Thermal System Design

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Introduction

The project task that the team must undertake is to design a thermal system for the pharmaceutical product. The company has ordered three jacketed reactors for producing a pharmaceutical product. A necessary requirement for the reactors is that they need to be heated using hot water at 60°C. The central heater system that provides hot water at around 80°C is shown in figure 1 as a process flow diagram. The system also has requirements that must be accounted into the design. Each reactor must have its own automatic temperature control loop and its own circulating pump. This will be accomplished by monitoring the water temperature going into the jacket and mixing 80°C as necessary. The flow rate of the 60°C water must be maintained at 70 USGPM. The pressure drop through the jacket is 5 PSIG at 70 USGPM. The following assumptions will be made for the thermal system of a maximum pressure drop through the heater will be 5 PSI, main water supply and return lines are 30m long each, and each run has 4 90°elbows, each line to/from the main supply/return lines to the reactors is 20m long, and has 3 90°elbows, and all pipe will be Sch 40 steel pipe.

The project report will include a P&ID diagram of the thermal system, discussion and all the necessary calculations to construct such system.

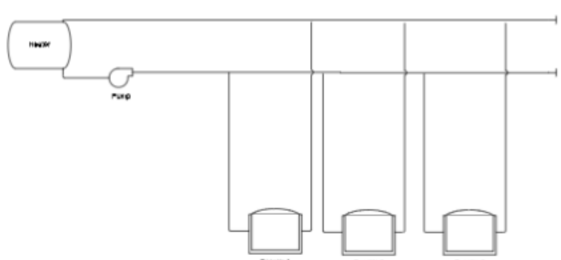

Figure 1: Process Flow Diagram for Jacketed Reactors [1]

Thermal System Engineering Design

This section will contain all the engineering design requirements such as the P&ID diagram, bill of materials, and discussion of the thermal system project undertaken and developed by the team.

P&ID Diagram

The following P&ID diagram will be examined and discussed under the discussion heading.

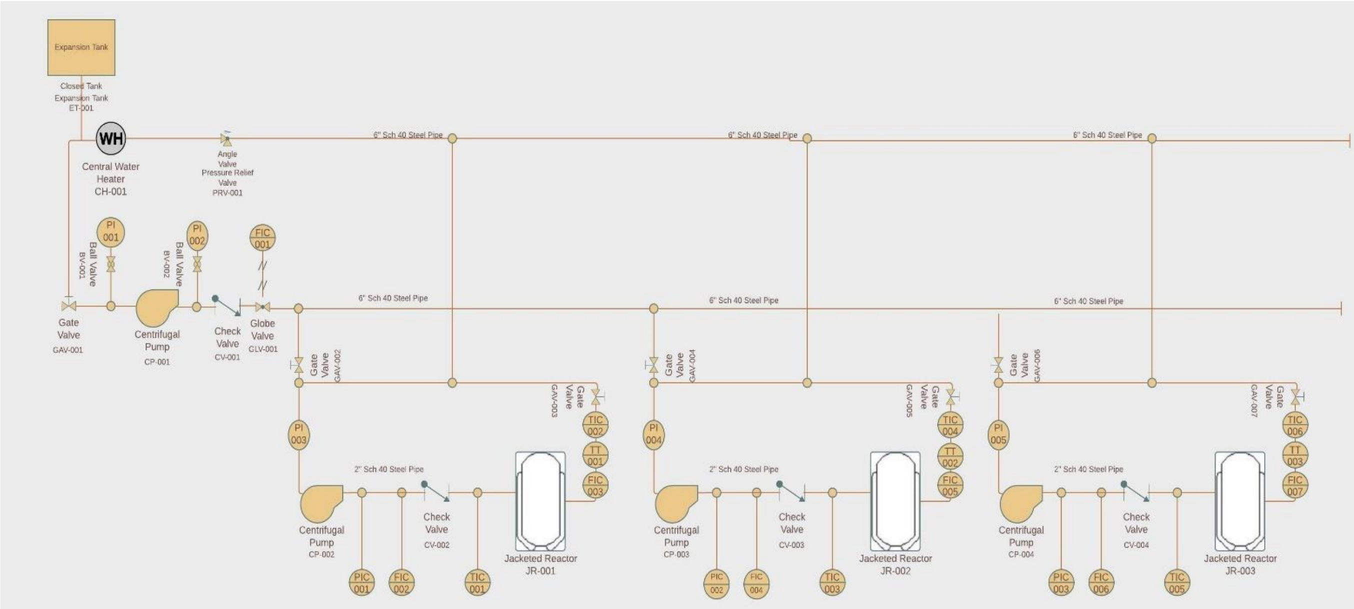

Figure 2: P&ID Thermal Systems Diagram

Bill of Materials

The following table is the Bill of Materials of the P&ID Thermal System Diagram.

Table 1: Bill of Materials

Tag Number	Quantity	Equipment	Specification
CH-001	1	Central Water Heater	N/A
ET-001	1	Expansion Tank	N/A
GAV-001	1	Gate Valves	6 inches
GAV-002	1		2 Inches
GAV-003	1		
GAV-004	1		
GAV-005	1		
GAV-006	1		
GAV-007	1		
BV-001	1	Ball Valves	2 Inches
BV-002	1	Ball Valves	
GLV-001	1	Globe Valves	6 inch
CV-001	1	Check Valves	6 Inch
CV-002	1		2 Inch
CV-003	1		
CV-004	1		
PRV-001	1	Pressure Relief Valve	6 inch
PI	5	Pressure Indicator	N/A
TT	3	Temperature Transmitter	N/A
PIC	3	Pressure Indicator Controller	N/A
TIC	6	Temperature Indicator Controller	N/A
FIC	7	Flow Indicator Controller	N/A
CP-001	1	Centrifugal Pump	Cornell Pump Company Catalogue 6H-F centrifugal pump
CP-002	1		MP Pumps Centrifugal Pump catalogue HTW 120
CP-003	1		
CP-004	1		
JR-001	1	Jacketed Reactor	N/A
JR-002	1		
JR-003	1		
6" Sch 40 Steel Pipe	2	Stainless Steel Pipe	30 m (each)
2" Sch 40 Steel Pipe	6	Stainless Steel Pipe	20 m (each)

Discussion

The following section of the project report will discuss the P&ID thermal design diagram and the reasoning for all the instruments used in the design. The piping material used for the thermal system was selected to be stainless steel. Stainless steel was used due to the system utilizing water as the fluid to regulate temperature of the whole thermal system. The piping material will be able to resist corrosion due to flowing water constantly running through the system.

Central Water Heater System

The initialization of the thermal system begins with the fluid (water) exiting the central water heater toward the centrifugal pump (see figure 3 for details). The fluid is then pumped and begins its journey to the three Jacketed Reactors via supply pipelines. The fluid is processed in the Jacketed Reactor system and ends its journey by returning to the central water heater system via return pipelines. The pressure indicators, flow indicator control, gate vales, ball valves, check valves, globe valves, pump and central water heater will be explained below.

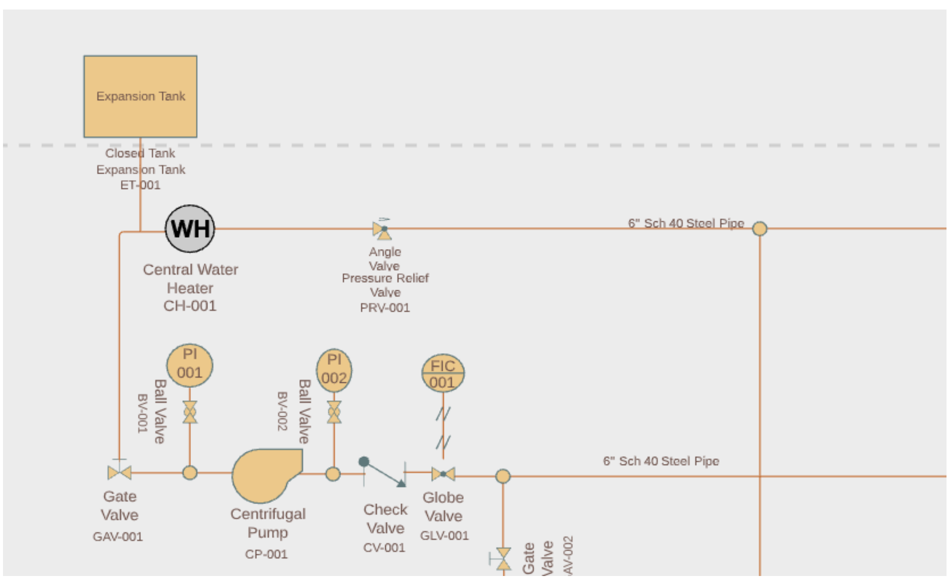

Figure 3: Central Water Heater System

- **Gate Valve:** The gate valve is placed before the centrifugal pump to act as a shut off valve for the whole system. The reason for a shut off valve is if the pump needs to be replaced or for maintenance purposes.

- **Ball valve:** The ball valves is placed before the pressure indicators to act as shut off valve to the pressure indicators. The reason is if the pressure indicators were damaged and needs replacement, the gages could be replaced without shutting off the whole system.

- **Check Valve:** The check valve is placed after the pump and is used to prevent any flow moving back towards the pump. This will prevent any damage to the pump.

- **Globe Valve:** The globe valve is placed after the check valve for the liquid throttling applications of the system. The globe valve will act as the control valve to regulate the flow of the system. Despite the high pressure drop due to globe valve it will help in maintaining the temperature of the liquid.

- **Pressure Indicator:** Two pressure indicators are placed at the entrance and exit of the pump. The pressure gauges will allow maintenance or staff monitor the pressure and alert them if any issue arises with the system.

- **Flow Indicator Control:** The flow indicator control was placed near the globe valve to control the flow rate of the fluid that is pumped into the Jacketed Reactor system. The flow indicator control system is placed into the control room. This will allow operator to assess the flow of the liquid and make any adjustments as required.

- **6" Sch 40 Steel Pipe:** The piping material for this system will be 6-inch Sch 40 Steel Pipe which is stainless steel. The length will be 30 meters each.

- **Central Water Heater:** Heater that heats the water (fluid) to 80°C and provides the fluid to the system.

- **Centrifugal Pump:** The centrifugal pump is one of the requirements to the system to provide adequate flow towards the reactor.

- **Expansion Tank:** To handle the thermal expansion of water as it heats up from heater.

- **Pressure Relief Valve:** To control the overall pressure in the system

Jacketed Reactor System

The Jacketed Reactor system for all three sections are all identical, thus figure 4 shown below is sufficient to reveal the process of the system. The requirement for the Jacketed Reactor is a control loop which cycles and regulates the temperature throughout the reactor. The reactor specifications require a 60°C fluid at 70 USPGM to ensure uniform heating of product. The gate valves, check valves, pressure indicator, temperature transmitter, pump, Jacketed Reactor and pressure/flow/temperature indicator controller will be explained below.

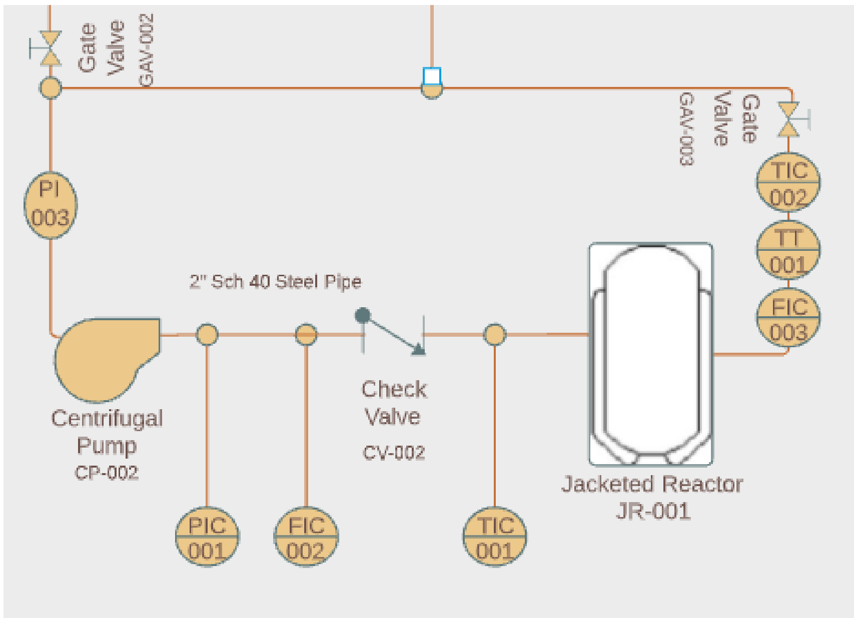

Figure 4: Jacketed Reactor System

- **Gate Valve:** The two-gate valve is placed before and after the Jacketed Reactor system to act as an shut off valve for each Jacketed Reactor System. This will allow the maintenance of the system without shutting off the whole system.

- **Check Valve:** The check valve is placed after the pump to prevent any flow back towards the pump. This will prevent any damages to the pump.

- **Pressure Indicator:** Pressure Indicator is placed before the pump. The pressure gauges will allow the monitoring of pressure of the system before entering pump to alert staff of any high or low pressure of the system.

- **Temperature Transmitter:** The temperature transmitter is placed after the reactor to notify the temperature indicator of the temperature flowing back to Central Water Heater System. This is to ensure that the system will be provided with 60°C fluid.

- **Temperature Indicator Controller:** The temperature indicator controller is placed after and before the reactor to notify the operator of the temperature of the fluid flowing in the system. This will allow the operator in the control room to adjust the temperature of the system according to the desired requirements of 60°C fluid.

- **Flow Indicator Controller:** The flow indicator controller is placed before and after the reactor to notify the operator of the flow of the fluid in the system. The operator in the control room will be able to adjust accordingly to keep the flow at 70 USGPM.

- **Pressure Indicator Controller:** The pressure indicator controller is placed before the reactor to notify the operator of the pressure being sent to the reactor. The operator in the control will then be able to adjust accordingly to keep adequate pressure.

- **Centrifugal Pump:** The centrifugal pump is one of the requirements to the system to provide adequate flow towards the reactor.

- **Jacketed Reactor:** The reactor used to create the pharmaceutical product.

- **2" Sch 40 Steel Pipe:** The piping material for this system will be 2-inch Sch 40 Steel Pipe which is stainless steel. The length will be 20 meters each.

Calculations

This section will contain the calculations of the Central Water Heater system, and the Jacketed Reactor system. It will also contain the calculations of pipe diameter, and head values for pump requirements.

The following assumptions will be made:

- Smooth Pipe
- Constant thermal properties of water
- No heat transfer to the environment
- Water at 1 atm pressure
- Uniform heat transfer throughout system
- Fully developed constant turbulent flow through pipes
- Steady state conditions (Steady Turbulent Flow)

Central Water Heater System Calculations

The flow rate needs to be determined by using the volumetric flow rate equation. Assuming worst case scenario when the water at the reactor loop is 20°C. Using this assumption flow rate could be determined which will be used to determine pipe diameter.

Known & Assumptions:

- $\Delta T_{Central\ Water\ Heater} = 80°\text{C} - 60°\text{C} = 20°\text{C}$ and $\Delta T_{Jacketed\ Reactor} = 60°\text{C} - 20°\text{C} = 40°\text{C}$
- $Q_{Jacketed\ Reactor} = 70\ USGPM$
- Mass rate is $\dot{m} = \rho Q$

$$\dot{m} c \Delta T_{Jacketed\ Reactor} = \dot{m} c \Delta T_{Central\ Water\ Heater}$$

$$Q_{Jacketed\ Reactor} \Delta T_{Jacketed\ Reactor} = Q_{Central\ Water\ Heater} \Delta T_{Central\ Water\ Heater}$$

$$Q_{Central\ Water\ Heater} = 140\ USGPM\ \times\ 3 = 420\ PSIG$$

The required flow rate was determined to be 140 PSIG. The thermal system has three automatic control loops, thus the flow rate must be multiplied by three which is 420 USGPM. For the rest of the calculations, the water temperature will be considered 80°C and pressure drop of 5 PSI through the central water heater.

Pipe Diameter

The pipe diameter of the central water heater pump was determined by calculating pressure drop through the heater. It was calculated by using the pressure drop to find the Reynolds number and friction factor by using the iteration method. The textbook Fluid Mechanics Eighth edition example problem 6.11 was used as reference [2].

Known & Assumptions:

- $\Delta P = 5\ PSI = 720\ lbf/ft^2$ pressure drop, 80°C fluid, total length of pipe $60m = 196.85\ ft$
- Flow Rate: 420 USGPM
- Steady state condition (Steady Turbulent Flow)
- Smooth Pipe (walls)
- $\rho = 1.94\ slug/ft^3$
- $Q = 420\ USGPM = 0.93576\ ft^3/s$
- $\mu = 0.741E - 5\ from\ table\ A.1$ [2] $(see\ apendix\ A.1)$

The friction factor, diameter, and Reynolds number are calculated using iterative process:

$$f = \frac{\pi^2 \Delta P d^5}{8\rho L Q^2}\ (Equation\ 1)$$

Plugging in the values into equation one yields:

$$\sqrt[5]{\frac{f}{2.656}} = d\ (Equation\ 2)$$

Reynolds number and the friction factor could be solved using these equations:

$$Re_d = \frac{4\rho Q}{\pi \mu d}(Equation\ 3)\ and\ \frac{1}{f^{1/2}} = 2.0\log\left(Re_d f^{\frac{1}{2}}\right) - 0.8\ (Equation\ 4)$$

These equations (2,3,4) were put into excel with an initial guess of $f = 0.02$ to develop multiple iterations for $Re_d, d, and\ f$. These iterations will determine an approximate estimate of the pipe diameter.

Table 2: Iterations

$f - Guess$	$Diameter\ (d)$ (ft)	$Reynolds\ Number\ (Re_d)$	$f - Calculated$
0.02	0.37614941	829273.3951	0.011467076
0.011467076	0.33654638	926857.9817	0.011831511
0.011831511	0.33865885	921076.4711	0.011810555
0.011810555	0.338538799	921403.0981	0.011811741
0.011811741	0.338545597	921384.5953	0.011811674

Diameter was determined to be 0.3385ft which 4.062 inches. This is then rounded to 6 inches nominal diameter due to following standard pipe sizing, safety, and governmental regulations. Thus, 6 inches nominal diameter was chosen for the pipe diameter.

Head Values

To purchase the correct pump to serve the requirements of the central water heater system, one must determine the pump head values. The pressure drop will be calculated between the valves and then calculating the local or minor losses from the sum of the four elbows minor coefficients. The water flowing to the reactor system will be at 80°C from the central water heater. Therefore, the water properties at 80°C will be considered. The textbook Fluid Mechanics Eighth edition example problem 6.16 was used as reference [2].

Known & Assumptions:

- SG of water at 80°C is 0.972 (See Appendix A.2 [3])
- $g = 32.17\ slug/ft^2$
- $\rho = 1.94\ slug/ft^3$
- $Q = 420$ USGPM $= 0.93576\ ft^3/s$
- Steady state condition (Steady Turbulent Flow)
- $\Delta P = 5\ PSI = 720\ lbf/ft^2$ pressure drops through central water heater
- Smooth Pipe (walls) and Pipe diameter is 6 $inches\ =\ 0.5\ ft$
- Pressure drop across valves is small fraction of pump pressure rise (usually 10%)

Pressure drop between valves is determined by the equation below:

$$\Delta P = SG\left(\frac{Q}{C_v}\right)^2 \ (Equation\ 1)$$

Table 3: Pressure Drop between valves for 6'' diameter pipe

Valve	Gate	Check	Globe
$\boldsymbol{C_v}$	2650	950	430
Pressure (PSIG) Using Equation 1	0.02441	0.18998	0.92731
Total Pressure Drop (PSIG)	1.1417		

*The gate and check $\boldsymbol{C_v}$ values were determined from the Velan valve Catalogue [4]

Minor or local loss is calculated as follows:

$$\Delta h = \frac{V^2}{2g}\left(\frac{fL}{d} + \Sigma \mathrm{K}\right) (Equation\ 2)$$

$$V = \frac{4Q}{\pi d^2} = 4.7657\ ft/s (Equation\ 3)$$

$$\Delta P = \rho g \Delta h\ (Equation\ 4)$$

The k values were determined by the Metro Pump catalogue of Friction Losses [7].

Table 4: Total Minor Loss for 6'' diameter pipe

Pipe Loss	**K value**
Screwed Regular 90° Elbow	0.45
Screwed Regular 90° Elbow	0.45
Screwed Regular 90° Elbow	0.45
Screwed Regular 90° Elbow	0.45
	$\Sigma \mathrm{K} = 1.8$

Using Equation 2 and 4:

$$\Delta h_{pl} = 2.2768\ ft\ pump\ head$$

$$\Delta P_{pl} = 142.0967\ \frac{lbf}{s^2} = 0.9867\ PSIG$$

Total Pressure and Minor Loss:

$$\Delta P_{Total} = \Delta P_V + \Delta P_{pl} + \Delta P_{heater} = 1.1417 + 0.9867 + 5 = 7.1284\ PSIG$$

$$= 1026.489\ lbf/ft\text{^}2$$

$$\Delta h_{Total} = \frac{\Delta P_{Total}}{\rho g} = 16.44\ ft$$

The total pump head of 16 .44 ft was found with a flow rate of 420 USGPM. From the Cornell Pump Company Catalogue 6H-F centrifugal pump was selected for its performance in high temperatures, satisfies flow rate (420 USGPM), and the pump head requirement of 16.44 ft (see figure 5)

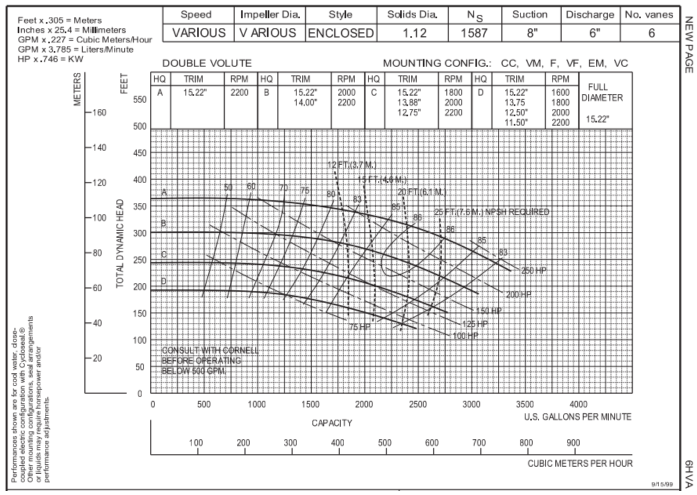

Figure 5: 6H-F Performance Curve [6]

Jacketed Reactor System Calculations

Pipe Diameter

The pipe diameter of the Jacketed reactor pump was determined by calculating pressure drop through the reactor. It was calculated by using the pressure drop to find the Reynolds number and friction factor by using the iteration method. The textbook Fluid Mechanics Eighth edition example problem 6.11 was used as reference [2].

Known & Assumptions:

- $\Delta P = 5\ PSIG = 720\ lbf/ft^2$ pressure drop, 60°C fluid, total length of pipe $40m = 131.234\ ft$
- Flow Rate: 70 USGPM
- Steady state condition (Steady Turbulent Flow)
- Smooth Pipe (walls)
- $\rho = 1.94\ slug/ft^3$
- $Q = 70\ USGPM = 0.15596\ ft^3/s$
- $\mu = 0.975E - 5\ from\ table\ A.1$ [2] $(see\ apendix\ A.1)$

The friction factor, diameter, and Reynolds number are calculated using iterative process:

$$f = \frac{\pi^2 \Delta P d^5}{8\rho L Q^2}\ (Equation\ 1)$$

Plugging in the values into equation one yields:

$$\sqrt[5]{\frac{f}{143.439}} = d\ (Equation\ 2)$$

Reynolds number and the friction factor could be solved using these equations:

$$Re_d = \frac{4\rho Q}{\pi \mu d}\ (Equation\ 3)\ and\ \frac{1}{f^{1/2}} = 2.0 \log\left(Re_d f^{\frac{1}{2}}\right) - 0.8\ (Equation\ 4)$$

These equations (2,3,4) were put into excel with an initial guess of $f = 0.02$ to develop multiple iterations for $Re_d, d, and\ f$. These iterations will determine an approximate estimate of the pipe diameter.

Table 5: Iterations

$\boldsymbol{f - Guess}$	$\boldsymbol{Diameter\ (d)}$ **(ft)**	$\boldsymbol{Reynolds\ Number\ (Re_d)}$	$\boldsymbol{f - Calculated}$
0.02	0.169384064	233264.1028	0.014739773
0.014739773	0.159354637	247945.2273	0.015028566
0.015028566	0.159974241	246984.8998	0.015009953
0.015009953	0.159934595	247046.1235	0.015011141
0.015011141	0.159937126	247042.2139	0.015011065

Diameter was determined to be 0.1599 ft which 1.9188 inches. This is then rounded to 2 inches nominal diameter due to following standard pipe sizing, safety, and governmental regulations. Thus, 2 inches nominal diameter was chosen for the pipe diameter.

Head Values

To purchase the correct pump to serve the requirements of the Jacketed Reactor system, one must determine the pump head values. The pressure drop will be calculated between the valves and then calculating the local or minor losses from the sum of the three elbows minor coefficients. The water flowing to the reactor system will be at 80°C before entering the gate valve (Figure 4). Therefore, the water properties at 80°C will be considered. The textbook Fluid Mechanics Eighth edition example problem 6.16 was used as reference [2].

Known & Assumptions:

- SG of water at 80°C is 0.972 (See Appendix A.2)[3]
- $g = 32.17\ slug/ft^2$
- $\rho = 1.94\ slug/ft^3$
- $Q = 70\ USGPM = 0.15596\ ft^3/s$
- Steady state condition (Steady Turbulent Flow)
- $\Delta P = 5\ PSIG = 720\ lbf/ft^2$ pressure drops through jacket
- Smooth Pipe (walls) and Pipe diameter is $2\ inches\ =\ 0.1667\ ft$
- Pressure drop across valves is small fraction of pump pressure rise (usually 10%)

Pressure drop between valves is determined by the equation below:

$$\Delta P = SG\left(\frac{Q}{C_v}\right)^2\ (Equation\ 1)$$

Table 6: Pressure Drop Between Valves for 2'' diameter pipe

Valve	Gate	Check	Gate
$\boldsymbol{C_v}$	1150	410	1150
Pressure (PSIG) Using Equation 1	0.003601	0.0283	0.003601
Total Pressure Drop (PSIG)	0.035502		

*The gate and check $\boldsymbol{C_v}$ values were determined from the Velan valve Catalog [4]

Minor or local loss is calculated as follows:

$$\Delta h = \frac{V^2}{2g}\left(\frac{fL}{d} + \Sigma K\right)(Equation\ 2)$$

$$V = \frac{4Q}{\pi d^2} = 7.14582\ ft/s(Equation\ 3)$$

$$\Delta P = \rho g \Delta h\ (Equation\ 4)$$

The k values were determined by Table 6.5 in Fluid Mechanics Eighth edition textbook (see Appendix A.3 [2].

Table 7: Total Minor Loss for 2'' diameter pipe

Pipe Loss	K value
Screwed Regular 90° Elbow	0.95
Screwed Regular 90° Elbow	0.95
Screwed Regular 90° Elbow	0.95
	ΣK = 2.85

Using Equation 2 and 4:

$$\Delta h_{pl} = 11.6399\ ft\ pump\ head$$

$$\Delta P_{pl} = 726.4478 \frac{lbf}{s^2} = 5.0447\ PSIG$$

Total Pressure and Minor Loss:

$$\Delta P_{Total} = \Delta P_V + \Delta P_{pl} + \Delta P_{jacket} = 0.035502 + 5.0447 + 5 = 10.0802\ PSIG$$

$$= 1451.5488\ lbf/ft\text{^}2$$

$$\Delta h_{Total} = \frac{\Delta P_{Total}}{\rho g} = 23.258 ft$$

The total pump head is 23.258 ft was found with a flow rate of 70 USGPM. From the MP Pumps Centrifugal Pump catalog HTW 120 [5] was selected for its performance in high temperatures (up to 204°C), satisfies the flow rate of 70 USGPM and pump head requirement of 23.258 ft (see figure 5).

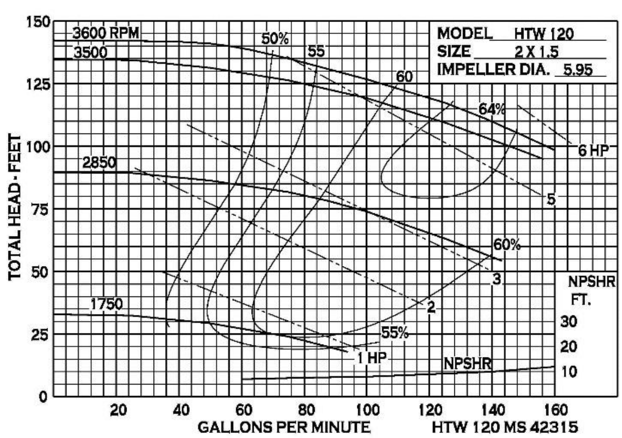

Figure 6: HTW 120 Performance Curve [5]

Conclusion

In closing, the final report was able to display the P&ID diagram for the thermal system design that contained three Jacketed reactor automatic temperature control loops. It was also able to calculate the pipe diameters for the central water heater and Jacketed reactor systems, which were 6’’ and 2’’, respectively. The pump head for central water heater system was determined to be 16.44 feet with 420 USGPM flow rate. The pump head for the Jacketed reactor system was determined to be 23.258 ft with 70 USGPM. Therefore, the thermal system was designed to meet the specific requirements tasked to the company and delivered a functional system with the ability to complete the task.

Appendix

T, °C	ρ, kg/m^3	μ, N · s/m^2	ν, m^2/s	T, °F	ρ, slug/ft^3	μ, lb · s/ft^2	ν, ft^2/s
0	1000	1.788 E−3	1.788 E−6	32	1.940	3.73 E−5	1.925 E−5
10	1000	1.307 E−3	1.307 E−6	50	1.940	2.73 E−5	1.407 E−5
20	998	1.003 E−3	1.005 E−6	68	1.937	2.09 E−5	1.082 E−5
30	996	0.799 E−3	0.802 E−6	86	1.932	1.67 E−5	0.864 E−5
40	992	0.657 E−3	0.662 E−6	104	1.925	1.37 E−5	0.713 E−5
50	988	0.548 E−3	0.555 E−6	122	1.917	1.14 E−5	0.597 E−5
60	983	0.467 E−3	0.475 E−6	140	1.908	0.975 E−5	0.511 E−5
70	978	0.405 E−3	0.414 E−6	158	1.897	0.846 E−5	0.446 E−5
80	972	0.355 E−3	0.365 E−6	176	1.886	0.741 E−5	0.393 E−5
90	965	0.316 E−3	0.327 E−6	194	1.873	0.660 E−5	0.352 E−5
100	958	0.283 E−3	0.295 E−6	212	1.859	0.591 E−5	0.318 E−5

Figure A.1: Viscosity and Density of Water at 1 atm [2]

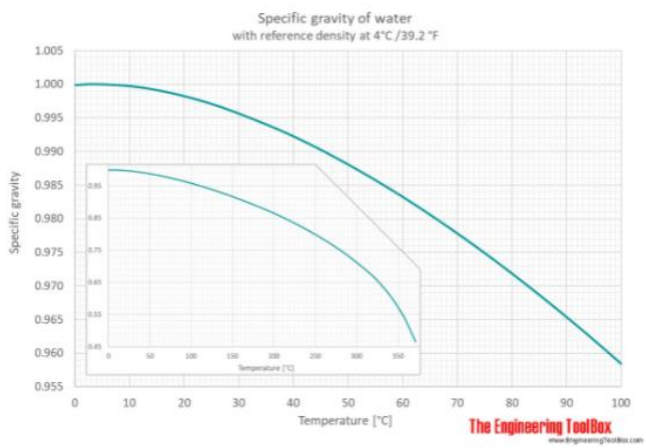

Figure A.2: Specific Water Gravity [3]

	Nominal diameter, in								
	Screwed				Flanged				
	½	1	2	4	1	2	4	8	20
Valves (fully open):									
Globe	14	8.2	6.9	5.7	13	8.5	6.0	5.8	5.5
Gate	0.30	0.24	0.16	0.11	0.80	0.35	0.16	0.07	0.03
Swing check	5.1	2.9	2.1	2.0	2.0	2.0	2.0	2.0	2.0
Angle	9.0	4.7	2.0	1.0	4.5	2.4	2.0	2.0	2.0
Elbows:									
45° regular	0.39	0.32	0.30	0.29					
45° long radius					0.21	0.20	0.19	0.16	0.14
90° regular	2.0	1.5	0.95	0.64	0.50	0.39	0.30	0.26	0.21
90° long radius	1.0	0.72	0.41	0.23	0.40	0.30	0.19	0.15	0.10
180° regular	2.0	1.5	0.95	0.64	0.41	0.35	0.30	0.25	0.20
180° long radius					0.40	0.30	0.21	0.15	0.10
Tees:									
Line flow	0.90	0.90	0.90	0.90	0.24	0.19	0.14	0.10	0.07
Branch flow	2.4	1.8	1.4	1.1	1.0	0.80	0.64	0.58	0.41

Figure A.3: Resistance Coefficients [2]