Design of a Steam Condensate Pumping System

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***Abstract*— The project work considers design of a pumping system for steam condensate operating at a pressure of 4 bar. The pumping system is designed to transfer steam condensate (saturated liquid) operating at 143.6ºC between two storage tanks. Developing pumping systems for critical process systems require special attention. Critical process system is one wherein failure of the system due to incorrect equipment selection or incorrect operation can have a huge impact on safety and/or have a huge environmental impact. Developing such process critical systems require the use of engineering standards and application of process safety management systems. In this project, steam condensate is operating at high temperature and therefore failure of the either material or equipment could pose a serious threat to the environment and/or mankind. In this project, emphasis is given to system development and the various steps in determining the pump specifications. The importance of net positive suction head (NPSH) calculations are considered in the analysis. DuPont process safety management (PSM) engineering standards are employed in selecting the appropriate materials. An excel model is developed to simulate the required head for various flow rates, pipe dimensions and tank pressures. The model can be used to develop system curve and pump curve can be superimposed on the system curve to choose the right pump for the given application.**

***Index Terms*—Design of pumping system, NPSH, cavitation, pumping model, process critical systems.**

I. Introduction

A pumping system is required to move liquids from a lower pressure to a higher pressure. Pumping systems are commonly seen residential units, in manufacturing and process industries, commercial buildings etc. Extreme care must be exercised while designing pumping systems handling hazardous liquids as failure of such systems can create a serious environmental and a safety hazard. System or an equipment whose failure would pose a serious environmental and/or a safety hazard are commonly termed as process critical system/equipment. It is very essential that the engineering standards and stringent procedures are applied while designing such systems.

In this project, a steam condensate pumping system is considered. Therein, steam condensate (saturated liquid) at 4 bar and 143.6º C is the pumping medium. It is required to pump the steam condensate between two storage tanks. Figure 1 describes the system that needs to be developed.

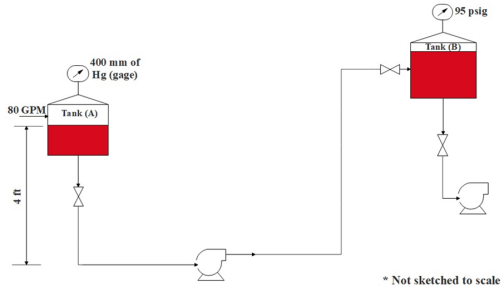


Fig. 1. Steam condensate pumping system

Tank "A" is operating at 400 mm of Hg (gauge) and the inlet flow rate to tank "A" is at 80 GPM. The tank "B" is operating at 95 psig. It is required to transfer steam condensate from tank "A" to tank "B". Since steam condensate is operating at elevated temperature, any leaks or failure from the system can be detrimental to the environment. Therefore, emphasis is given to the pump and material selection. Importance of NPSH calculations are detailed in this study. DuPont PSM engineering standards are employed in selecting appropriate materials and insulation for the pumping system. A pumping model is developed to simulate the head loss in the system.

The design of pumping systems have been widely discussed in the literature. Several textbooks and pump manufacturers have described the steps in designing a pumping system and only pertinent references are discussed herein. Janna [1] discusses pump and piping systems that includes types of pumps, pump testing methods, piping system design practices, pipe and tubing standards, etc. Tuzson [2] discusses the centrifugal pump design that includes pump specifications, system modeling, pump types, pump configurations, cavitation, performance calculations, system modeling, etc. Jones [3] discusses the design of a pumping station that includes the selection of piping, valves, pump types, pump selection, installation, etc. DuPont PSM Engineering standards [4] that are widely employed in process plants all over globe are employed in this project work. Munson et.al [5] presented the equations required for modeling fluid flows through conduits and presented information on loss coefficients in pipe fittings. Silaipillayarputhur et.al [6] developed a pumping system for a heat transfer fluid. Therein, the details for choosing an appropriate pump, head loss calculations, net positive suction head (NPSH) calculations were detailed and such concepts were applied while designing pumping system for a heat

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exchanger. The Duriron Company [7] presented a pump engineering manual wherein the pump requirements for the chemical process industries were discussed. Various critical items such as operations, maintenance and technical information on pumps were discussed in the manual.

II. NOMENCLATURE

$NPSH(A)$	net positive suction head available (psig)
P_i	inlet pressure to the pump (psig)
P_v	vapor pressure of the fluid being pumped (psig)
$P_{Tank(A)}$	tank A pressure (mm of Hg; gage)
$H_{available}$	available head in the tank A (ft)
D	diameter of the pipe after the pump (m)
Re	Reynolds number (dimensionless)
V	velocity of flow (m/s)
h_L	total head loss due to friction (m)
g	acceleration due to gravity, 9.81 m/s^2
f	friction factor – Moody chart
L	total piping length (m)
$K_{components}$	loss coefficient from elbows, valves, etc.
H_{Total}	total head loss (m)
$H_{friction}$	head loss due to friction in piping (m)
$H_{vertical}$	head loss due to vertical piping (m)
P_d	required discharge pressure (psig)
$P_{Tank(B)}$	total pressure to overcome in tank B (psig)
$P_{Excess(B)}$	Excess pressure at tank B inlet (psig)
$(\Delta P)_{pump}$	pressure requirement for the pump (psig)

Greek Symbols

ε	surface roughness for steel pipe (mm)
υ	kinematic viscosity (m^2/s)

III. DEVELOPMENT OF PUMPING SYSTEM

This section presents the governing equations required for the development of the pumping system. Thereafter, the development of a pumping model is discussed and the pump's requirements are determined. Based on the engineering standards the available material options are presented and suitable materials are chosen for the project.

While designing any pumping system, it is important to determine the pump specifications such as the flow rate and the pressure it needs to develop. It should be noted that proper understanding of NPSH calculations and pressure drop calculations are very vital in determining the pump's specifications.

NPSH (Net positive suction head) calculations

Calculation of NPSH is one of the very basic calculation an engineer/designer needs to perform while designing a pumping system. The available NPSH would indicate whether a selected pump would cavitate under the given conditions. The available NPSH or NPSH(A) is given as follows:

$$NPSH(A) = P_i - P_v \quad (1)$$

The inlet pressure is the summation of the available tank "A" pressure and the head pressure available in tank "A". Thus:

$$P_i = P_{Tank(A)} + H_{available} \quad (2)$$

Upon calculation, as described in Figure 4, it can be clearly seen that the available NPSH (i.e.) NPSH(A) is negative. A negative NPSH indicates that the liquid being pumped will generate vapor (super heated vapor) at the pump's inlet. The design of the pump is such that it cannot handle vapor, and the pump will cavitate. Likewise, it must be recalled from [6] that centrifugal pumps create vacuum at the eye of the impeller and this aspect further reduces the inlet pressure. Keeping all these in mind, to be safe, pump manufacturers usually suggest to maintain the NPSH(A) around 20 psig. In this project, this can be accomplished by adding Nitrogen to tank "A". Nitrogen is an inert gas and doesn't react with steam condensate. Most tanks in process plants are rated for at least 150 psig as the lowest rating for pipe fittings is 150 psig. Therefore, addition of Nitrogen to the tank for raising the NPSH(A) should not create any safety issue. However, to protect the tank against any unintentional over pressurization, it is necessary to add a relief valve to tank "A".

Pump Selection and Pump's Flow Rate Calculation

From Figure 1, it can be seen that the inlet flow rate to tank A is 80 GPM. Per the industry standards, to address any future expansions, it is customary to size the pump at 1.5X the requirement. Thus the flow rate that the pump must develop is set at 120 GPM. Likewise, a centrifugal pump can be chosen for the given application as the viscosity of steam condensate is not very high and maintaining extreme precision in flow rate is not necessary. However, steam condensate is operating at elevated temperature. To prevent any accidental leak from the pump, a canned motor pump (leak proof pump) with stainless steel internals can be chosen for the application.

Head Loss Calculation

Determining the head loss in the piping system is an important aspect in determining the pressure that the pump needs to develop. Friction factor can be determined by using Moody chart or by using Colebrook-White equation [5]. The Colebrook-White equation may be given as

$$f = \frac{0.25}{\left[\log\left(\frac{\varepsilon}{3.7D} + \frac{5.74}{Re^{0.9}}\right)\right]^2} \quad (3)$$

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where ε is the roughness of the pipe and Re is the Reynolds number. Reynolds number is given by

$$\mathrm{Re} = \frac{VD}{\upsilon} \quad (4)$$

The roughness for steel pipes [5] can be approximated as 0.046 mm. The head loss due to friction may be given as [5]

$$h_L = \frac{V^2}{2g}\left[\sum \frac{fL}{D} + \sum K_{components}\right] \quad (5)$$

Where $\sum \frac{fL}{D}$ corresponds to the major losses in the piping system and $\sum K_{components}$ refers to the losses from elbows, tees, valves, etc., and these are popularly referred as minor losses.

Loss Coefficients for Pipe Components

	K
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
180° return bends	
180° return bend, flanged	0.2
180° return bend, threaded	1.5
Tees	
Line flow, flanged	0.2
Line flow, threaded	0.9
Branch flow, flanged	1.0
Branch flow, threaded	2.0
Union, threaded	0.08
Valves	
Globe, fully open	10
Angle, fully open	2.0
Gate, fully open	0.15
Gate, ¼ closed	0.26
Gate, ½ closed	2.1
Gate, ¾ closed	17
Swing check, forward flow	2.0
Swing check, backward flow	∞
Ball valve, fully open	0.05
Ball valve, ⅓ closed	5.5

Fig. 2. Loss Coefficients for Pipe Components [5]

The total head loss is a summation of frictional head loss and head loss due to vertical piping. Thus:

$$H_{Total} = H_{friction} + H_{vertical} \quad (6)$$

Pump ΔP Calculation

Pump is usually recognized by its type, material of construction, the flow rate it needs to develop and the pressure it needs to develop. For the given application, a canned motor pump having a flow rate of 120 GPM is required. In order to determine the pump's ΔP, it is required to determine the required discharge pressure of the pump.

$$P_d = H_{Total} + P_{Tank(B)} + P_{Excess(B)} \quad (7)$$

Thus, the pressure that the pump needs to develop is given as

$$(\Delta P)_{pump} = P_d - P_i \quad (8)$$

Modified layout of the pumping system

Consider Figure 3 describing the modified layout of the pumping system. In practice, in process industries, all equipment and tanks have double blocking valves. This is primarily done for safety purposes, wherein if one valve leaks, the other valve can contain. The same logic is applied in this project as well. The pump, tanks and the control valve can all be isolated and removed as they are protected by double blocking valves.

One of the constraints in this project is to maintain the level in tank A at 50% at all times. However, we have chosen a pump that will deliver a flow rate of 120 GPM, while the inlet flow rate to tank is only 80 GPM. This will make the tank to go empty and the pump will begin to cavitate. This issue can be resolved by introducing a level controller system for tank "A".

The level controller for tank "A" will communicate with the control valve situated in the discharge side of the pump; and this control valve will in turn open up such that only certain fluid flow rate is discharged to tank "B". The excess fluid in the piping flows through the by-pass and re-enters tank "A" and therefore the tank level is maintained at 50% at all times.

Recall that Nitrogen must be introduced to tank "A" such that the NPSH for the pump is brought to safe limits. However, the tank is rated only for 150 psig. Therefore, to protect the tank from over pressurization, relief valve is introduced such that it relieves any excess pressure. Likewise, the tank pressure is also monitored by a pressure sensor and the pressure controller feeds information to a Nitrogen control valve which in turn regulates the flow of nitrogen into the tank.

Development of pumping system

Using the equations described, an excel pumping model was developed for the given application. The model computed the NPSH, pressure drop and the pump selection calculations. Recognize that all calculations have been detailed in Figure 4. Based on calculations, it is seen that the canned motor pump requires to develop 120 GPM at 116 ft of head.

Material Selection

DuPont PSM Engineering standards [4] were employed for material selection. From [4] it is seen that for a flow rate of 120 GPM, it is suitable to use a 2.5" schedule (SCH) 40 pipe. It must be recognized that in pumping systems, the pump's suction pipe is always bigger than the discharge pipe. This is done to keep the pump flooded with enough liquid at all times and to prevent air in the piping. Therefore, in this project, the pump's suction piping is chosen as a 3" SCH 40 pipe and the pump's discharge piping as 2.5" SCH 40 pipe. Per [4], the following are the material alternatives for the steam condensate system.

Pipe Material
ERW to ASTM A587* (NPS ½ - 4); or ASTM A106, ASTM A53, SCH 80 pipe

Fittings

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3000 lb Socket-welding, forged steel, ASTM A105, ASME B16.11 or XS Butt-welding, carbon steel, ASTM A234 Grade WPB seamless

Studs/Bolts
A193 Gr B7

Nuts
A194 Gr 2H

Gasket
G63G4 or G63F4 Flexattalic gasket

Flanges
Socket-welding flanges Class 300 forged steel, ASTM A105, ASME B16.5.
Welding-neck flanges Class 300 forged steel, ASTM A105, ASME B16.5.
Slip-on flanges Double-welded, Class 300 forged steel, ASTM A105, ASME B16.5.

Valves
G35B or G35V flanged gate valve
T35A or T35AB flanged globe valve

Insulation
1" insulation; Type A or T inside cover and Type T outside cover

The details of the materials are clearly described in [4].

IV. CONCLUSIONS

The project concentrates on the development of a steam condensate pumping system. Therein, steam condensate, at 4 bar requires to be pumped between two storage tanks. Detailed development of the pumping system consisting of pump selection, NPSH calculations, system pressure drop calculations and material selection are considered in the project. An Excel model was developed to model the pumping system. Engineering standards were employed such that the system is safe for operation.

While developing a pumping system for critical process applications where the medium is either toxic or operating under high temperature or pressure, care must be exercised in choosing the appropriate material for the system. This is essential because any failure could lead to hazardous leak that could in turn affect the environment and pose a threat to human safety. Therefore applying engineering standards is essential while developing process critical systems. In this project, DuPont process safety management standards are applied and these standards are recognized globally in the industry sector.

Likewise, cavitation is an important phenomenon that must be considered while developing any pumping system. Cavitation leads to vapor formation at the pump's inlet and pumps are designed to move only fluids. Cavitation leads to the damage of pump internals, excessive vibration, noise, fluctuating outputs, etc. All these lead to eminent failure. NPSH calculations helps to recognize the phenomenon of cavitation and this has been described in this study.

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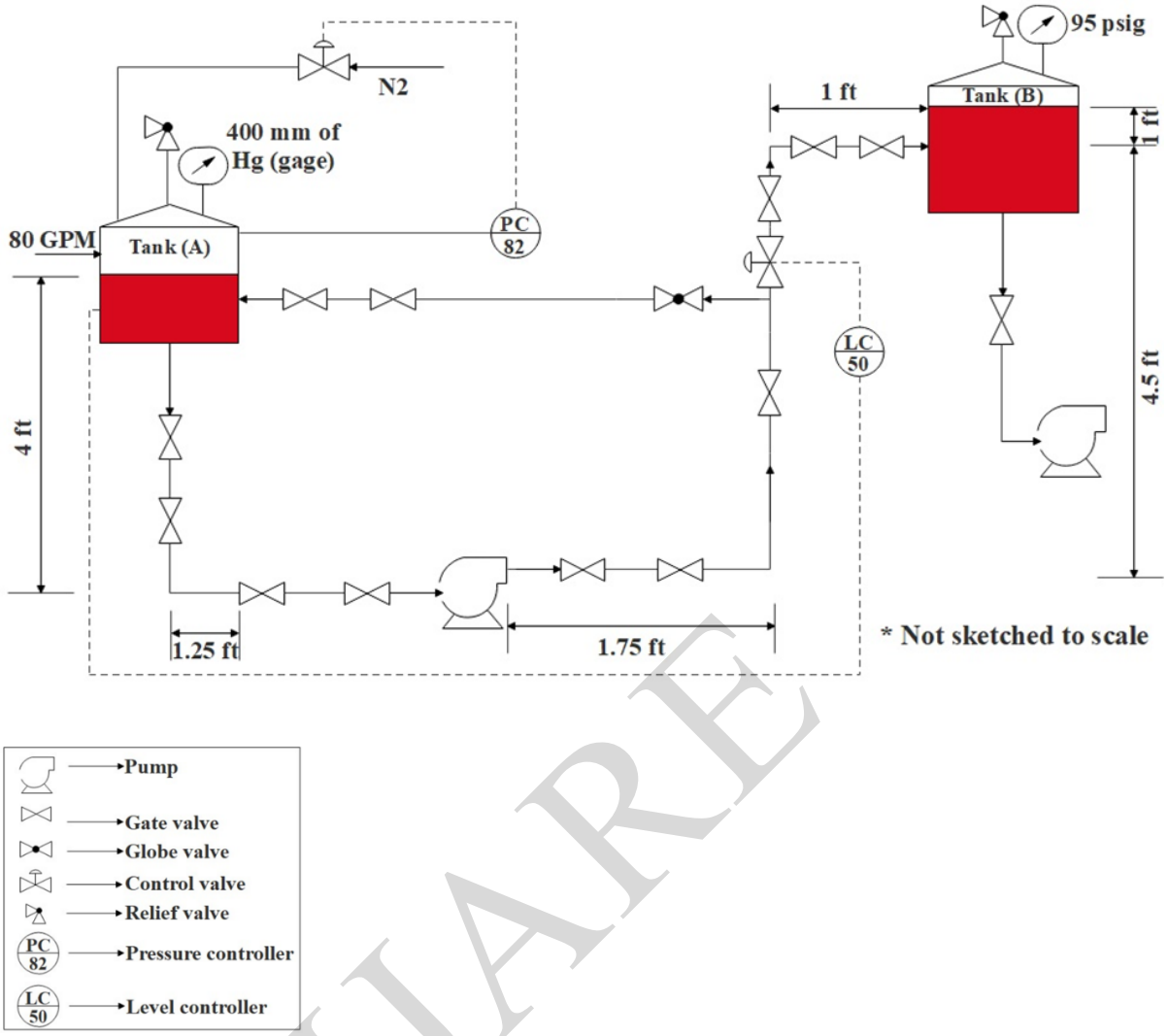


Fig. 3. Modified layout of pumping system

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MODELING PUMPING SYSTEM							
Fluid	Steam Condensate						
Service Temperature (°C)	143.6					Result	
Supply Tank Pressure (mm of Hg, gage)	400	0.526	bar	7.74	psig	The pump must develop	120 GPM @ 116 ft of head
Available Head (ft)	4	1.585	psig			Pump Type	Centrifugal, Canned Motor
Inlet Flow Rate to Supply Tank (GPM)	80						
Total Piping length (ft)	8	2.438	m				
Vertical length (ft)	4.5						
Discharge Tank Pressure (psi, gage)	95						
Head to overcome in Discharge Tank (ft)	1						
Density of mercury (kg/m^3)							
Density of Steam Condensate (lb/ft^3)		915.248	kg/m^3				
Density of steam Condensate (lb/ft^3)	62.43						
S.G of Steam Condensate	0.915						
Vapor Pressure (psia)	75						
Vapor Pressure at (psig)	60.3						
Kinematic Viscosity (m^2/s)	0.000000201						
Pump Type	Canned motor, Centrifugal						
Selected Pipe Size (OD)	2.5	inches					
Pipe Schedule	40						
Pipe Thickness	0.203	inches					
Surface Roughness for steel pipe (ks, ε)	0.046	mm					
Number of gate valves anticipated	6						
Number of globe valves anticipated	1						
Loss coefficient / gate valve	0.15						
Loss coefficient / globe valve	10						
Excess Pressure for ease of flow in Discharge Tank	20	psig					

NPSH Calculation				
Inlet Pump Pressure	9.3	psig		
NPSH (available)	-51.0	psig		
NPSH (required)	20.0	psig		
Addition of N_2 required (to attain NPSHR)	Yes			
Tank pressure due to N_2 addition	80.0	psig		
NPSH (available) after N_2 addition	21.3	psig		
Inlet Pump Pressure after N_2 addition	81.6	psig		
Flow Calculation				
Required Flow Rate	*120.0*	*GPM*	*454.249*	*lit/min*
Selected Pipe Size (OD)	2.5	inches	0.0635	m
Pipe Schedule	40.0			
Pipe Thickness	0.2	inches		
Pipe ID	2.1	inches	0.05319	m
Flow Area	0.002	m^2		
Velocity of flow	3.4	m/s		
Reynolds number of flow	901667.9			
ΔP Calculation				
Surface Roughness for steel pipe (k_s, ε)	0.046	mm		
Friction factor f - Colebrook equation	0.0194			
ε/D	0.0009			
Friction factor f - Moody chart	0.020			
Number of gate valves anticipated	6.0			
Number of globe valves anticipated	1.0			
Loss coefficient / gate valve	0.15			
Loss coefficient / globe valve	10.0			
Total Piping length (ft)	8.0	2.4384	m	
Head loss due to friction in piping (m)	0.5			
Head loss due to vertical piping (ft)	4.5	1.3716	m	
Number of elbows	2.0			
Loss coefficient / elbow	0.3			
Sudden expansion	1.0			
Loss Coefficient / expansion	1.0			
Head loss due to fittings	7.4			
Total Head Loss (m)	9.3			
Total Pressure Loss in Piping (Pa)	83604.5	0.83605	bar	
Total Pressure Loss in Piping	12.3	psig		
Discharge tank pressure (psig)	95.0			
Head to overcome in Discharge Tank (ft)	1.0			
Head pressure to overcome in Discharge Tank (psig)	0.4			
Total pressure to overcome in Discharge Tank	95.4	psig		
Excess Pressure for ease of flow in Discharge Tank	20.0	psig		
Pump Discharge Pressure	128	psig		
ΔP Requirement for the Pump	46	psig		
Δ P Requirement for the Pump	*116.4*	*ft*		

Fig. 4. Excel model of the pumping system

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