	2.5	140
Pipe P8	578.006	2.5	140
Pipe P9	2.69	4	140
Pipe P19	290.465	3	140
Pipe P16	78.053	3	140
Pipe P13	675.057	2.5	140
Pipe P14	39.547	2.5	140
Pipe P17	203.603	3	140
Pipe P15	259.066	2.5	140
Pipe P18	192.838	3	140
Pipe P20	72.933	3	140
Pipe P3	77.230	4	140
Pipe P5	67.184	4	140
Pipe P4	425.832	2.5	140
Pipe P11	14.015	4	140

Figure 4-13 Table of all input data

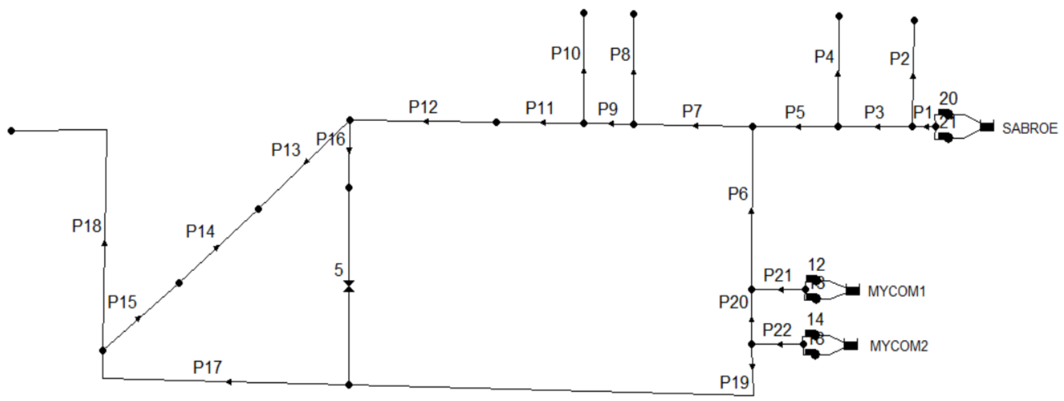


Figure 4-14 ID of the pipes in the system

As for the demands of the various lines in the system, these are values that we must input into the property of junction. (From topic 3.2.2 Pipe information)

Node ID	Demand GPM
Junc 3	0.00
Junc 4	0.00
Junc 5	0.00
Junc 12	0.00
Junc 13	0.00
Junc 14	0.00
Junc 15	0.00
Junc 18	0.00
Junc 19	0.44
Junc Yellow	167.09
Junc 21	0.00
Junc 22	0.00
Junc Blue	138.40
Junc 24	0.00
Junc Red2	35.22
Junc Orange2	6.60
Junc Orange1	260.47
Junc 28	0.00
Junc Purple	0.44
Junc 30	0.00
Junc 31	50.60
Junc Red1	249.83

Figure 4-15 Input demand at all junctions

After inputting the parameters into our system, we will have to configure the hydraulic option that we will use to solve our system. And click Run Calculation.

Hydraulics Options

Property	Value
Flow Units	GPM
Headloss Formula	H-W
Specific Gravity	1
Relative Viscosity	1
Maximum Trials	40
Accuracy	0.001
If Unbalanced	Continue
Default Pattern	1
Demand Multiplier	1.0
Emitter Exponent	0.5
Status Report	Yes
Max. Head Error	0
Max. Flow Change	0
Demand Model	PDA
Minimum Pressure	29
Required Pressure	29.1
Pressure Exponent	0.5
CHECKFREQ	2
MAXCHECK	10
DAMPLIMIT	0

Figure 4-16 Hydraulic option input window

4.5 Result

Figure 4-17, Figure 4-18 and Figure 4-19 are the result of system simulation of the chilled water system. Figure 4-17 shows results of pressure at every junction and chilled water flow rate at every pipe of the system. The Figure 4-17 also represents simulation of operating system at 100 percent system load, the result shows that the pumps cannot supply chilled water for blue, yellow and orange (1) production lines adequately, which require minimum pressure at 29 psi or 2 bar. The pump number 20 of SABROE chiller system cannot deliver enough head for the system, which causes self-shutdown of the pump. From Figure 4-7, The shade of colors on junctions and lines represents value of pressure and flow rate of water in the pipes, respectively.

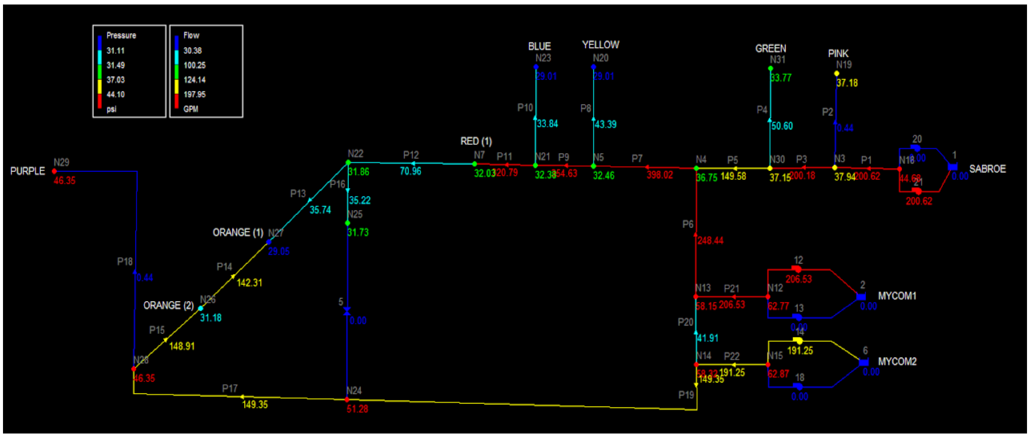


Figure 4-17 Chilled water system simulation at minimum pressure required 29 psi

In Figure 4-18, The demand flow rate or actual flow rate of Junction N20, N23 and N27 are less than base demand flow rate, which means pumps have not enough head to deliver chilled water for blue, yellow and orange (1) production lines at 100 percent system load due to high demand of pressure and flow rate because of limit by pipe size.

Network Table - Nodes

Node ID	Base Demand GPM	Demand GPM	Head ft	Pressure psi
Junc N3	0	0.00	87.57	37.94
Junc N4	0	0.00	84.81	36.75
Junc N5	0	0.00	74.90	32.46
Junc N12	0	0.00	144.87	62.77
Junc N13	0	0.00	134.21	58.15
Junc N14	0	0.00	134.59	58.32
Junc N15	0	0.00	145.09	62.87
Junc N18	0	0.00	103.12	44.68
Junc N19	0.44	0.44	85.81	37.18
Junc N20	167.087	43.39	66.94	29.01
Junc N21	0	0.00	74.72	32.38
Junc N22	0	0.00	73.53	31.86
Junc N23	138.402	33.84	66.94	29.01
Junc N24	0	0.00	118.35	51.28
Junc N25	35.22	35.22	73.23	31.73
Junc N26	6.60	6.60	71.95	31.18
Junc N27	260.47	178.05	67.04	29.05
Junc N28	0	0.00	106.97	46.35
Junc N29	0.44	0.44	106.97	46.35
Junc N30	0	0.00	85.74	37.15
Junc N31	50.6	50.60	77.94	33.77
Junc N7	249.83	249.83	73.93	32.03
Resvr 1	#N/A	-200.62	0.00	0.00
Resvr 2	#N/A	-206.53	0.00	0.00
Resvr 6	#N/A	-191.25	0.00	0.00

Figure 4-18 Network Table - Nodes

The Figure 4-19 shows that pipe P7, P21, P22, P6, P9, P14 and P15 exceeds the maximum flow rate of variable flow/variable speed of >4400 hours/year in ASHRAE 90.1 Standard from table 2.3 in chapter 2.

Network Table - Links

Link ID	Length ft	Diameter in	Roughness	Flow GPM	Velocity fps	Unit Headloss ft/Kft	Friction Factor	Status
Pipe P7	117.102	4	140	398.02	10.16	84.60	0.018	Open
Pipe P21	104.621	3	140	206.53	9.37	101.93	0.019	Open
Pipe P22	118.709	3	140	191.25	8.68	88.40	0.019	Open
Pipe P1	653.944	4	140	200.62	5.12	23.79	0.019	Open
Pipe P2	248.184	0.5	140	0.44	0.72	7.10	0.037	Open
Pipe P6	344.180	3	140	248.44	11.28	143.51	0.018	Open
Pipe P10	894.95	2.5	140	33.84	2.21	8.69	0.024	Open
Pipe P8	578.006	2.5	140	43.39	2.84	13.77	0.023	Open
Pipe P9	2.69	4	140	354.63	9.05	68.32	0.018	Open
Pipe P19	290.465	3	140	149.35	6.78	55.92	0.020	Open
Pipe P16	78.053	3	140	35.22	1.60	3.85	0.024	Open
Pipe P13	675.057	2.5	140	35.74	2.34	9.62	0.024	Open
Pipe P14	39.547	2.5	140	142.31	9.30	124.28	0.019	Open
Pipe P17	203.603	3	140	149.35	6.78	55.92	0.020	Open
Pipe P15	259.066	2.5	140	148.91	9.73	135.16	0.019	Open
Pipe P18	192.838	3	140	0.44	0.02	0.00	0.046	Open
Pipe P20	72.933	3	140	41.91	1.90	5.31	0.024	Open
Pipe P3	77.230	4	140	200.18	5.11	23.69	0.019	Open
Pipe P5	67.184	4	140	149.58	3.82	13.81	0.020	Open
Pipe P4	425.832	2.5	140	50.60	3.31	18.31	0.022	Open
Pipe P11	14.015	4	140	320.79	8.19	56.74	0.018	Open
Pipe P12	113.876	4	140	70.96	1.81	3.47	0.023	Open
Pump 12	#N/A	#N/A	#N/A	206.53	0.00	-144.87	0.000	Open
Pump 13	#N/A	#N/A	#N/A	0.00	0.00	0.00	0.000	Closed
Pump 14	#N/A	#N/A	#N/A	191.25	0.00	-145.09	0.000	Open
Pump 18	#N/A	#N/A	#N/A	0.00	0.00	0.00	0.000	Closed
Pump 20	#N/A	#N/A	#N/A	0.00	0.00	0.00	0.000	Closed
Pump 21	#N/A	#N/A	#N/A	200.62	0.00	-103.12	0.000	Open
Valve 5	#N/A	12	#N/A	0.00	0.00	0.00	0.000	Closed

Figure 4-19 Network Table - Links

In conclusion, the result shows the shortcomings of the system, which are minimum pressure and flow rate required at 100 percent system demand. Therefore, changing pipe size is an option to decrease pressure drop in the pipes that have long pipe length and a lot of fittings, which followed ASHRAE 90.1 standard. The details of improvement will be discussed in topic 4.6.

4.6 Improvement

4.6.1 Improvement of pipe

The result of current system simulation by setting the minimum pressure at terminal equal to 29.1 psi or 2 bar production lines shows that some of the pipes exceed maximum flow rate recommended of ASHRAE Standard 90.1 and below than required flow rate of production lines. By changing pipe size, the improved system can fulfill the chilled water demand of the production lines.

Table 4.28 shows the result of pipe size improvement that the pipe size selections are based on ASHRAE Standard 90.1 recommended flow rate according to the size of pipe and considered from demand of the production lines. Pipes P6, P7, P9, P11, P14, P15, P21 and P22 are undersized for 100 percent demand flow rate of production, which is considered by Table 2-3 to select the appropriate size. Pipes P8, P10, P14 and P15 original size are unable to deliver adequate flow rate to fulfill the demand of the production line. The result shows that improved pressure of pipes P8, P10, P13, P14 and P15 are higher than the base pressure of simulation with adequate flow rate for the production lines.

In particular, some of the pipes are still undersized for 100 percent demand load. For this reason, most of the production demand flow rate is from estimation, which is high-rate estimation. Therefore, the actual working system will have less flow rate from simulation and save the economic cost of a bigger size of pipe.

Table 4.28 Improved pipe

Name	Original Diameter (inch)	Original Flow rate (GPM)	Improved Diameter (inch)	Improved Flow rate (GPM)	$P_{original}$/ $P_{improved}$	Note
P6	3	248.44	6	615.37	-	Flow rate exceed ASHRAE standard for 3 inch pipe (Table 2.3)
P7	4	398.02	6	701.28	-	Flow rate exceed ASHRAE standard for 4 inch pipe (Table 2.3)
P8	2.5	43.4	4	167.09	29.01/38.24	Actual Flow rate lower than Demand Flow rate at Node 20 (Yellow)
P9	4	354.63	6	534.19	-	Flow rate exceed ASHRAE standard for 4 inch pipe (Table 2.3)
P10	2.5	33.84	4	138.40	29.01/38.67	Actual Flow rate lower than Demand Flow rate at Node 23 (Blue)

Table 4.28 Improved pipe (continue)

Name	Original Diameter (inch)	Original Flow rate (GPM)	Improved Diameter (inch)	Improved Flow rate (GPM)	$P_{original}$/ $P_{improved}$	Note
P11	4	320.79	6	395.78	-	Flow rate exceed ASHRAE standard for 4 inch pipe (Table 2-3)
P13	2.5	35.74	3	110.73	-	Actual Flow rate lower than Demand Flow rate at Node 27 (Orange (1))
P14	2.5	142.31	3	149.74	29.05/33.46	Flow rate exceed ASHRAE standard for 2.5 inch pipe (Table 2.3) and Actual Flow rate lower than Demand Flow rate at Node 27 (Orange (1))

Table 4.28 Improved pipe (continue)

Name	Original Diameter (inch)	Original Flow rate (GPM)	Improved Diameter (inch)	Improved Flow rate (GPM)	$P_{original}$/ $P_{improved}$	Note
P15	2.5	148.91	3	156.34	29.05/33.46	Flow rate exceed ASHRAE standard for 2.5 inch pipe (Table 2.3) and Actual Flow rate lower than Demand Flow rate at Node 27 (Orange (1))
P21	3	206.53	4	413.92	-	Flow rate exceed ASHRAE standard for 3 inch pipe (Table 2.3)
P22	3	191.25	4	358.22	-	Flow rate exceed ASHRAE standard for 3 inch pipe (Table 2.3)

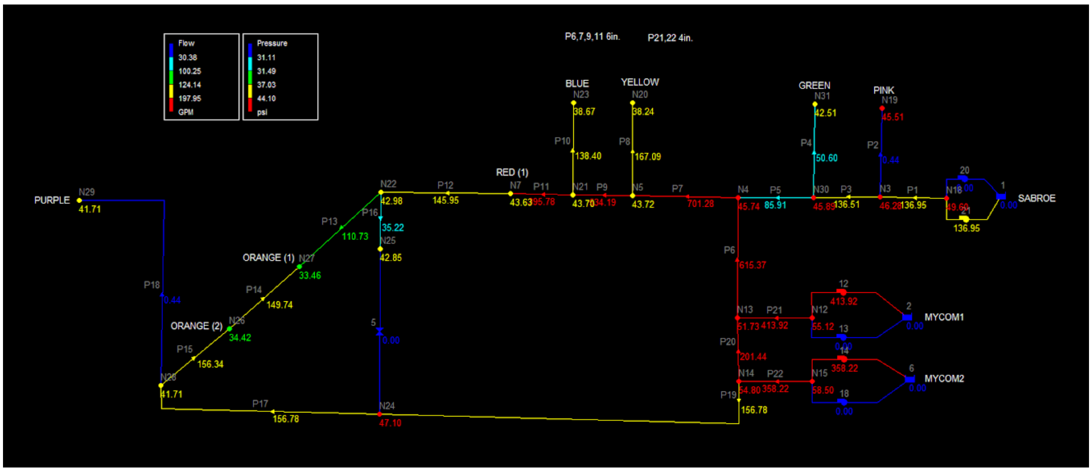


Figure 4-20 Result pressure and water flow rate of the improved system

Network Table - Nodes

Node ID	Base Demand GPM	Demand GPM	Head ft	Pressure psi
Junc N3	0	0.00	106.80	46.28
Junc N4	0	0.00	105.57	45.74
Junc N5	0	0.00	100.91	43.72
Junc N12	0	0.00	127.22	55.12
Junc N13	0	0.00	119.38	51.73
Junc N14	0	0.00	126.48	54.80
Junc N15	0	0.00	135.01	58.50
Junc N18	0	0.00	114.47	49.60
Junc N19	0.44	0.44	105.04	45.51
Junc N20	167.09	167.09	88.25	38.24
Junc N21	0	0.00	100.85	43.70
Junc N22	0	0.00	99.19	42.98
Junc N23	138.402	138.40	89.25	38.67
Junc N24	0	0.00	108.71	47.10
Junc N25	35.22	35.22	98.89	42.85
Junc N26	6.60	6.60	79.44	34.42
Junc N27	260.47	260.47	77.22	33.46
Junc N28	0	0.00	96.25	41.71
Junc N29	0.44	0.44	96.25	41.71
Junc N30	0	0.00	105.90	45.89
Junc N31	50.6	50.60	98.10	42.51
Junc N7	249.83	249.83	100.69	43.63
Resvr 1	#N/A	-136.95	0.00	0.00
Resvr 2	#N/A	-413.92	0.00	0.00
Resvr 6	#N/A	-358.22	0.00	0.00

Figure 4-21 Network Table – Nodes (Improved)

Network Table - Links

Link ID	Length ft	Diameter in	Roughness	Flow GPM	Velocity fps	Status
Pipe P7	139.17	6	140	701.28	7.96	Open
Pipe P21	86.123	4	140	413.92	10.57	Open
Pipe P22	122.611	4	140	358.22	9.15	Open
Pipe P1	653.944	4	140	136.95	3.50	Open
Pipe P2	248.184	0.5	140	0.44	0.72	Open
Pipe P6	524.98	6	140	615.37	6.98	Open
Pipe P10	970.31	4	140	138.40	3.53	Open
Pipe P8	746.786	4	140	167.09	4.27	Open
Pipe P9	2.69	6	140	534.19	6.06	Open
Pipe P19	290.465	3	140	156.78	7.12	Open
Pipe P16	78.053	3	140	35.22	1.60	Open
Pipe P13	683.52	3	140	110.73	5.03	Open
Pipe P14	39.547	3	140	149.74	6.80	Open
Pipe P17	203.603	3	140	156.78	7.12	Open
Pipe P15	276.196	3	140	156.34	7.10	Open
Pipe P18	192.838	3	140	0.44	0.02	Open
Pipe P20	72.933	3	140	201.44	9.14	Open
Pipe P3	77.230	4	140	136.51	3.49	Open
Pipe P5	67.184	4	140	85.91	2.19	Open
Pipe P4	425.832	2.5	140	50.60	3.31	Open
Pipe P11	14.015	6	140	395.78	4.49	Open
Pipe P12	113.876	4	140	145.95	3.73	Open
Pump 12	#N/A	#N/A	#N/A	413.92	0.00	Open
Pump 13	#N/A	#N/A	#N/A	0.00	0.00	Closed
Pump 14	#N/A	#N/A	#N/A	358.22	0.00	Open
Pump 18	#N/A	#N/A	#N/A	0.00	0.00	Closed
Pump 20	#N/A	#N/A	#N/A	0.00	0.00	Closed
Pump 21	#N/A	#N/A	#N/A	136.95	0.00	Open
Valve 5	#N/A	12	#N/A	0.00	0.00	Closed

Figure 4-22 Network Table – Links (Improved)

4.6.2 Improvement of pumps

The energy consumption of distribution pumps are also improved. As you can see in the figure 4-22, The average efficiency of the improved system are higher than the average efficiency of existing system in figure 4-23 about 12 percent approximately for pump 12, 13 (MYCOM-1), 14 and 18 (MYCOM-2) and the energy consumption of MYCOM's pumps to deliver one mega gallon of chilled water are lower than the existing system about 150 kilowatts hours of electricity per mega gallon (kW-hr/Mgal) and 36.03 kW-hr/Mgal for SABROE-2's pump.

Pump	Percent Utilization	Average Efficiency	Kw-hr /Mgal
12	100.00	63.05	721.90
13	0.00	0.00	0.00
14	100.00	60.43	754.33
18	0.00	0.00	0.00
20	0.00	0.00	0.00
21	100.00	68.94	469.95

Figure 4-23 Energy Table (Existing system)

Pump	Percent Utilization	Average Efficiency	Kw-hr /Mgal
12	100.00	75.42	570.93
13	0.00	0.00	0.00
14	100.00	73.40	602.58
18	0.00	0.00	0.00
20	0.00	0.00	0.00
21	100.00	65.39	433.92

Figure 4-24 Energy Table (Improved system)

Chapter 5. Discussion and Conclusion

5.1 Discussion

From the result of the existing system simulation, various values of supply water demand are from pipe size estimation, measured by operator and similar machine. Using the EPANET computer program to simulate system operation, which is a public access program. The result shows that the current system cannot operate on 100 percent system load. The reason is from many values estimation that could increase the percentage error of simulation and the system does not operate on 100 percent system load in general. However, the simulation can be reliable with accurate required variables.

In the limitation of time and COVID-19 outbreak, we cannot obtain every required data in detailly. The value estimation and system simplification are inevitable. Despite estimating values, the field survey information can support information for estimation.

The EPANET computer program is a program that builds for civil engineering, which uses Newton-Raphson mathematical method to calculate and simulate the water distribution system. For this reason, the result may be unstable due to mathematical method requires legit input to get stable output. However, the program can be used in purpose to simulate the system operation.

For further research and analysis, Pipe Flow Expert software is more suitable for building system engineering.

5.2 Conclusion

In the beginning, we have researched and studied about the chilled water piping system and ASHRAE 90.1 Standard to understand the material for this project. We have visited APF processing Ltd. coconut factory to collect the required data to simulate and check the current system with ASHRAE 90.1 Standard. From the result, some of the branch pipes in the system have undersized for the operating at 100 percent system load, which causes insufficient supply water for production lines and poor pump efficiency. By applying ASHRAE 90.1 standard to change undersized pipes in the system, the result shows that the improved pipe size can solve insufficient supply water and improve pump efficiency. The MYCOM and SABROE2 chiller's pumps decrease 150 kW-hr/Mgal and 30 kW-hr/Mgal of energy consumption, respectively. As a simulation result, the chiller's pumps of SABROE2, MYCOM1 and MYCOM2 is decreased energy consumption compared to the existing system per unit gallon by 7.667%, 20.913% and 20.117% respectively.

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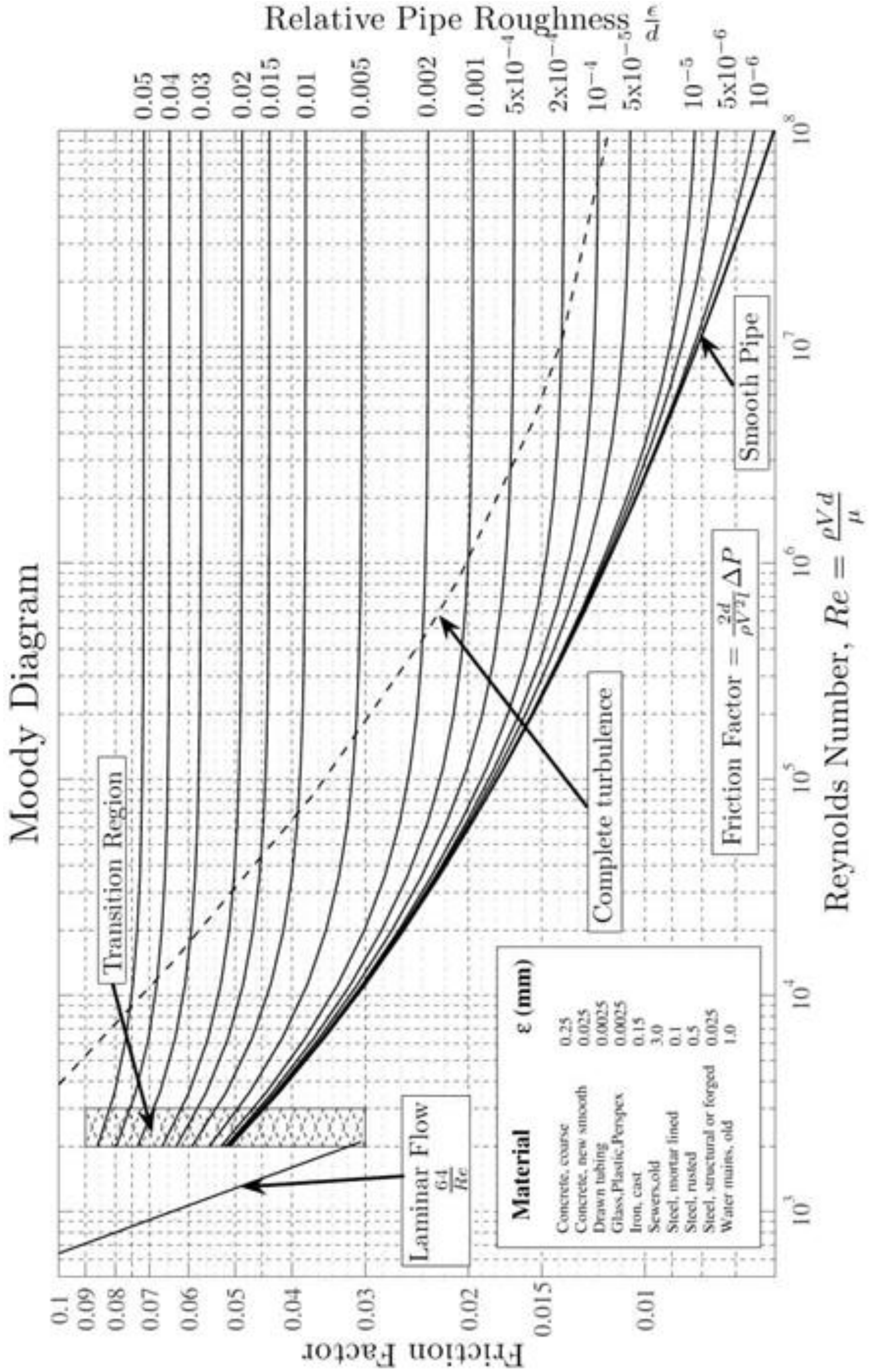
Appendix

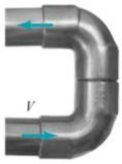
Appendix-1 Moody chart



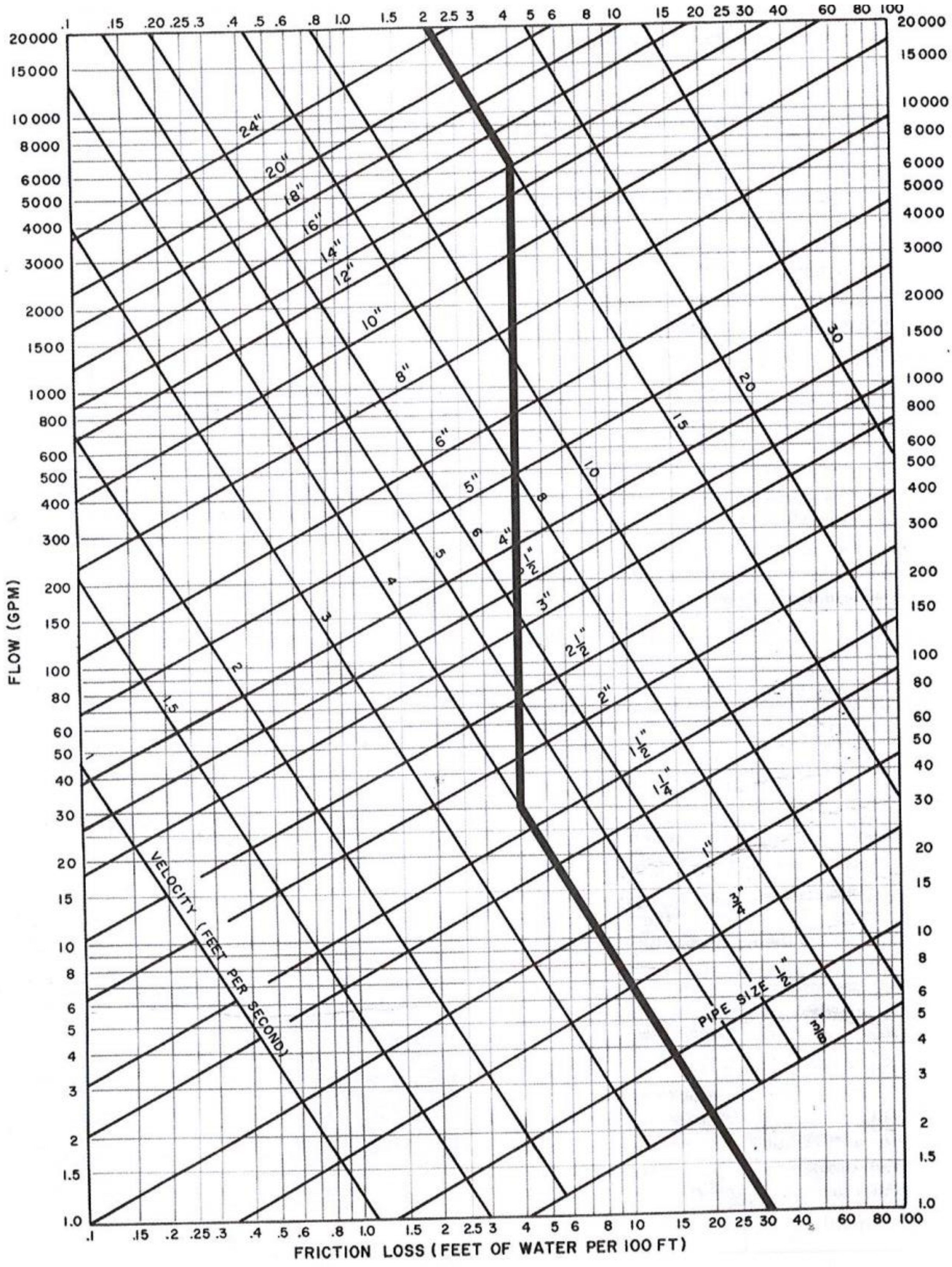
Appendix-2 Loss coefficient (K_L) of Fittings and Valves

Component	K_L
a. Elbows	
Regular 90°, flanged	0.3
Regular 90°, threaded	1.5
Long radius 90°, flanged	0.2
Long radius 90°, threaded	0.7
Long radius 45°, flanged	0.2
Regular 45°, threaded	0.4
b. 180° return bends	
180° return bend, flanged	0.2
180° return bend, threaded	1.5
c. Tees	
Line flow, flanged	0.2
Line flow, threaded	0.9
Branch flow, flanged	1.0
Branch flow, threaded	2.0
d. Union, threaded	0.08
***e. Valves**	
Globe, fully open	10
Angle, fully open	2
Gate, fully open	0.15
Gate, $\frac{1}{4}$ closed	0.26
Gate, $\frac{1}{2}$ closed	2.1
Gate, $\frac{3}{4}$ closed	17
Swing check, forward flow	2
Swing check, backward flow	∞
Ball valve, fully open	0.05
Ball valve, $\frac{1}{3}$ closed	5.5
Ball valve, $\frac{2}{3}$ closed	210






Appendix-3 Pipe friction chart of SCH 40 pipe



Appendix-4 Allowable working pressure at temperature

ALLOWABLE WORKING PRESSURE AT TEMPERATURE

Temperature (°C):					50	100	150	200	250	300	325	350	375	400	425	450	475	500	525	550	575	600	625	650	675	700
Design Strength (MPa):					138	138	138	133	125	119	117	114	112	111	110	108	107	106	106	103	95	81	65	50	39	30
Size			Sch	WT	Allowable Working Pressure (MPa)																					
DN	NPS	mm	No	(mm)																						
10	⅜	17.15	10S	1.65	25.4	25.4	25.4	24.5	23.0	21.9	21.5	21.0	20.6	20.4	20.2	19.9	19.7	19.5	19.5	18.9	17.5	14.9	11.9	9.2	7.2	5.5
		17.15	40S	2.31	36.9	36.9	36.9	35.5	33.4	31.8	31.3	30.5	29.9	29.7	29.4	28.9	28.6	28.3	28.3	27.5	25.4	21.6	17.4	13.4	10.4	8.0
		17.15	80S	3.20	53.9	53.9	53.9	51.9	48.8	46.4	45.7	44.5	43.7	43.3	42.9	42.1	41.8	41.4	41.4	40.2	37.1	31.6	25.4	19.5	15.2	11.7
15	½	21.34	5S	1.65	20.0	20.0	20.0	19.3	18.1	17.3	17.0	16.5	16.3	16.1	16.0	15.7	15.5	15.4	15.4	14.9	13.8	11.8	9.4	7.3	5.7	4.4
		21.34	10S	2.11	26.1	26.1	26.1	25.2	23.7	22.5	22.2	21.6	21.2	21.0	20.8	20.5	20.3	20.1	20.1	19.5	18.0	15.3	12.3	9.5	7.4	5.7
		21.34	40S	2.77	35.4	35.4	35.4	34.1	32.0	30.5	30.0	29.2	28.7	28.4	28.2	27.7	27.4	27.2	27.2	26.4	24.3	20.8	16.7	12.8	10.0	7.7
		21.34	80S	3.73	49.8	49.8	49.8	48.0	45.1	43.0	42.2	41.2	40.4	40.1	39.7	39.0	38.6	38.3	38.3	37.2	34.3	29.2	23.5	18.1	14.1	10.8
20	¾	26.67	5S	1.65	15.8	15.8	15.8	15.2	14.3	13.6	13.4	13.0	12.8	12.7	12.6	12.4	12.2	12.1	12.1	11.8	10.9	9.3	7.4	5.7	4.5	3.4
		26.67	10S	2.11	20.5	20.5	20.5	19.8	18.6	17.7	17.4	17.0	16.7	16.5	16.4	16.1	15.9	15.8	15.8	15.3	14.1	12.0	9.7	7.4	5.8	4.5
		26.67	40S	2.87	28.7	28.7	28.7	27.7	26.0	24.7	24.3	23.7	23.3	23.1	22.9	22.5	22.2	22.0	22.0	21.4	19.8	16.8	13.5	10.4	8.1	6.2
		26.67	80S	3.91	40.6	40.6	40.6	39.1	36.8	35.0	34.4	33.6	33.0	32.7	32.4	31.8	31.5	31.2	31.2	30.3	28.0	23.8	19.1	14.7	11.5	8.8
25	1	33.40	5S	1.65	12.5	12.5	12.5	12.0	11.3	10.8	10.6	10.3	10.1	10.0	9.9	9.8	9.7	9.6	9.6	9.3	8.6	7.3	5.9	4.5	3.5	2.7
		33.40	10S	2.77	21.6	21.6	21.6	20.8	19.6	18.6	18.3	17.8	17.5	17.4	17.2	16.9	16.7	16.6	16.6	16.1	14.9	12.7	10.2	7.8	6.1	4.7
		33.40	40S	3.38	26.8	26.8	26.8	25.8	24.3	23.1	22.7	22.2	21.8	21.6	21.4	21.0	20.8	20.6	20.6	20.0	18.5	15.7	12.6	9.7	7.6	5.8
		33.40	80S	4.55	37.4	37.4	37.4	36.0	33.8	32.2	31.7	30.9	30.3	30.0	29.8	29.2	29.0	28.7	28.7	27.9	25.7	21.9	17.6	13.5	10.6	8.1
32	1¼	42.16	5S	1.65	9.8	9.8	9.8	9.4	8.9	8.4	8.3	8.1	7.9	7.9	7.8	7.7	7.6	7.5	7.5	7.3	6.7	5.7	4.6	3.5	2.8	2.1
		42.16	10S	2.77	16.8	16.8	16.8	16.2	15.2	14.5	14.3	13.9	13.7	13.5	13.4	13.2	13.1	12.9	12.9	12.6	11.6	9.9	7.9	6.1	4.8	3.7
		42.16	40S	3.56	22.0	22.0	22.0	21.2	19.9	19.0	18.7	18.2	17.9	17.7	17.6	17.2	17.1	16.9	16.9	16.4	15.2	12.9	10.4	8.0	6.2	4.8
		42.16	80S	4.85	30.9	30.9	30.9	29.8	28.0	26.6	26.2	25.5	25.1	24.8	24.6	24.2	24.0	23.7	23.7	23.1	21.3	18.1	14.6	11.2	8.7	6.7
40	1½	48.26	5S	1.65	8.5	8.5	8.5	8.2	7.7	7.3	7.2	7.0	6.9	6.8	6.8	6.7	6.6	6.5	6.5	6.4	5.9	5.0	4.0	3.1	2.4	1.9
		48.26	10S	2.77	14.6	14.6	14.6	14.1	13.2	12.6	12.4	12.1	11.8	11.7	11.6	11.4	11.3	11.2	11.2	10.9	10.0	8.6	6.9	5.3	4.1	3.2
		48.26	40S	3.68	19.7	19.7	19.7	19.0	17.9	17.0	16.7	16.3	16.0	15.9	15.7	15.4	15.3	15.2	15.2	14.7	13.6	11.6	9.3	7.1	5.6	4.3
		48.26	80S	5.08	28.0	28.0	28.0	27.0	25.4	24.1	23.7	23.1	22.7	22.5	22.3	21.9	21.7	21.5	21.5	20.9	19.3	16.4	13.2	10.1	7.9	6.1
50	2	60.33	5S	1.65	6.8	6.8	6.8	6.5	6.1	5.8	5.7	5.6	5.5	5.4	5.4	5.3	5.2	5.2	5.2	5.1	4.7	4.0	3.2	2.5	1.9	1.5
		60.33	10S	2.77	11.6	11.6	11.6	11.1	10.5	10.0	9.8	9.5	9.4	9.3	9.2	9.0	9.0	8.9	8.9	8.6	8.0	6.8	5.4	4.2	3.3	2.5
		60.33	40S	3.91	16.6	16.6	16.6	16.0	15.0	14.3	14.1	13.7	13.5	13.3	13.2	13.0	12.9	12.7	12.7	12.4	11.4	9.7	7.8	6.0	4.7	3.6
		60.33	80S	5.54	24.1	24.1	24.1	23.2	21.8	20.8	20.4	19.9	19.6	19.4	19.2	18.9	18.7	18.5	18.5	18.0	16.6	14.2	11.4	8.7	6.8	5.2
65	2½	73.03	5S	2.11	7.2	7.2	7.2	6.9	6.5	6.2	6.1	5.9	5.8	5.8	5.7	5.6	5.6	5.5	5.5	5.3	4.9	4.2	3.4	2.6	2.0	1.6
		73.03	10S	3.05	10.5	10.5	10.5	10.1	9.5	9.0	8.9	8.6	8.5	8.4	8.3	8.2	8.1	8.0	8.0	7.8	7.2	6.1	4.9	3.8	3.0	2.3
		73.03	40S	5.16	18.2	18.2	18.2	17.5	16.5	15.7	15.4	15.0	14.8	14.6	14.5	14.2	14.1	14.0	14.0	13.6	12.5	10.7	8.6	6.6	5.1	4.0
		73.03	80S	7.01	25.3	25.3	25.3	24.4	22.9	21.8	21.5	20.9	20.5	20.4	20.2	19.8	19.6	19.4	19.4	18.9	17.4	14.9	11.9	9.2	7.2	5.5
80	3	88.90	5S	2.11	5.9	5.9	5.9	5.6	5.3	5.0	5.0	4.8	4.8	4.7	4.7	4.6	4.5	4.5	4.5	4.4	4.0	3.4	2.8	2.1	1.7	1.3
		88.90	10S	3.05	8.5	8.5	8.5	8.2	7.7	7.4	7.2	7.1	6.9	6.9	6.8	6.7	6.6	6.6	6.6	6.4	5.9	5.0	4.0	3.1	2.4	1.9
		88.90	40S	5.49	15.8	15.8	15.8	15.2	14.3	13.6	13.4	13.0	12.8	12.7	12.6	12.3	12.2	12.1	12.1	11.8	10.9	9.3	7.4	5.7	4.5	3.4
		88.90	80S	7.62	22.4	22.4	22.4	21.6	20.3	19.3	19.0	18.5	18.2	18.0	17.8	17.5	17.4	17.2	17.2	16.7	15.4	13.1	10.5	8.1	6.3	4.9
90	3½	101.60	5S	2.11	5.1	5.1	5.1	4.9	4.6	4.4	4.3	4.2	4.1	4.1	4.1	4.0	4.0	3.9	3.9	3.8	3.5	3.0	2.4	1.9	1.4	1.1
		101.60	10S	3.05	7.4	7.4	7.4	7.2	6.7	6.4	6.3	6.2	6.0	6.0	5.9	5.8	5.8	5.7	5.7	5.6	5.1	4.4	3.5	2.7	2.1	1.6
		101.60	40S	5.74	14.4	14.4	14.4	13.8	13.0	12.4	12.2	11.9	11.6	11.5	11.4	11.2	11.1	11.0	11.0	10.7	9.9	8.4	6.8	5.2	4.1	3.1
		101.60	80S	8.08	20.6	20.6	20.6	19.9	18.7	17.8	17.5	17.1	16.8	16.6	16.5	16.2	16.0	15.9	15.9	15.4	14.2	12.1	9.7	7.5	5.8	4.5
100	4	114.30	5S	2.11	4.5	4.5	4.5	4.4	4.1	3.9	3.8	3.7	3.7	3.6	3.6	3.5	3.5	3.5	3.5	3.4	3.1	2.7	2.1	1.6	1.3	1.0
		114.30	10S	3.05	6.6	6.6	6.6	6.4	6.0	5.7	5.6	5.5	5.4	5.3	5.3	5.2	5.1	5.1	5.1	4.9	4.5	3.9	3.1	2.4	1.9	1.4
		114.30	40S	6.02	13.3	13.3	13.3	12.9	12.1	11.5	11.3	11.0	10.8	10.7	10.6	10.4	10.3	10.2	10.2	10.0	9.2	7.8	6.3	4.8	3.8	2.9
		114.30	80S	8.56	19.4	19.4	19.4	18.7	17.5	16.7	16.4	16.0	15.7	15.6	15.4	15.1	15.0	14.9	14.9	14.4	13.3	11.4	9.1	7.0	5.5	4.2
125	5	141.30	5S	2.77	4.8	4.8	4.8	4.6	4.4	4.2	4.1	4.0	3.9	3.9	3.8	3.8	3.7	3.7	3.7	3.6	3.3	2.8	2.3	1.7	1.4	1.0
		141.30	10S	3.40	5.9	5.9	5.9	5.7	5.4	5.1	5.0	4.9	4.8	4.8	4.7	4.6	4.6	4.6	4.6	4.4	4.1	3.5	2.8	2.2	1.7	1.3
		141.30	40S	6.55	11.7	11.7	11.7	11.2	10.6	10.1	9.9	9.6	9.5	9.4	9.3	9.1	9.0	9.0	9.0	8.7	8.0	6.8	5.5	4.2	3.3	2.5
		141.30	80S	9.53	17.3	17.3	17.3	16.7	15.7	14.9	14.7	14.3	14.0	13.9	13.8	13.5	13.4	13.3	13.3	12.9	11.9	10.2	8.2	6.3	4.9	3.8
150	6	168.28	5S	2.77	4.0	4.0	4.0	3.9	3.7	3.5	3.4	3.3	3.3	3.2	3.2	3.2	3.1	3.1	3.1	3.0	2.8	2.4	1.9	1.5	1.1	0.9
		168.28	10S	3.40	5.0	5.0	5.0	4.8	4.5	4.3	4.2	4.1	4.0	4.0	4.0	3.9	3.9	3.8	3.8	3.7	3.4	2.9	2.3	1.8	1.4	1.1
		168.28	40S	7.11	10.6	10.6	10.6	10.2	9.6	9.1	9.0	8.8	8.6	8.5	8.4	8.3	8.2	8.1	8.1	7.9	7.3	6.2	5.0	3.8	3.0	2.3
		168.28	80S	10.97	16.7	16.7	16.7	16.1	15.1	14.4	14.2	13.8	13.5	13.4	13.3	13.1	12.9	12.8	12.8	12.5	11.5	9.8	7.9	6.0	4.7	3.6
200	8	219.08	5S	2.77	3.1	3.1	3.1	3.0	2.8	2.7	2.6	2.6	2.5	2.5	2.5	2.4	2.4	2.4	2.4	2.3	2.1	1.8	1.5	1.1	0.9	0.7
		219.08	10S	3.76	4.2	4.2	4.2	4.1	3.8	3.6	3.6	3.5	3.4	3.4	3.4	3.3	3.3	3.2	3.2	3.1	2.9	2.5	2.0	1.5	1.2	0.9
		219.08	40S	8.18	9.3	9.3	9.3	9.0	8.4	8.0	7.9	7.7	7.6	7.5	7.4	7.3	7.2	7.2	7.2	7.0	6.4	5.5	4.4	3.4	2.6	2.0
		219.08	80S	12.70	14.7	14.7	14.7	14.2	13.4	12.7	12.5	12.2	12.0	11.9	11.8	11.5	11.4	11.3	11.3	11.0	10.2	8.7	6.9	5.3	4.2	3.2
250	10	273.05	5S	3.40	3.0	3.0	3.0	2.9	2.8	2.6	2.6	2.5	2.5	2.4	2.4	2.4	2.4	2.3	2.3	2.3	2.1	1.8	1.4	1.1	0.9	0.7
		273.05	10S	4.19	3.8	3.8	3.8	3.6	3.4	3.2	3.2	3.1	3.0	3.0	3.0	2.9	2.9	2.9	2.9	2.8	2.6	2.2	1.8	1.4	1.1	0.8
		273.05	40S	9.27	8.4	8.4	8.4	8.1	7.7	7.3	7.2	7.0	6.9	6.8	6.7	6.6	6.6	6.5	6.5	6.3	5.8	5.0	4.0	3.1	2.4	1.8
		273.05	80S	12.70	11.7	11.7	11.7	11.3	10.6	10.1	9.9	9.7	9.5	9.4	9.3	9.2	9.1	9.0	9.0	8.7	8.1	6.9	5.5	4.2	3.3	2.5
300	12	323.85	5S	3.96	3.0	3.0	3.0	2.9	2.7	2.6	2.5	2.5	2.4	2.4	2.4	2.3	2.3	2.3	2.3	2.2	2.1	1.8	1.4	1.1	0.8	0.6
		323.85	10S	4.57	3.5	3.5	3.5	3.3	3.1	3.0	2.9	2.9	2.8	2.8	2.8	2.7	2.7	2.7	2.7	2.6	2.4	2.0	1.6	1.3	1.0	0.8
		323.85	40S	9.53	7.3	7.3	7.3	7.0	6.6	6.3	6.2	6.0	5.9	5.9	5.8	5.7	5.7	5.6	5.6	5.4	5.0	4.3	3.4	2.6	2.1	1.6
		323.85	80S	12.70	9.8	9.8	9.8	9.5	8.9	8.5	8.3	8.1	8.0	7.9	7.8	7.7	7.6	7.5	7.5	7.3	6.8	5.8	4.6	3.6	2.8	2.1
350	14	355.60	5S	3.96	2.7	2.7	2.7	2.6	2.5	2.3	2.3	2.2	2.2	2.2	2.2	2.1	2.1	2.1	2.1	2.0	1.9	1.6	1.3	1.0	0.8	0.6
		355.60	10S	4.78	3.3	3.3	3.3	3.2	3.0	2.8	2.8	2.7	2.7	2.6	2.6	2.6	2.5	2.5	2.5	2.5	2.3	1.9	1.5	1.2	0.9	0.7
		355.60	40S	9.53	6.6	6.6	6.6	6.4	6.0	5.7	5.6	5.5	5.4	5.3	5.3	5.2	5.1	5.1	5.1	4.9	4.6	3.9	3.1	2.4	1.9	1.4
		355.60	80S	12.70	8.9	8.9	8.9	8.6	8.1	7.7	7.5	7.4	7.2	7.2	7.1	7.0	6.9	6.8	6.8	6.6	6.1	5.2	4.2	3.2	2.5	1.9
400	16	406.40	5S	4.19	2.5	2.5	2.5	2.4	2.3	2.2	2.1	2.1	2.0	2.0	2.0	2.0	1.9	1.9	1.9	1.9	1.7	1.5	1.2	0.9	0.7	0.5
		406.40	10S	4.78	2.9	2.9	2.9	2.8	2.6	2.5	2.4	2.4	2.3	2.3	2.3	2.2	2.2	2.2	2.2	2.1	2.0	1.7	1.4	1.0	0.8	0.6
		406.40	40S	9.53	5.8	5.8	5.8	5.6	5.2	5.0	4.9	4.8	4.7	4.7	4.6	4.5	4.5	4.4	4.4	4.3	4.0	3.4	2.7	2.1	1.6	1.3
		406.40	80S	12.70	7.8	7.8	7.8	7.5	7.0	6.7	6.6	6.4	6.3	6.2	6.2	6.1	6.0	6.0	6.0	5.8	5.3	4.6	3.7	2.8	2.2	1.7
450	18	457.20	5S	4.19	2.2	2.2	2.2	2.2	2.0	1.9	1.9	1.8	1.8	1.8	1.8	1.7	1.7	1.7	1.7	1.7	1.5	1.3	1.1	0.8	0.6	0.5
		457.20	10S	4.78	2.5	2.5	2.5	2.5	2.3	2.2	2.2	2.1	2.1	2.0	2.0	2.0	2.0	2.0	2.0	1.9	1.8	1.5	1.2	0.9	0.7	0.6
		457.20	40S	9.53	5.1	5.1	5.1	4.9	4.6	4.4	4.3	4.2	4.2	4.1	4.1	4.0	4.0	3.9	3.9	3.8	3.5	3.0	2.4	1.9	1.4	1.1
		457.20	80S	12.70	6.9	6.9	6.9	6.6	6.2	5.9	5.8	5.7	5.6	5.5	5.5	5.4	5.3	5.3	5.3	5.1	4.7	4.0	3.2	2.5	1.9	1.5
500	20	508.00	5S	4.78	2.3	2.3	2.3	2.2	2.1	2.0	1.9	1.9	1.9	1.8	1.8	1.8	1.8	1.8	1.8	1.7	1.6	1.3	1.1	0.8	0.6	0.5
		508.00	10S	5.54	2.7	2.7	2.7	2.6	2.4	2.3	2.3	2.2	2.2	2.1	2.1	2.1	2.1	2.0	2.0	2.0	1.8	1.6	1.3	1.0	0.8	0.6
		508.00	40S	9.53	4.6	4.6	4.6	4.4	4.2	4.0	3.9	3.8	3.7	3.7	3.7	3.6	3.6	3.5	3.5	3.4	3.2	2.7	2.2	1.7	1.3	1.0
		508.00	80S	12.70	6.2	6.2	6.2	5.9	5.6	5.3	5.2	5.1	5.0	5.0	4.9	4.8	4.8	4.7	4.7	4.6	4.2	3.6	2.9	2.2	1.7	1.3
550	22	558.80	5S	4.78	2.1	2.1	2.1	2.0	1.9	1.8	1.8	1.7	1.7	1.7	1.7	1.6	1.6	1.6	1.6	1.6	1.4	1.2	1.0	0.8	0.6	0.5
		558.80	10S	5.54	2.4	2.4	2.4	2.3	2.2	2.1	2.0	2.0	2.0	1.9	1.9	1.9	1.9	1.9	1.9	1.8	1.7	1.4	1.1	0.9	0.7	0.5
600	24	609.60	5S	5.54	2.2	2.2	2.2	2.1	2.0	1.9	1.9	1.8	1.8	1.8	1.8	1.7	1.7	1.7	1.7	1.7	1.5	1.3	1.0	0.8	0.6	0.5
		609.60	10S	6.35	2.5	2.5	2.5	2.4	2.3	2.2	2.2	2.1	2.1	2.0	2.0	2.0	2.0	2.0	2.0	1.9	1.7	1.5	1.2	0.9	0.7	0.6
		609.60	40S	9.53	3.8	3.8	3.8	3.7	3.5	3.3	3.2	3.2	3.1	3.1	3.1	3.0	3.0	2.9	2.9	2.9	2.6	2.2	1.8	1.4	1.1	0.8
		609.60	80S	12.70	5.1	5.1	5.1	4.9	4.6	4.4	4.3	4.2	4.2	4.1	4.1	4.0	4.0	3.9	3.9	3.8	3.5	3.0	2.4	1.9	1.4	1.1

Important - refer to the associated Notes to this table.

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