Cooperative Education Report

Surge Analysis in Pipeline

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ชื่อโครงงานสหกิจศึกษา การวิเคราะห์ความดันสูงสุดชั่วขณะภายในระบบท่อ
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บทคัดย่อ

การเปลี่ยนแปลงความเร็วของของเหลวเนื่องจากการปิดเปิดวาล์วอย่างรวดเร็วหรือความผิดปกติขณะที่ปั๊มดำเนินการ ก่อให้เกิดแรงดันสูงฉับพลันสะสมอยู่ภายในระบบท่อ แม้ว่าท่อจะสามารถยืดหยุ่นได้เล็กน้อยเพื่อลดการเกิดการเปลี่ยนแปลงของความดันอย่างกะทันหัน แต่หากไม่มีวิธีป้องกันการเกิดความดัน ความดันส่วนนี้อาจจะก่อให้เกิดความเสียหายกับระบบท่อและปั๊มได้ ยิ่งไปกว่านั้นเหตุการณ์นี้อาจจะทำให้ระดับของเหลวที่ขนส่งลดลง ซึ่งหากความดันในท่อมีค่าต่ำกว่าความดันไอของของเหลวจะส่งผลกระทบต่อระบบท่อและปั๊มที่ใช้ในการขนส่งอย่างมาก

จุดประสงค์ของการศึกษานี้เพื่อหาความดันสูงชั่วขณะในระบบท่อที่เป็นเหตุให้ท่อขนส่งโพพิลีนไกลคอลและไดโพพิลีนไกลคอลจากสถานีจ่ายของเหลวไปจนถึงเรือขนส่งสินค้า เคลื่อนที่จากตำแหน่งเดิมและมีบางส่วนเสียหาย โดยใช้ซอฟต์แวร์ FloMASTER V8.1 ซึ่งสามารถศึกษาพลศาสตร์ของไหลเชิงคำนวณของตัวแปรที่สนใจทั้งขึ้นกับเวลาและไม่ขึ้นกับเวลาได้ ผลจากการศึกษาแสดงให้เห็นว่ากรณีศึกษาที่มีการปิดวาล์วอย่างรวดเร็วทำให้เกิดความดันสูงชั่วขณะเกินกว่าทั้งความดันที่กำหนดและความดันที่ยอมรับได้ของระบบ

ดังนั้นจึงมีการเลือกใช้วิธีการลดความดันสูงที่เกิดขึ้น ซึ่งการติดตั้งถังขยายที่บรรจุแก๊สเฉื่อยที่สามารถอัดตัวได้ในตำแหน่งที่เหมาะสม เป็นวิธีที่มีประสิทธิภาพมากที่สุดสำหรับการศึกษานี้เนื่องจากมีเสถียรภาพ ความสะดวกและความยืดหยุ่นในการติดตั้ง

Cooperative Title: Pipeline Surge Analysis

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ABSTRACT

Transient behavior can be introduced by a rapid change of liquid velocity mainly arising from sudden valve open, closure or pump operations and large pressure forces that are propagated away from the source throughout the pipeline. The elasticity of the pipe boundaries prevents these sudden changes in pressure from taking place instantaneously throughout the fluid. These disturbances may result in pump and device failures, system fatigue or pipe ruptures. Many transient events can lead to column separation, which can also result in catastrophic pipeline failures due to pressure drop below vapor pressure.

The purpose of this study is to investigate the surge pressure contributing to pipe dislocation and support failure while transferring the process liquid (Dipropylene glycol and Propylene glycol) from pump station to loading arm by means of the steady state and transient simulation using FloMASTER V8.1, computational fluid dynamic (CFD) software. The surge results which exceed both of the design pressure (17 bar) and allowable pressure (18.7 bar) were obtained from a rapidly closed valve in a long distance from the pump station.

Therefore, three common mitigation methods were compared. Air vessel with optimal total volume and location was selected to suppress the overpressure due to its stability, efficiency, convenient installation, and flexibility.

ACKNOWLEDGEMENT

My special thanks are extended to Technip Engineering (Thailand) company for offering this opportunity in a cooperative education program. I am appreciated to be a part of this company to work in professional environment which helped me get a closer look at the application of various aspects of the subject and bring my study beyond the walls of my classroom, especially, learning the analysis of hydraulic transient by means of FloMASTER V8.1 simulation software which is specific tool for surge study and there are only a few people can use it. I have obtained invaluable experience and developed my potential and skills.

I also would like to thank Mrs. Donlaporn Archavajirada, Senior process engineer and Miss Thirada Sirikojakorn, Process engineer for her advice, assistance, and supporting me to complete this project.

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Miss Pawisa Kanokpaka

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CHAPTER I

INTRODUCTION

1.1 Background

TechnipFMC Thailand was established since 1997 with the aim of providing world-class project execution and developing a strong local presence in the energy sector. It has extensive experience in marketplace and has been contracted to a broad range of different projects. It provides all the services from FEED studies, basic and detailed engineering, which are provided the best technological solutions to client-specific needs at the most critical phase for total investment cost, procurement, construction, project management up to commissioning.

Surge analysis is often obtained as the project to determine the overpressure and large force acting on the pipeline that can result in severity to the system. The total force acting within a pipe is obtained by summing the steady-state and transient pressures in the line. Transient pressures are most important when the rate of flow is changed rapidly, for example, rapid valve closure or pump stoppage. The disturbance caused by this surge must be determined so that the pipeline can be properly designed to withstand these additional loads.

According to one of TechnipFMC's surge analysis in pipeline project, there are several possible scenarios transferring the process liquids- Dipropylene glycol (DPG) and propylene glycol (PG) in pipeline that can result in pipe dislocation and pipe shoe support failure at jetty area. FloMASTER v8.1, a software based on computational fluid dynamic models, is used as a tool in order to build complicated pipeline networks, simulate the behavior of transient pressure and flow through different scenarios and provide suitable surge mitigations for both systems to suppress the overpressure and prevent catastrophe during operation.

1.2 Objectives

1. To investigate the process liquid pipe dislocation and pipe shoe support at the jetty area by means of surge analysis.
2. To provide the optimal surge mitigation method.

1.3 Expected Outputs

1) The worst scenarios generating the surge pressure bringing about pipe problems are determined.

2) The most effective surge mitigation method was selected to minimize the surge problems under design pressure and allowable pressure conforming to code practice.

CHAPTER II

THEORY

In this chapter, there are various theories and principles that important for surge analysis study which include surge pressure, analysis of surge and surge mitigation methods.

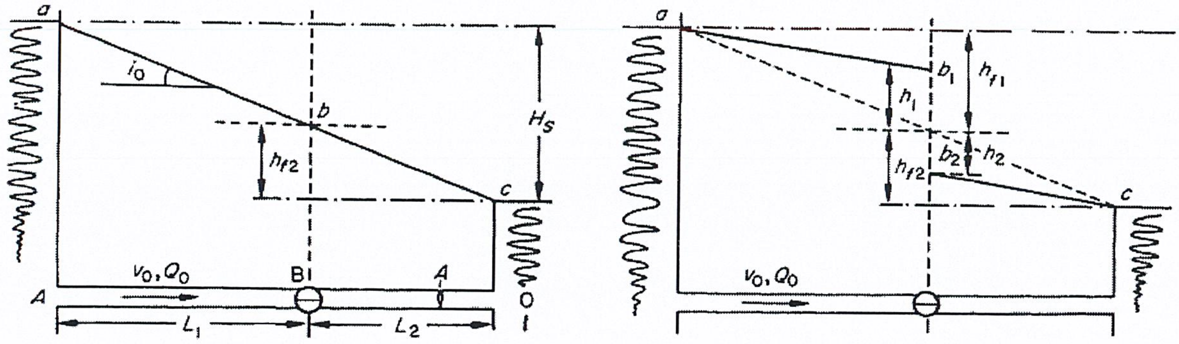
2.1 Surge pressure [1]

The term "surge pressure" often known as water hammer or hydraulic transient is used to describe the phenomenon occurring in a closed conduit when there is either acceleration or retardation of the flow. When it varies rapidly from one instant to the next at any given location in the conduit, the kinetic energy of fluid was converted into strain energy in the pipe walls causing a "pulse wave" of abnormal pressure to travel from the disturbance into the pipe system. The hammering sound that is sometimes heard indicates that a portion of the fluid's original kinetic energy is converted not only into pressure but also into an acoustic form as well as other energy losses (including fluid friction).

2.1.1 Hydraulic gradient [2]

If the liquid were completely incompressible and flew in a completely rigid pipe, there would be a change of pressure on altering the rate of flow, due to the inertia of the flowing liquid and there is no shock at the beginning and end of the closure. It is assumed that the velocity head and losses are neglected, the hydraulic gradient at abc point along the pipe is presented in Figure 2.1(a) when the valve is fully opened at steady state condition. In this case, the slope of the hydraulic gradient is a function of the flow.

When the valve was closed at t = +st, the upstream the pressure was raised about h_1 while dropped downstream pressure is h_2 as shown in Figure 2.1(b). The change of pressure head h_1 and h_2 was caused by inertia force. The liquid that travelled from A to the location of the valve is unable to move further. In other words, liquid suffers from a negative acceleration and there will be a corresponding change of pressure.



a) Initial steady conditions valve open

(b) Immediately after valve movement begins $t = +\delta t$ where δt is very small

Figure 2.1. Hydraulic gradient along the pipeline. (John Pickford, 1969).

2.1.2 Causes of surge pressure [3]

Surge is caused by rapid velocity changes of the fluid. The steep pressure gradients that may occur under some surge conditions and which cannot be avoided by appropriate means (e.g. non-slam check valves) should be evaluated with regard to the effects on the supports and the design pressure of the system. The common scenarios resulting in surge problem that introduced by DEP 31.38.01.11-Gen, February 2017 are

a) rapid valve closure with and without pump tripping;

b) pump tripping;

c) pump start-up;

d) pump trip followed by restart.

2.1.3 Types of surge pressure

There are two types of surge pressure phenomena i.e., propagation of pressure wave and column separation that lead to large positive and negative pressure waves within the system.

2.1.3.1 Propagation of pressure wave [4]

Pressure and velocity waves in a single-conduit, frictionless pipeline following its sudden closure. When a valve is suddenly closed, the pressure wave Δh moves upstream valve with wave velocity. Behind the wave front, the liquid is compressed, and the pipe wall is stretched. After the wave front reaches the upstream end, a relief wave with a head of -Δh is generated. It travels toward the valve and reaches it at a time $t = T_r$. These pressure waves travel back and forth along the pipeline. The areas of steady-state pressure head are shaded medium dark, those of increased pressure dark, those of reduced pressure light as shown in Figure 2.2 that displays the pressure and velocity wave in a closed conduit.

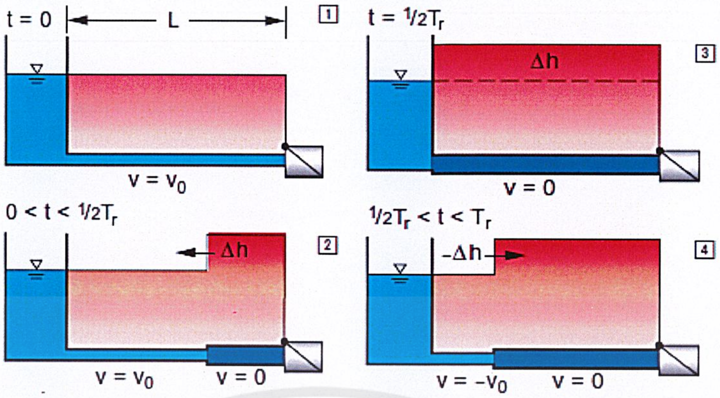


Figure 2.2. Pressure and velocity wave in a closed conduit. (KSB Know-how volume1, 2012).

2.1.3.2 Column separation [5]

The term transient column separation is used to refer to the phenomenon of the formation and growth of cavities within a liquid due to the reduction of transient state pressures to the vapor pressure of the liquid. The cavity may become so large to fill the entire cross section of the pipe and thus the divide liquid into two columns as shown in Figure 2.3.

The low pressures that may lead to column separation or cavitating flows are produced by negative or rarefaction waves. These waves are reflected as positive waves from various boundaries (e.g., a reservoir) in the system. It could compress the bubbles in the cavitation-flow region and progressively reduce the size of the cavity where column separation had occurred. When the cavities collapse or when the separated columns rejoin, extremely high pressures occur. These pressures may burst the pipe.

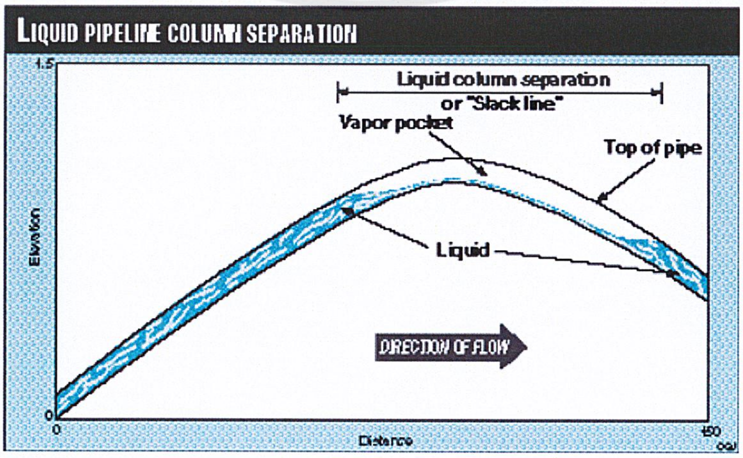


Figure 2.3. Column separation (Burnett, 2015).

2.2 Analysis of the surge

The pressure surge at wave velocity could be calculated by Joukowsky Equation based on the mass and momentum equation. Pressure change (ΔP) and pressure wave propagation (a) are calculated by equation (2.1) and (2.2), respectively which are

$$\Delta P = \rho \text{ x } a \text{ x } \Delta v \qquad (2.1)$$

where:

ΔP	Pressure change (bar)
ρ	Liquid density (kg/m^3)
Δv	Flow velocity change (m/s)
a	Pressure wave propagation velocity (m/s)

$$a = \sqrt{\frac{1}{\rho\left(\frac{1}{\beta_f}+\frac{1}{\beta_p}\right)}} \qquad (2.2)$$

where:

ρ	Fluid density (kg/m^3)
ßf	Fluid Bulk Modulus (N/m^2)
ßp	Bulk Modulus of the pipe (N/m^2) which is calculated as tE/ DC

where:

D	Internal diameter of the pipe (m)
t	Pipe wall thickness (m)
E	Young's (Elastic) Modulus of pipe material (N/m^2)
C	For most engineering applications, it is reasonable to appropriate C = 1, in view of other uncertainties which arise (such as Fluid Stiffness due to gas content).

In practice, surge pressure in long pipeline systems shall be calculated using Equation (2.3) and Equation (2.4).

$$P_{surge} = \frac{0.02L}{D} \text{ x } \rho \text{ x } v_{fluid} \text{ x } v_{eff} \quad \text{when } \frac{L}{DN} \text{ x } v_{eff} < 0.55 \qquad (2.3)$$

$$P_{surge} = C \text{ x } \rho \text{ x } v_{fluid} \text{ x } 10^{-5} \quad \text{when } \frac{L}{DN} \text{ x } v_{eff} \geq 0.55 \qquad (2.4)$$

where:

L	piping length between pump and valve (m)
DN	nominal diameter pipe (mm)
v_{eff}	effective valve closure speed (m/s)

P_{surge} surge pressure (barg)

v_{fluid} fluid velocity in pipe (m/s)

ρ density of fluid (kg/m3)

C system system sonic velocity (m/s)

For actuated valves, the valve closure speed is 25 mm/s (1 in/s) and the effective valve closure speed should be determined as following

- Gate valves 0.5 m/s (1.64 ft/s)
- Butterfly valves 0.17 m/s (0.55 ft/s)
- Globe and Ball valves 0.1 m/s (0.33 ft/s)

Severity of surge in pipeline system [6]

The consequences of surge do not become apparent until long after the event. There is a pipe rupture, one of the real examples is presented in Figure 2.4. This picture showed how the rapid pressure changes from transient events have resulted in catastrophic damage. The sinkhole is a result of a pipe burst. The posterior analysis of the system revealed that this burst occurred due to excessive pressure build up in the system as a result of a pump failure. Therefore, it is important for engineers to be cognizant of the various causes of such events and develop the appropriate design and operational criteria.

Figure 2.4. 66-in water main ruptures as a result of hydraulic initiated by a pump failure (Leslie, 2008).

2.3 Surge mitigation method

There are numerous surge mitigation methods to reduce the undesirable transient i.e., pipeline replacement, slow-closing valves, installation of protection devices such as surge tanks, air valves, air vessels, one-way surge tanks, and pressurized relief valves.

2.3.1 Slow-closing valve [7]

The slow-closing valve method can be a time-consuming procedure aiming to prevent the occurrence of low pressures since it gradually decreases the flow. Swaffield suggests 80-20 rule by quick opening with a faster rate 80% of the full open valve flow coefficient (Cv) over 20% of the full closure time and follows by extremely slow closing the last 20% of the full open Cv over the rest of the time. Figure 2.5 shows the slow-closing controlled valve in a pipeline system.

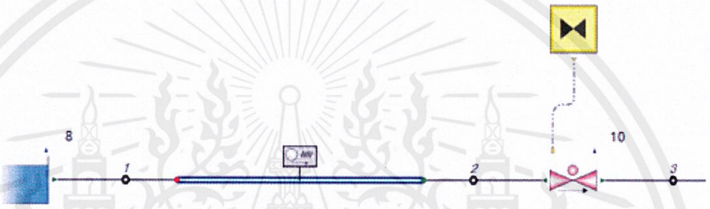


Figure 2.5. Controlled valve slow closure modelling.

2.3.2 Installation of surge tank [8]

A surge tank is an open chamber or a tank connected to the pipeline. The main purpose of a surge tank is to reduce the amplitude of pressure fluctuations by reflecting the incoming pressure waves and supplies or stores excess liquid. Figure 2.6 shows the location at which a surge tank is installed while Figure 2.7 shows a schematic of a simple surge tank system.

The equation for the minimum cross-sectional area of a surge tank is presented by Thoma equation (equation 2.5). Moreover, Charles Jaeger proposed a safety factor, e as shown in equation (2.6). He suggested that the area of the surge tank should be n times the Thoma area. As a rough guide for preliminary design, e may be taken as 1.5 for a simple tank. [5]

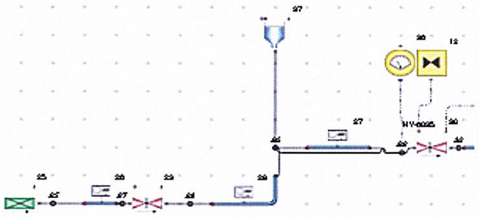
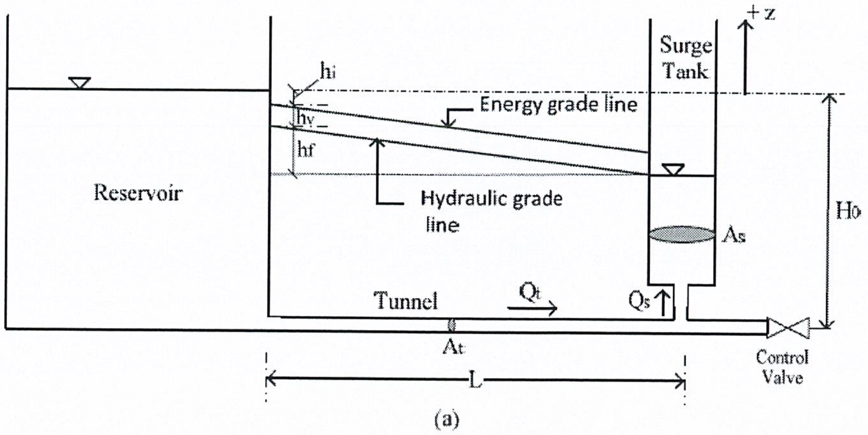


Figure 2.6. Location of surge tank in the pipeline system.



(a)

Figure 2.7. Schematic of a simple surge tank system (adopted from Chaudry 1987).

Head loss, H_{w0}, H_{wm}, H_1 of the system are calculated by using the moody diagram as shown in Figure 2.8.

$$A_{th} = e\frac{L_t A_t}{2\alpha g H_1}$$

$$e = 1 + 0.482\frac{Z_{max}}{H_o}$$

$$\alpha = \frac{H_{w_o} {A_t}^2}{Q^2}$$

$$H_1 = H_o - H_{w_o} - 3H_{w_m} \qquad (2.5)$$

where

A_{th} is the Thoma area

e is the safety coefficient

L_t and A_t are the length and area of the headrace tunnel, respectively

H_o is the gross head in the turbine = head of the reservoir

H_{wo} is the head loss in the headrace tunnel = loss from the length

H_{wm} is the head loss in the penstock (the horizontal length of a pipeline) = loss from enlargement plus straight pipe

Z_{max} is the maximum water level in the surge tank

Q is the discharge in the tunnel

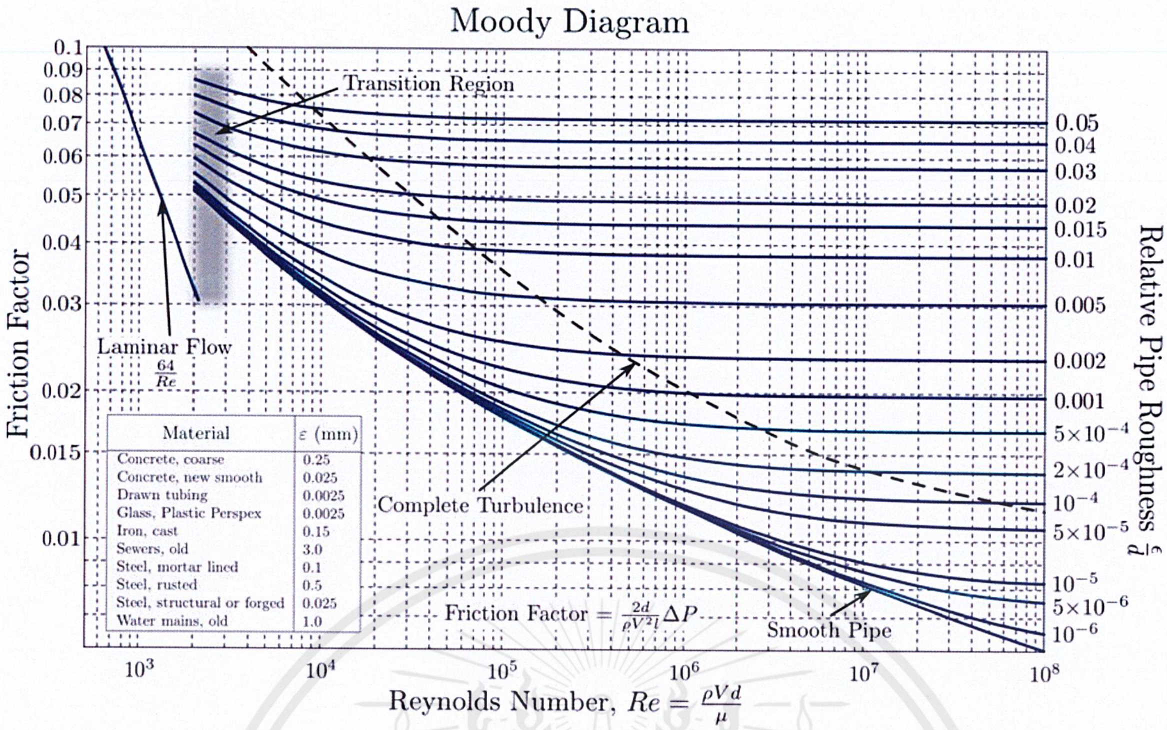


Figure 2.8. Moody diagram used for investigation of fanning friction factor (f) (Lewis Ferry Moody, 1944).

H_{w0} is determined by using Reynolds number, Relative pipe roughness, fanning friction factor according to Darcy-Weisbach equation as shown in equation (2.6).

$$h_f = f\frac{L}{D}\frac{v^2}{2g} \tag{2.6}$$

H_{wm} has resulted from straight pipe to valve, 0.866 m and enlargement from orifice to the main pipe by equation (2.7).

$$h_{fe} = \frac{K_e V^2}{2} \tag{2.7}$$

where K_e is expansion loss coefficient = $(1- S_a/S_b)^2$ and S_a is orifice area, S_b is the main pipe area. In addition, the “Chinese design code for surge chamber of hydropower stations” suggests that the minimum and maximum area of the orifice must be 25% and 45% of the area of the headrace tunnel.

2.3.3 **Air vessel** [9], [10]

Air vessel was popular equipment for preventing surge due to their stability, convenient installation, and management advantages. The main purpose of the air chamber is to avoid negative pressures and column separation that may occur during daily operation conditions. On the other hand, this device can suppress excessive positive pressure as well. Figure 2.9 shows the location of air vessel in the pipeline system. Air vessel could be estimated the vessel volume by equation (2.8) – (2.9).

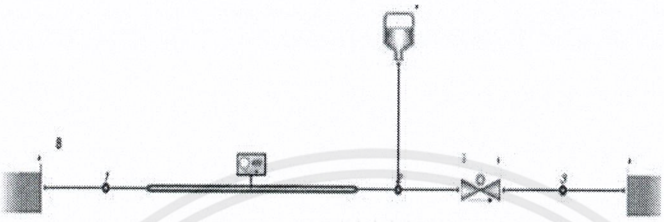


Figure 2.9. Location of air vessel in the pipeline system.

The initial air volume [V_a] could be determined by the equation

$$[V_a]_{\min} = \max\left[\frac{v_0^2 Lfmp_0}{\varphi_2^2 g H_0^2}, \frac{v_0^2 Lfmp_0}{g h_{\min}^2}\right]$$

where $p_0 \approx H_0 + p_a$. (2.8)

The approximate analytical size of the air vessel could be eventually described as:

$$V_T = V_a(1+\varphi_1) = k|V_a|_{\min}(1+\varphi_1) \quad (2.9)$$

where

v_0 is fluid velocity; L is the entire length of pipeline; f is the cross-sectional area of main pipe.

polyprotic index (m) is 1.2 which is between 1.0 and 1.4 for an isothermal, slow transients and large air volume and for small-size chambers and rapid transients, an adiabatic expansion or compression of the air.

H_0 is elevation of reservoir – elevation of valve closed

P_a is atmospheric head, 10.36 m [5]

P_0 is $H_0 + P_a$

h_{min} is the lowest initial operating pressure along the pipeline at a steady operating state, usually appearing at local high elevations.

g is gravitational force, 9.81 m/s^2

φ_2 is the limited rate of pressure rise in system

φ_1 is the ratio of liquid to gas

$[V_a]_{min}$ is minimum air volume which is required for the safe operation of the pipeline system.

V_T is total air vessel volume

Optimal location of installing air vessel [9]

Traditionally, air vessels have been installed behind a check valve at the upstream end of a pipeline to mitigate negative pressure and allow for convenient maintenance and operation, as air vessels need frequent replenishment of air. However, the pipeline behind the air vessel is long and the inertia of water for the system is large, the positive pressure caused by backflow is enormous. As such, a large volume of air vessels is necessary to overcome the large positive pressure. Therefore, the optimal location for an air vessel and the influence of that location on water hammer protection in liquid system are investigated.

On the basis of the incompressibility theory of water and simple harmonic vibration theory, a formula of calculating the optimal installing air vessel location can be obtained from equation (2.10)

$$L = L_0 + L_1 = (H_1 - H_B)\frac{\cos\alpha}{\sin(\alpha + \beta)} \tag{2.10}$$

Schematic diagram that show data for optimal location air vessel is shown in Figure 2.10.

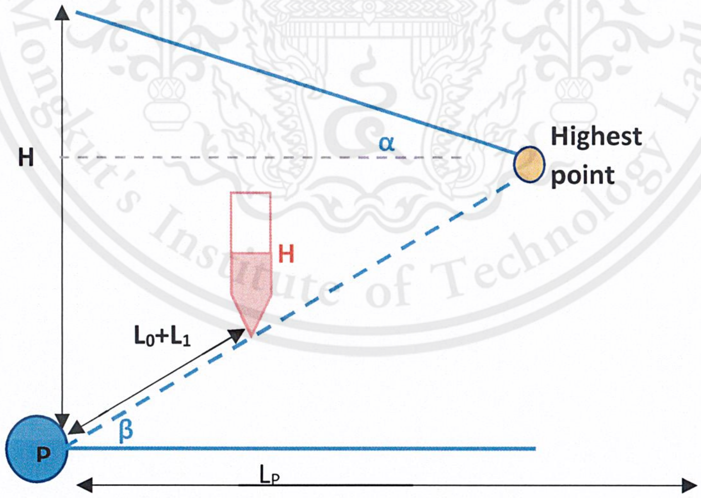


Figure 2.10. Schematic showing the data of optimal location of air vessel.

Where L_0+L_1 is protection location.

L_P is entire length of pipeline.

H_B is head installing air vessel.

H_0 is highest elevation.

H_1 is head above pump station.

CHAPTER III

METHODOLOGY

In this chapter, there are several steps toward the results. Methodology for study of surge analysis was divided into 8 steps as shown in Figure 3.1.

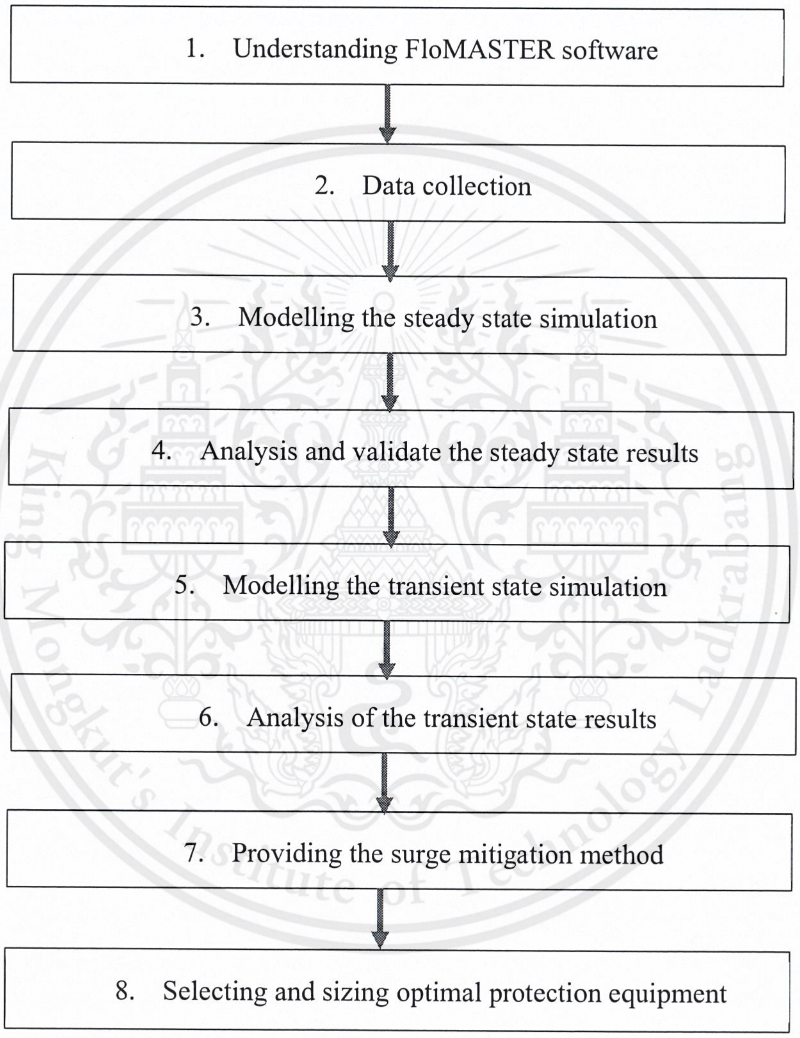
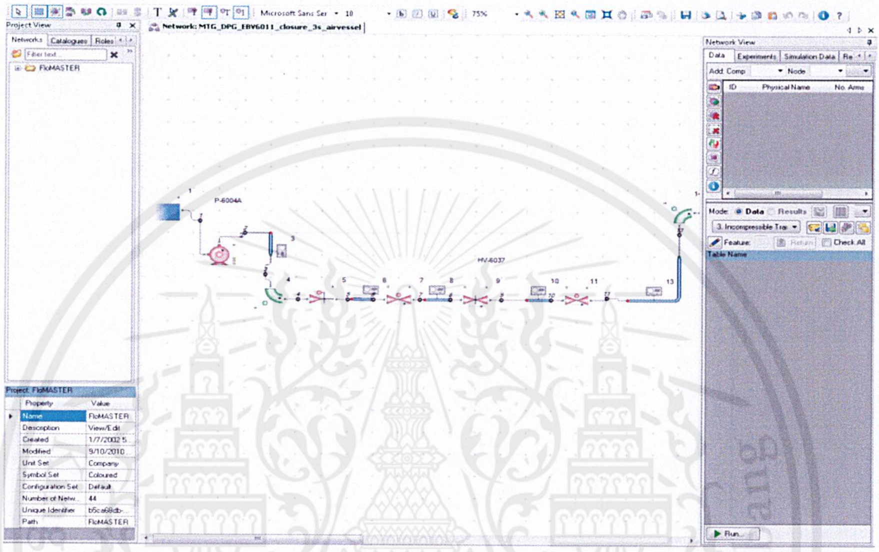


Figure 3.1. Workflow diagram.

3.1 Understanding the FloMASTER

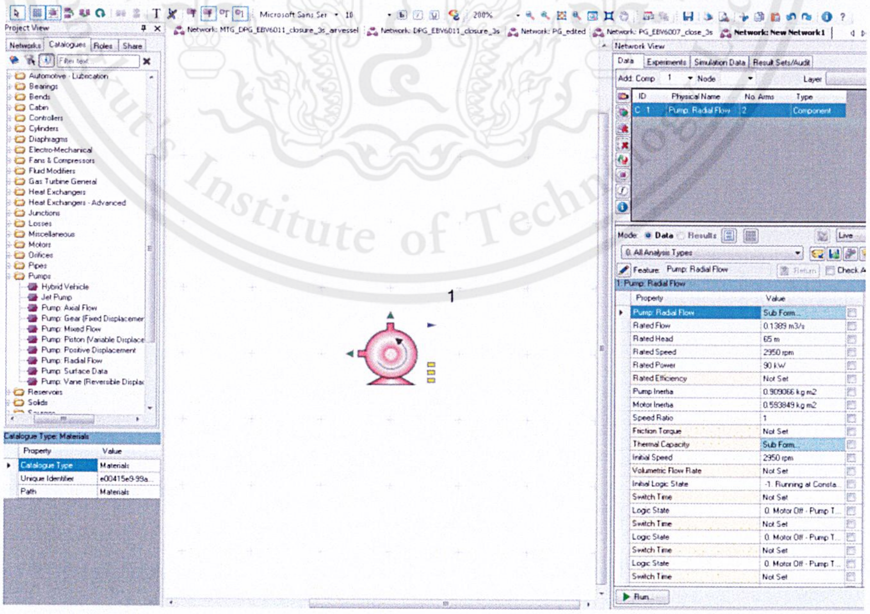
FloMASTER is an advanced CAE/CFD software developed by Mentor Graphic Company for modeling and analysis of fluid mechanics in complex piping systems of any scale. FloMASTER's Graphical User Interface (GUI) in Figure 3.2 helps engineers to simulate pressure surge, temperature and understand the overall fluid in the system accurately and quickly. All main components including pipe, pump and valve have been modelled to provide higher fidelity and realistically response as shown the example of radial pump modelling in Figure 3.3.



Project: FloMASTER

Property	Value
Name	FloMASTER
Description	View/Edit
Created	1/7/2002 5...
Modified	9/10/2010 ...
Unit Set	Company
Symbol Set	Coloured
Configuration Set	Default
Number of Netw...	44
Unique Identifier	b5ca68db-...
Path	FloMASTER

Figure 3.2. FloMASTER's Graphical User Interface (GUI).



Catalogue Type: Materials

Property	Value
Catalogue Type	Materials
Unique Identifier	e00415e9-99a...
Path	Materials

ID	Physical Name	No. Arms	Type
C 1	Pump: Radial Flow	2	Component

Mode: Data

0. All Analysis Types

Feature: Pump: Radial Flow

1: Pump: Radial Flow

Property	Value
Pump: Radial Flow	Sub Form...
Rated Flow	0.1389 m3/s
Rated Head	65 m
Rated Speed	2950 rpm
Rated Power	90 kW
Rated Efficiency	Not Set
Pump Inertia	0.909066 kg m2
Motor Inertia	0.593849 kg m2
Speed Ratio	1
Friction Torque	Not Set
Thermal Capacity	Sub Form...
Initial Speed	2950 rpm
Volumetric Flow Rate	Not Set
Initial Logic State	-1. Running at Consta...
Switch Time	Not Set
Logic State	0. Motor Off - Pump T...
Switch Time	Not Set
Logic State	0. Motor Off - Pump T...
Switch Time	Not Set
Logic State	0. Motor Off - Pump T...
Switch Time	Not Set

Figure 3.3. Radial pump component and required input parameters.

3.2 Data collection

Case studies and scenarios of surge analysis was carried out for a pipeline to transfer process liquid (PL) from tank to jetty area. The process line is shown in Figure 3.4. These 2 case studies that are

Case 1: Dipropylene Glycol in 8” pipeline with transfer flow rate 300 m^3/h

Case 2: Propylene Glycol in 10” pipeline with transfer flow rate 500 m^3/h

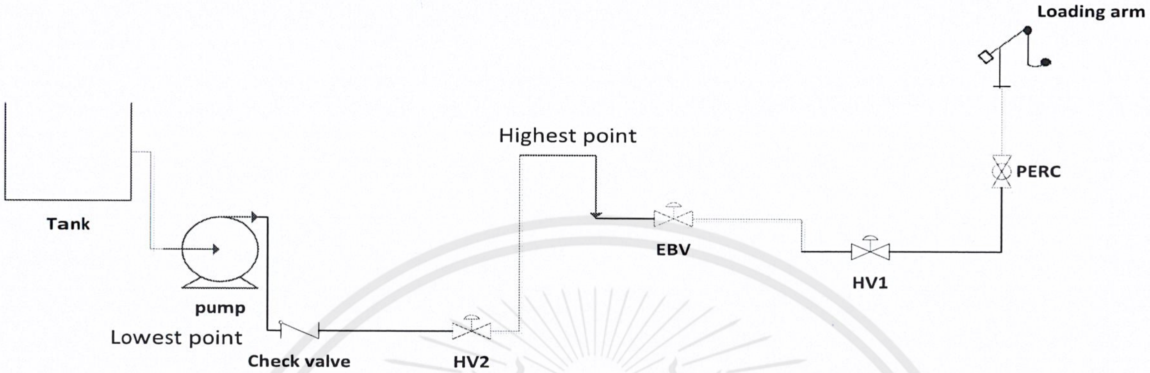


Figure 3.4. PL transferring route from pump to loading arm.

These two liquids flow from tank to loading arm using by radial pump and passes through the non-slam check valve, diaphragm valves, HV2, EBV, HV1 and ball valve PERC at loading arm which total of pipeline length of DPG and PG system are 366.6 m and 463.6 m, respectively.

In each case, there are 9 scenarios that were carried out and divided into 3 groups – pump operation, rapid valve closure and other special cases. The description of those scenarios is presented in Table 3.1.

Table 3.1. Design scenarios performed in surge analysis.

Group	Scenario	Description
1. Pump operation	A1	Pumps tripping
2. Rapid valve closure	B1	EBV Closing in 3 seconds
	B2	HV1 Closing in 5 seconds
	B3	HV2 Closing in 5 seconds
	B4	PERC loading arm valve Closing in 5 seconds
3. Other special scenarios	C1	Pump minimum flow IV valve fail opened
	C2	HV2 automatically open during pump starting
	C3	IV valve closed during PERC stopping
	C4	IV valve opened during PERC stopping

3.3 Modelling the steady state simulation

The steady state models of two case studies presented in Figure 3.5 were initially developed by collected data from client such as isometric drawing to design the overall pipeline system and input required parameters into each component based on modelling condition in order to determine the pressure profiles throughout the process system prior transitioning to transient initialization.

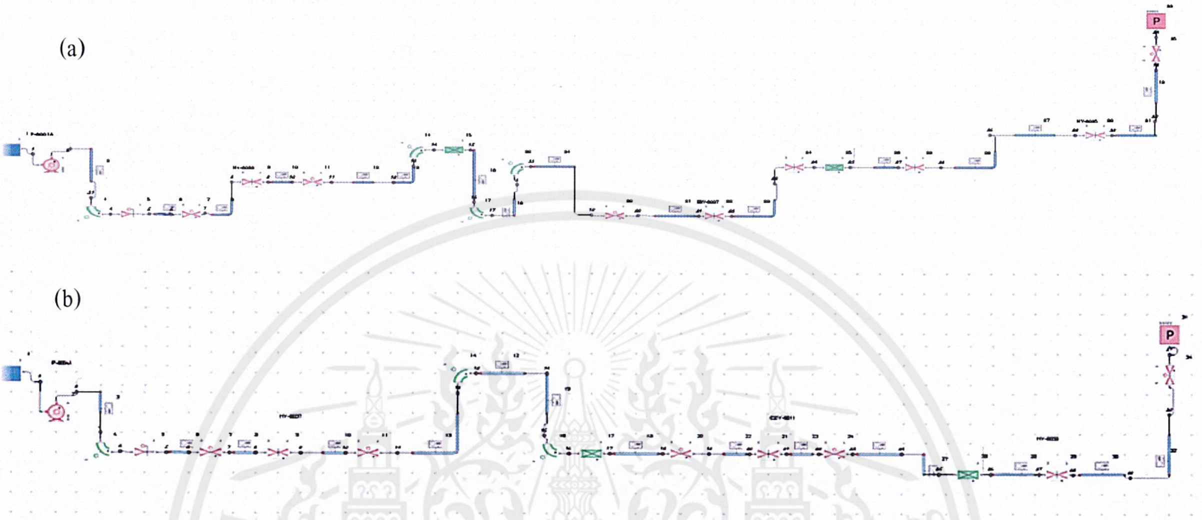


Figure 3.5. Steady state model of PG transferring system (a) and DPG transferring system (b).

3.4 Analysis and validate the steady state results

The model validation is subjected to verify hydraulic pressure and flow profiles to ensure that it is good to fit to real data (e.g. pump discharge pressure against pump performance data reading, flow rate correspond to friction loss against flowing conditions.) and ensure that pump can deliver the fluid to the required destination with the suitable pressure drop across the control valve.

3.5 Modelling the transient state simulation

According to case studies of surge analysis, the event scheduling and sequence run of each scenario of two process liquids (Dipropylene glycol and propylene glycol) transferring systems are listed in the Table 3.2-3.9.

Group 1 is related to pump operation scenario.

A1: Pump tripping

Table 3.2. Sequence of tripping.

Time (s)	Event	Remark
0 – 15	Pump motor off at 15 s	Pump tripped
15 – Simulation End	Run the transient until reach steady state	Record peak pressure and time during surge

Group 2 is rapid valve closure scenario.

B1: EBV valve Closing in 3 seconds

Table 3.3. Sequence of the EBV valve closing in 3 seconds without pump tripping.

Time (s)	Event	Remark
0 – 300	Start transient simulation until the system reach steady state condition	-
300 – 303	Valve start to close and fully close at 303 s	-
303 – Simulation End	Run the transient until reach new steady state	Record peak pressure and time during surge

C2: HV2 automatically open during starting (DPG system)

Table 3.6. Sequence of HV2 automatically open during pump start.

Time (s)	Event	Remark
0 – 10	Start transient simulation until the system reach steady state condition	- Valve closed at time = 0 - Pump run at the beginning
10 - 20	Valve is started to open and fully open within 10 s	
20 – Simulation End	Run the transient until reach new steady state	Record peak pressure and time during surge

C2: HV2 automatically open during starting (PG system)

Table 3.7. Sequence of HV2 automatically open during pump start.

Time (s)	Event	Remark
0 – 23	Start transient simulation until the system reach steady state condition	- Valve closed at time = 0 - Pump run at the beginning
23 - 33	Valve is started to open and fully open within 10 s	
33 – Simulation End	Run the transient until reach new steady state	Record peak pressure and time during surge

C3: IV valve closed during PERC stopping

Table 3.8. Sequence of IV valve closed during PERC stopping.

Time (s)	Event	Remark
0 – 100	Start transient simulation until the system reach steady state condition	All valves open
100 – 115	Minimum flow valve is fully closed	Valve at destination still open
115 – 185	Run the transient until reach new steady state	
185 – Simulation End	Destination valve is closed	Record peak pressure and time during surge

C4: IV valve opened during PERC stopping

Table 3.9. Sequence of IV valve opened during PERC stopping.

Time (s)	Event	Remark
0 – 100	Start transient simulation until the system reach steady state condition	- Destination valve opens - Minimum flow valve closes
100 – 115	Minimum flow valve is partially opened at minimum flow ratio	Valve at destination still open
115 – 185	Run the transient until reach new steady state	
185 – Simulation End	Destination valve is closed	Record Peak Pressure and time during surge

3.6 Analysis of the transient state results

For transient model validation, if the existing system is provided with site data record at any transient scenario, it will be considered for transient model validation.

3.6.1 Interpretation of transient results

FloMASTER dynamic simulation provide the trend of interested results and figure out the instantaneous peak pressure toward each node. For example, the pressure profile of scenario B1, sudden EBV valve closure in 3 seconds after it had been reached the steady state for 300 seconds. While flow rate decreased from 0.0833 m^3/s to 0 m^3/s, the peak pressure was generated at time 303 seconds as shown in Figure 3.6. Moreover, it can be observed the phenomenon among the simulation such as cavity collapse due to column separation from cavity volume as shown in Figure 3.7.

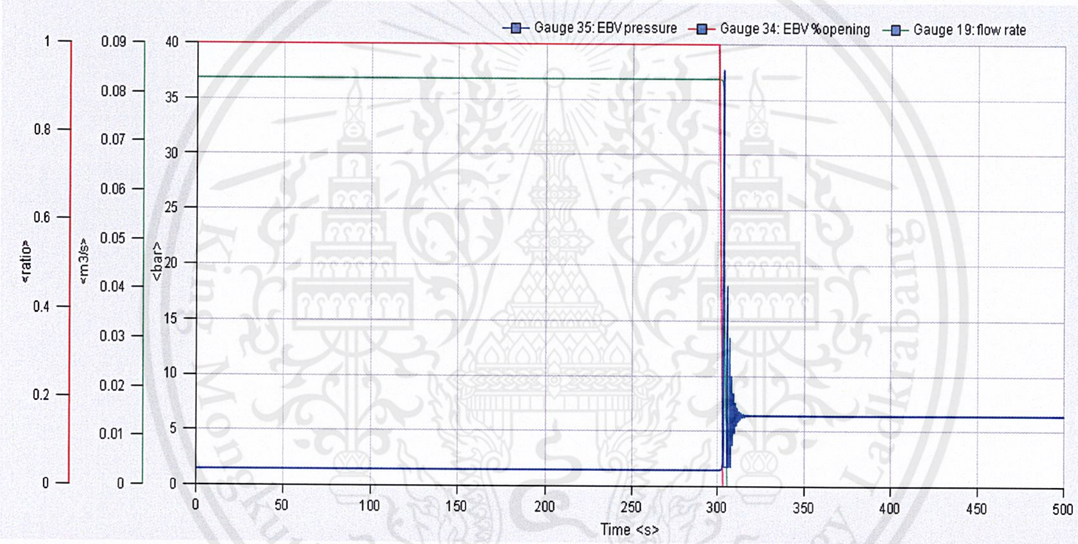


Figure 3.6. Pressure profile developed in front of valve EBV.

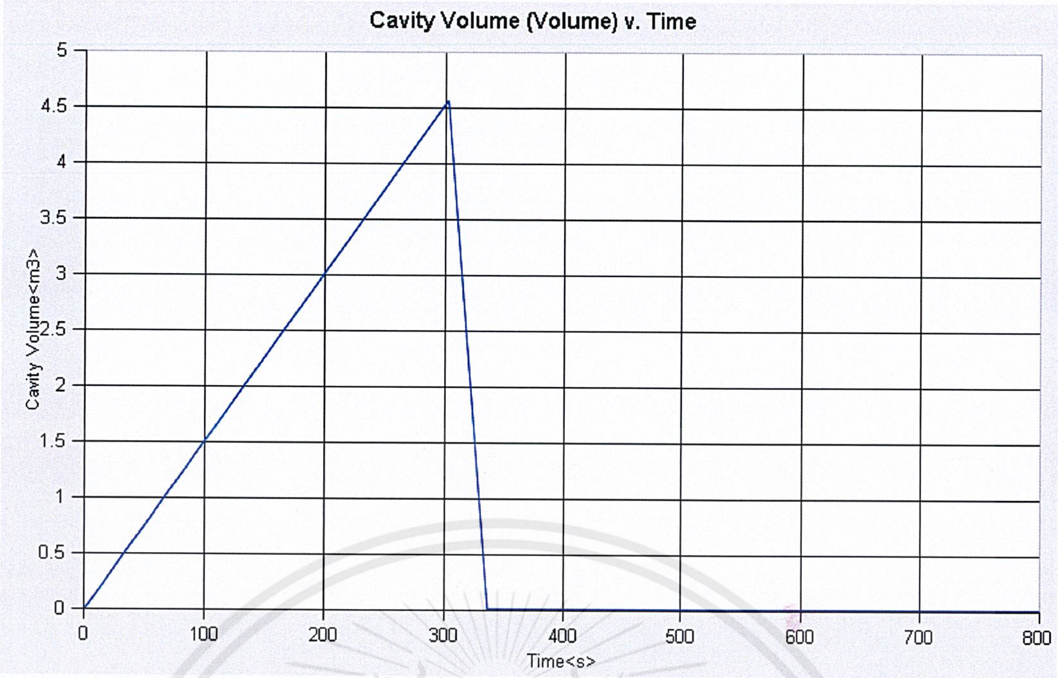


Figure 3.7. Cavity collapse at highest point of system.

3.6.2 Practical Design Limit for Transient Effect

In this project, the design limitation is considered as pipeline design pressure which is 17 bar and instantaneous peak pressure compare to ASME Code B31.4 that allowable pipeline transportation 110% of design pressure, 18.7 bar.

Additionally, the hydrodynamic force acting on components has to be under the allowable stress of pipe A312-TP304 & 304L Dual grade followed by ASME Code Section II, Part D, Table 1A, 2017 Edition that is the range of 115 to 138 MPa. For this project, the minimum allowable stress is 4,040 kN.

CHAPTER IV

RESULTS AND DISCUSSIONS

In this chapter, the pressure of DPG and PG transferring system at crucial points including pump discharge, lowest elevation, highest elevation, front of valve and pipe before loading arm from steady state and transient simulation will be discussed. Moreover, the surge mitigation method is provided to reduce the surge pressure from the worst scenarios of these two systems.

4.1 Steady state simulation results

The steady state results which are the pressure at several crucial points of the pipeline system from tank to loading arm are presented in Table 4.1.

Table 4.1. Pressure at several crucial points of the pipeline system from tank to loading arm.

System	**Pressure at node level (bar)**								
	D/S pump	**Lowest point**	**Highest point**	**Jetty**	**Valve**				
					EBV	**HV1**	**IV minimum flow valve**	**HV2**	**PERC**
DPG	5.27	5.22	3.73	1.15	1.47	1.17	4.5	5.17	1.01
PG	3.59	2.84	1.02	1.12	1.63	1.13	2.28	3.51	1.01

Typically, the results from the steady state model should be validated using operated data. However, the simulation was established based on the Front-End Engineering Design (FEED) stage, there is no site data available.

4.2 Transient simulation results

The transient flow was subsequently simulated under the condition of design pressure 17 bar and allowable pressure conformed to ASME B31.4 which is 110% of design pressure (18.7 bar) through 9 scenarios as well as the hydrodynamic force acting on the components was reported under consideration of allowable stress. as described in section 3.6.2.

Pressure at several crucial points of the DPG and PG system of 9 scenarios are presented in Table. 4.2 - 4.3. For DPG system, pressure at crucial points of pump tripping scenario (A1) and minimum flow IV valve failed open (C1) are lower than the results from steady state simulation but it is still higher than the vapor pressure of DPG which is 0.98 bar so that it can avoid cavitation of pump.

Next, EBV valve closing in 3 seconds (scenario B1) and HV1 valve closing in 5 seconds (scenario B2), it generates the pressure at discharge pump, lowest elevation, highest elevation, front of valve excepting jetty area which is extremely increased compared to steady state results and exceeds the allowable pressure of this system due to the effect of wave propagation and column separation.

Although the pressure from HV2 closing in 5 seconds scenario (B3) at crucial points slightly rises compared to steady state results, it is still lower than peak pressure from scenario allowable pressure, B1, and B2. Since the smaller volume of liquid after valve closure due to shorter distance between pump and valve, it results in lower pressure surge according to the equation from SHELL DEP 31.38.01.11-Gen, Section 2.2 that is $P_{surge} = (0.02 \text{ X } L)/D \text{ x } \rho \text{ x } V_{fluid} \text{ x } V_{eff}$ when the same system has the same properties of nominal diameter, fluid density, velocity and same valve type which brings about same effective valve closure speed. Moreover, the lowest pressure of scenario B3 is at the highest elevation due to the occurrence of column separation after valve closure and head loss from an elevation that contributes to remarkable pressure drop.

In addition, the peak pressure of PERC valve closing in 5 seconds scenario (B4) at all crucial points is higher than scenario B3, but it is lowered than scenario B1 and B2 that has a shorter distance from the pump to valve because it has no additional effect of the column separation. It indicates that column separation is one of the reasons that generate catastrophic consequences in the pipeline. However, this scenario B4 generates the larger overpressure at the jetty area than other scenarios due to pressure wave propagated at the upstream PERC valve that is located after pipe around the jetty area.

For scenario HV2 automatically open during pump starting (C2), IV valve closed during PERC stopping (C3), and IV valve opened during PERC stopping (C4), the pressure at all crucial points is little increased compare to steady state results. Particularly, the pressure from scenario C3 and C4 at upstream PERC valve and pipe around jetty is noticeably increased compared to other points in the system but it is still under the allowable pressure of the system.

In case of PG system, it has a relatively similar trend with DPG system. The pressure at crucial points from all scenarios is risen compared to steady state results of PG system. In addition, scenario B1 and B2 generate higher overpressure at pump discharge, lowest elevation, highest elevation and upstream valve than other scenarios and allowable pressure. Especially, the pressure at the highest elevation of the system from scenario B4 is almost as high as the pressure from scenario B1 and B2 and the pressure developed at the jetty area is also largest compared to other scenarios.

There is a slight increase of pressure at all points compared to steady state results from scenario C1 to C4, but it is still lowered than scenario B1 to B4 and does not exceed allowable pressure. Even the pressure at the jetty of scenario B3 and B4 are higher than the others in PG system, it is lowered scenario B4.

It is determined that the rapid valve closure scenario generates the peak pressure of two systems that are higher than either design pressure (17 bar) or allowable pressure (18.7 bar). Therefore, the worst scenarios of both systems in this project are scenario B1, B2, and B4.

The example of dynamic behavior of rapid HV1 valve closure within 5 seconds (scenario B2) of PG system displayed in Figure 4.1. The hydrodynamic force exerting on HV1 in Figure 4.2 was also reported to indicate wave propagation. Moreover, the small cavity collapse was detected as shown in Figure 4.3.

Figure 4.1 illustrates the change of pressure at crucial points in system including discharge of pump, lowest point, highest point, upstream HV1 valve from time 0 to 400 seconds.

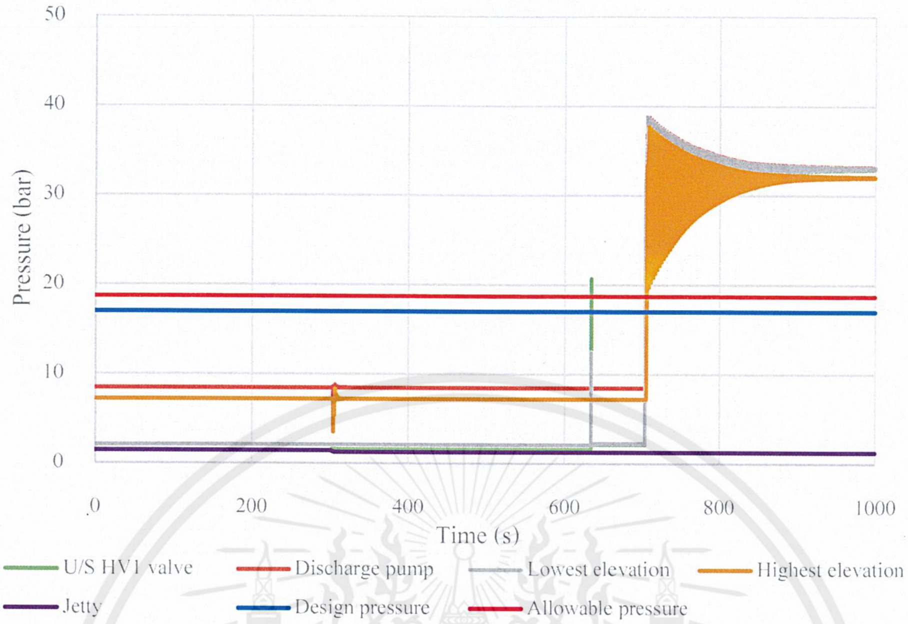


Figure 4.1. Pressure profile of HV1 closing in 5 seconds.

After the system runs at the steady state for 300 s and then suddenly closes the valve at time 305 s, the pressure at upstream HV1 valve remarkably exceeds both design pressure (blue line) and allowable pressure (red line) at about time 650 s. Then, the pressure at all interested points excepting jetty area significantly rises to about 38 bar about time 700 s before it decreases to around 32 bar due to line packing together with column separation as obviously shown in Figures 4.2 and 4.3, respectively.

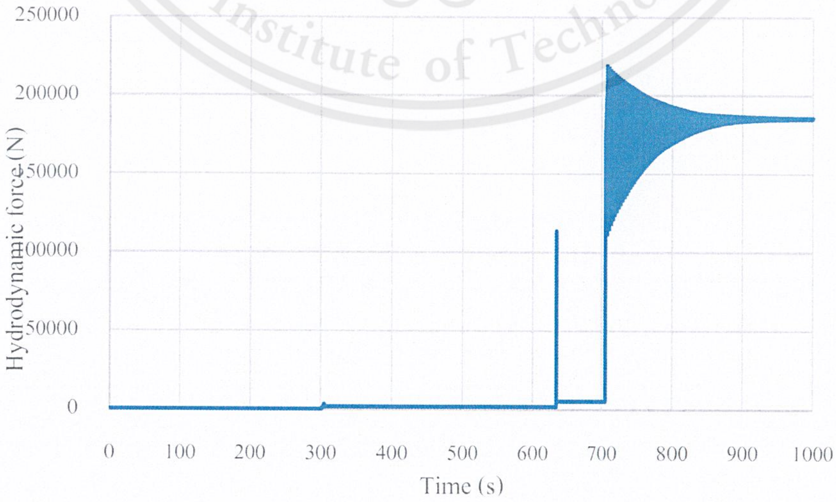


Figure 4.2. Hydrodynamic force exerted on the closed HV1 valve.

Figure 4.2 shows that there is no generated hydrodynamic force in the first period. After closing the valve at time 305 seconds, the hydrodynamic force exerting on HV1 valve marginally rises, then it sharply increases at about time 650 s, and it dramatically climbs to the peak of 218,700 N at about time 700 s in a positive direction. It is determined that pressure propagates in front of the closed valve and generates the peak pressure to the system. However, it is still in the range of allowable stress of pipe 4,040 kN.

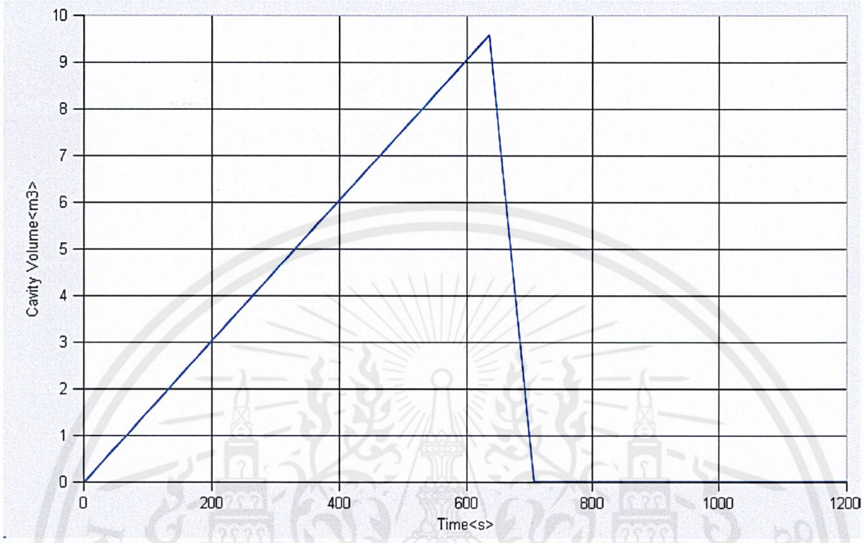


Figure 4.3. Cavity volume at downstream closed HV1 valve.

Figure 4.3 shows that there is small cavity collapse detected at about time 650 s after sudden valve closure. It indicates the occurrence of column separation and subsequently leads to surge pressure.

Table 4.2. Pressure at crucial points in DPG system of different scenarios from simulation.

Simulation	**Group**	**Scenario**	**Pressure of DPG transferring system**				
			D/S pump	**Lowest point**	**Highest point**	**Valve**	**Jetty**
Steady state	-	-	5.27	5.22	3.73	Detail in Table 4.1	1.15
Transient state	Pump operation	A1	1.94	2.10	1.08	-	1.11
	Rapid valve closure	B1	32.98	37.35	27.03	27.03	1.11
		B2	35.77	33.78	26.12	35.77	1.75
		B3	6.80	6.79	1.02	16.16	1.14
		B4	6.59	19.72	12.73	20.91	20.75
	Other special scenarios	C1	4.44	4.40	3.06	4.32	1.12
		C2	5.78	5.08	4.78	5.09	1.51
		C3	7.51	11.45	7.79	11.79	11.80
		C4	6.43	6.60	7.30	11.52	11.53

Table 4.3. Pressure at crucial points in PG system of different scenarios from simulation.

Simulation	**Group**	**Scenario**	**Pressure of PG transferring system**				
			D/S pump	**Lowest point**	**Highest point**	**Valve**	**Jetty**
Steady state	-	-	3.59	2.84	1.02	Detail in Table 4.1	1.12
Transient state	Pump operation	A1	7.78	7.39	6.67	-	1.43
	Rapid valve closure	B1	38.69	38.59	37.63	38.75	1.41
		B2	38.69	38.75	37.63	38.66	1.28
		B3	11.03	11.09	1.28	11.77	1.43
		B4	4.46	11.34	29.27	35.00	33.35
	Other special scenarios	C1	7.30	7.30	6.07	2.36	1.43
		C2	10.51	10.51	9.36	10.46	1.43
		C3	4.30	6.94	13.47	16.18	16.22
		C4	4.19	6.778	13.11	15.78	15.23

4.3 Surge mitigation

Three methods of water hammer control including slow-closing valve, surge tank, and air vessel according to the detail in section 2.3 are investigated in this project to select the most optimal method for suppressing the overpressure from worst scenarios according to the Table 4.2 - B1, B2, and B4.

The scenario rapid HV1 closure in 5 seconds (B2) of PG system is selected as a based case for suppression of the surge transient from the largest overpressure.

4.3.1 Slow-closing valve

The graph shows the results from reducing the overpressure by traditional slow-closing valve method and two-stage valve closure method as presented in Figure 4.4. The overpressure was generated at the upstream HV1 valve from scenario B2 without any mitigation methods (green line). After extending valve closure time to 50 seconds which is the traditional slow-closing valve method, the pressure is slightly risen to marginally over design pressure before dropping to about 10 bar (yellow line). However, the peak pressure is sharply generated to about 12 bar which is less than the traditional method after using two-stage valve closure which employs quick closure of 80% of a valve followed by slow closing the rest (orange line) in the given figure.

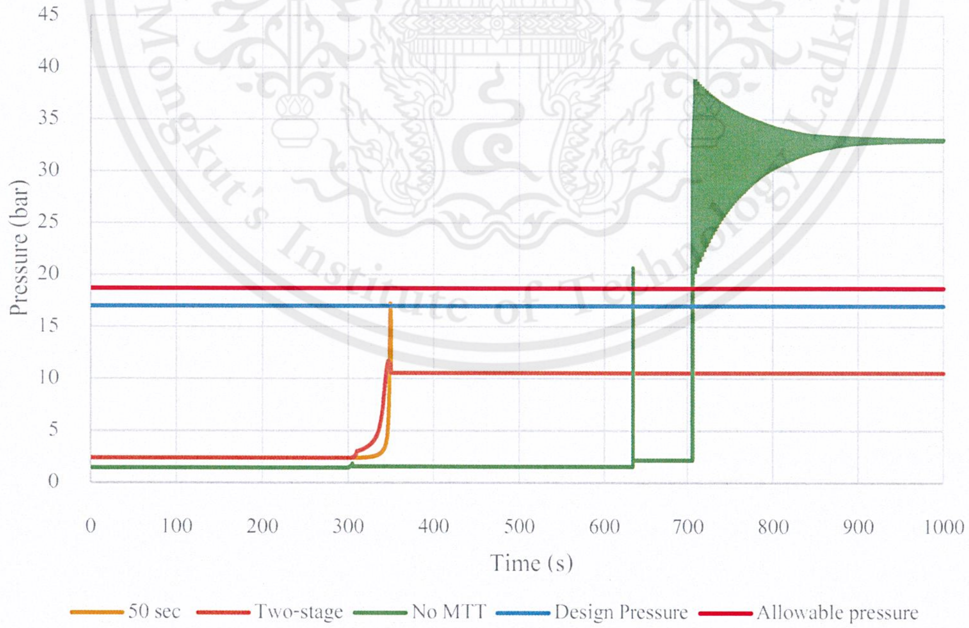


Figure 4.4. Pressure profile at HV1 for slow-closing valve method.

4.3.2 Open surge tank

The graph shows the change of pressure (bar) from time 0 to 1000 seconds as shown in Figure 4.5. It indicates that the installation of a surge tank in the system can dramatically decrease the overpressure to lower than design and allowable pressure. Nevertheless, the vapor cavity still forms at a downstream closed valve after installation of a surge tank as shown in Figure 4.6.

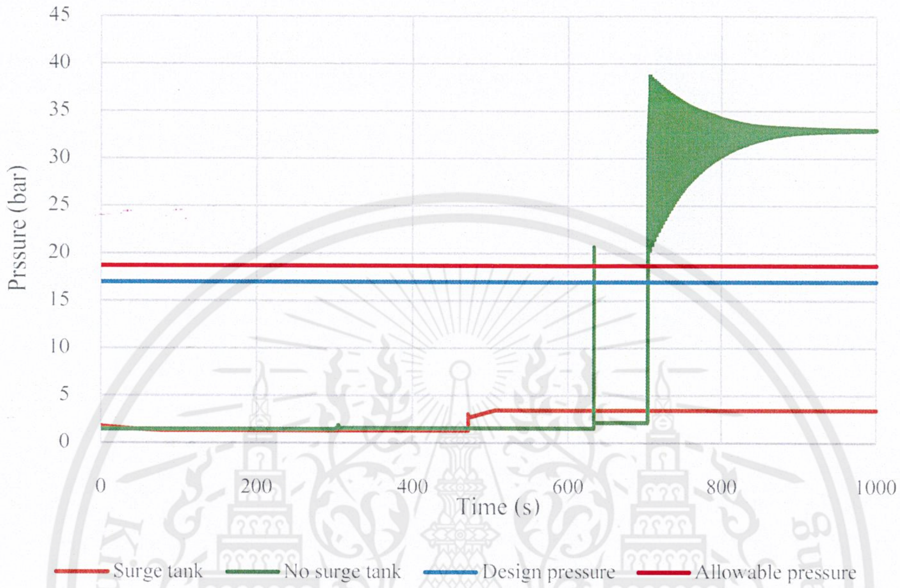


Figure 4.5. Pressure profile at HV1 for installation of surge tank.

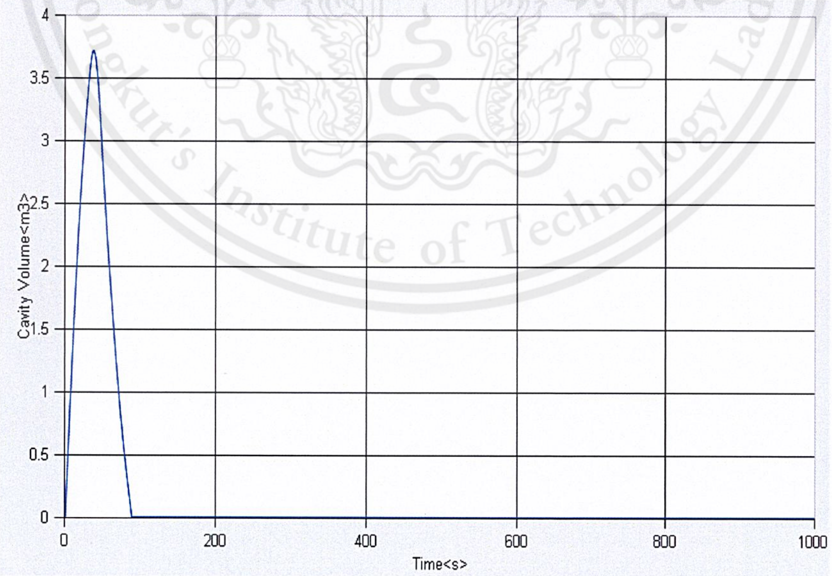


Figure 4.6. Cavity volume at downstream closed valve after installation of surge tank.

4.3.3 Air vessel

The graph shows the change of pressure (bar) from time 0 to 1000 seconds as shown in Figure 4.7. The findings show that the air vessel can significantly reduce to lower than design and allowable pressure. Figure 4.8 shows that there is no vapor cavity formation after the installation of the air vessel.

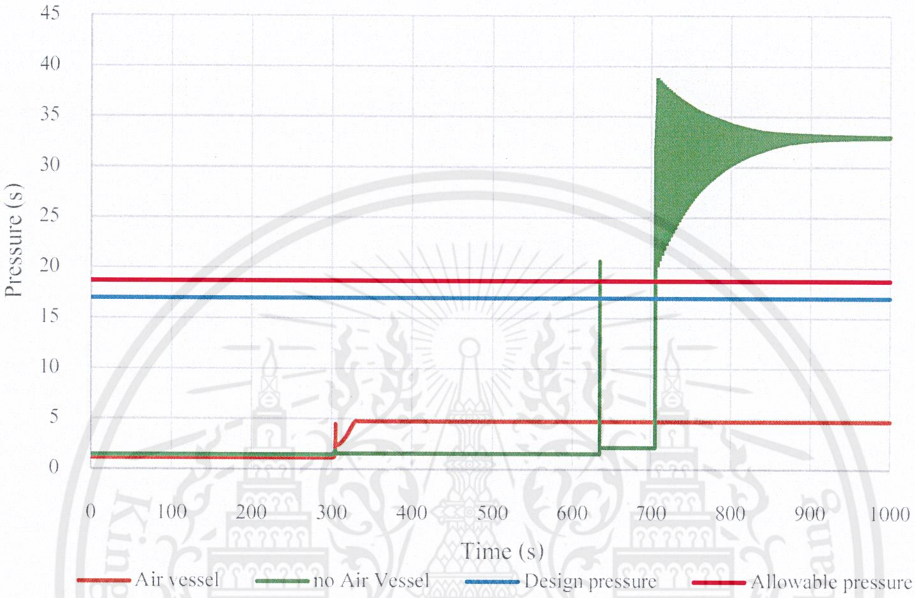


Figure 4.7. Pressure profile at HV1 for installation of air vessel.

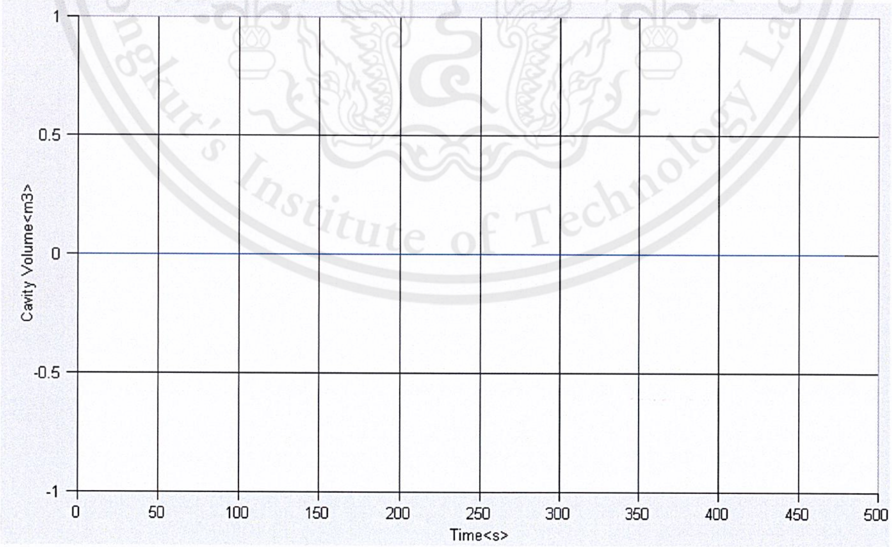


Figure 4.8. Cavity volume at downstream closed valve after installation of air vessel.

4.4 Comparison and selecting the optimal method

The results of different mitigation methods for DPG transferring system in HV1 closing within 5 seconds (B2) are compared to select the most appropriate method for solving the overpressure in various worst cases of this project. The change of pressure from time 0 to 800 s is shown in Figure 4.9.

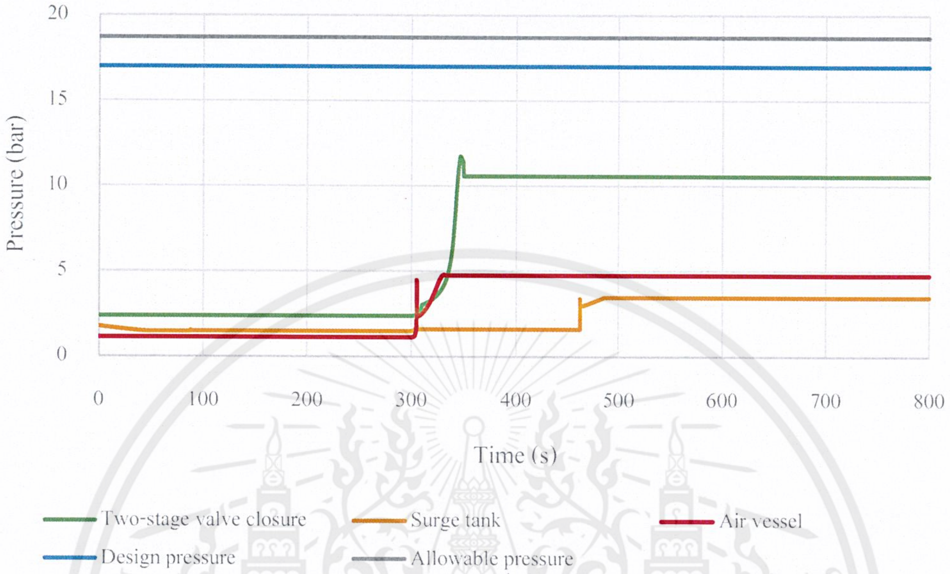


Figure 4.9. Pressure profile after mitigating surge by different methods.

These three methods could be employed to surge suppression because they could reduce the overpressure to be less than allowable pressure. In case of slow-closing valve, it is not practical for operation since more process operating time is required. It also results in a lower capacity to the system and increases loss of product. Hence, a surge tank and air vessel should be further considered.

Although the surge tank is one of the protection equipment to decrease the overpressure due to the propagation of pressure waves, it requires a very tall column to extend above the hydraulic grade line (HGL). However, for limited site area, air vessel which is required smaller volume is a better alternative.

For the above reasons, air vessel is a chosen method to mitigate the transient problem in this project owing to their stability, convenient installation, and flexibility compared with other protective devices. [11]

4.5 Mitigating surge by air vessel

Besides optimization of air vessel volume, it should be installed at an appropriate location in the system based on preliminary calculation conforming to the equation in section 2.3.3.1.

Scenario B2 of PG system is used as an example of finding the appropriate location to install air vessel in the system. The installed locations are in front of valve, behind check valve and optimal location (recommended by journal "Formula for selecting optimal location of air vessel in long-distance pumping Systems" [9]) are investigated. The pressure profile of all cases from time 0 to 1000 seconds expressed in Figure 4.10.

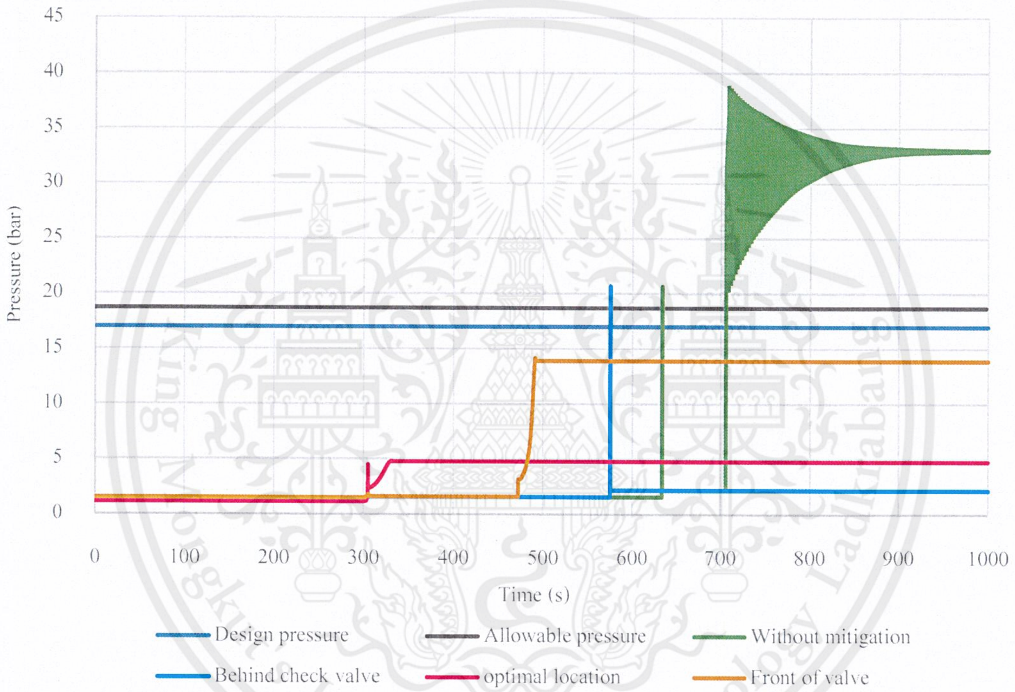


Figure 4.10. Pressure profile at upstream pressure after installation of air vessel at different locations.

It shows that the installation of air vessel at optimal location (red line) and front of valve (yellow line) can effectively suppress the overpressure at all points and the value is lower than ASME B31.4 allowable pressure which is 18.7 bar. Nonetheless, the vapor cavity is detected after installing in front of valve which can subsequently occur catastrophic in pipeline system. Moreover, the instantaneous pressure at some point in the system after installation of air vessel behind the check valve still exceeds the allowable pressure.

Therefore, the most effective method to suppress the immense positive pressure and negative pressure is the installation of air vessel with optimal total volume and location. When applied the air vessel into the scenario B1, B2 and B4, the results of pressure at the upstream valve before and after installation of air vessel are shown in Table 4.4.

Table 4.4. Comparison of pressure at upstream valve before and after installation of air vessel.

Scenarios	**DPG**				**PG**			
	Pressure at U/S valve (bar)		**Air vessel volume (m^3)**	**Optimal location (m)**	**Pressure at U/S valve (bar)**		**Air vessel volume (m^3)**	**Optimal Location (m)**
	without Air Vessel	with Air Vessel			without Air Vessel	with Air Vessel		
B1	37.83	7.28	2.08	345.56	38.75	5.04	4.56	425.38
B2	35.77	7.31	2.16		38.66	4.79	5.57	
B4	20.91	7.21	2.48		35.00	4.53	6.54	

The hydraulic transient simulation indicates that the pressure after installation of air vessel size from at optimal location is reduced significantly. The suitable air vessel volume and location of all scenarios are presented in the same table. Furthermore, this method of sizing air vessel does not result in cavity collapse for all locations which ensures that the cavitation does not occur.

The largest air vessel volume is required for lowering overpressure generated from scenario B4 because the calculation is based on length between the pump and closed valve that the PERC valve position at the longest distance from the pump station.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

In this chapter, the study of surge analysis in pipeline of DPG and PG systems transferring from tank to jetty through 9 scenarios was concluded and suggested the recommendations for this project.

5.1 Conclusions

- The overpressure from these scenarios can be determined by transient simulation via FloMASTER V8.1 software enabling the fluid flow effects within a complex system.
- Hydraulic transient, also called pressure surge or water hammer, is caused by the rapid change of flow mainly arising from pump tripping, start-up, suddenly close of open valve. For this project, the worst scenarios resulting in immense pressure are rapid valve closure at long distance from the pump station, scenario B1, B2, and B4.
- In comparison, three common mitigation methods including two-stage valve closure, installation of surge tank and air vessel, the air vessel are an effective device to reduce surge under design pressure (17 bar) and allowable pressure according to ASME B31.4 110% of design pressure (18.7 bar)
- The optimization of total air vessel volume sizing is carried out by equation derived from the incompressible flow and simple harmonic equation referred to section 2.3.3 so that air vessel should be located at the position based on preliminary calculation referred to section 2.3.3.1.

5.2 Recommendations

The recommendations from transient result findings are served as follow,

- Vapor cavity volume should be considered for transient analysis because it can also affect either pressure surge in the system or cavitation at the pump station.
- The air vessel height and cross-sectional area can be suitably adjusted to the available processing area because the ratio of these two parameters has no impact on pressure suppression.
- The other effective protection devices can be further studied such as the poppet relief valve which is one of the fast-active protection devices.

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2) Hw_m is resulted from straight pipe to valve, 0.866 m and enlargement from orifice to main pipe. h_f is 0.027

From equation (2.7), $$h_{fe} = \frac{K_e V^2}{2}$$

where K_e is expansion loss coefficient = $(1 - S_a/S_b)^2$ and S_a is orifice area, S_b is the main pipe area. In addition, the "Chinese design code for surge chamber of hydropower stations" suggests that the minimum and maximum area of the orifice must be 25% and 45% of the area of the headrace tunnel. Therefore, S_a/S_b is 0.45 then h_{fe} is 0.964. Thus, Hw_m is summation of h_f and h_{fe} that is 0.991 m

Finally, the $H1 = H_0 - Hw_0 - 3HW_m = 11.711 - 5.09 - 3(0.991) = 3.648$ m and α is 0.798. From $e = 1.5$, Z_{max} can be obtained 12.15 m which is the height of a surge tank.

Consequently, the minimum area of a surge tank is 0.666 m^2.

Preliminary calculation of air vessel sizing

The initial air volume $[V_a]$ could be determined by the equation

$$[V_a]_{\min} = \max\left[\frac{v_0^2 L f m p_0}{\varphi_2^2 g H_0^2}, \frac{v_0^2 L f m p_0}{g h_{\min}^2}\right]$$

where $p_0 \approx H_0 + p_a$. (2.8)

The approximate analytical size of the air vessel could be eventually described as:

$$V_T = V_a(1 + \varphi_1) = k|V_a|_{\min}(1 + \varphi_1) \quad (2.9)$$

Additional data used in the equation (5) and (6)

Polyprotic index (m) = 1.2

H_0 = elevation of reservoir – elevation of valve closed = 11.711 – 2.257 = 9.454 m

P_a = atmospheric head = 10.36 m [9]

$P_0 = H_0 + P_a = 19.814$ m

h_{min} = 4.33 bar = 42.77 m

$[V_a]_{min}$ can be obtained 3.624 m^3

The ratio of liquid to gas is $\varphi_1 = 42.77 / 1.2*19.814 = 0.398$

Thereby, V_T is 1.1(3.816)(1+0.398) = 5.572 m^3.

After air vessel is selected the surge protection equipment, it should be installed at the optimal location in the system which is calculated from equation (2.10) in section 2.3.3.1.

Preliminary calculation of optimal location

$$L = L_0 + L_1 = (H_1 - H_B)\frac{\cos\alpha}{\sin(\alpha + \beta)} \tag{2.10}$$

According to equation above, the required information is displayed in Figure A2.

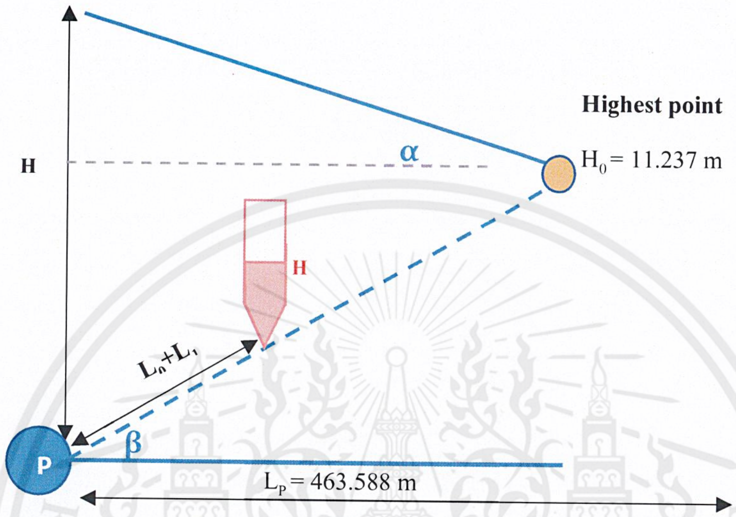

Figure A2. Schematic for optimal location preliminary calculation of HV1 rapidly closed.

H_1 = elevation at highest point + pressure above pump level

=11.237 + (11.711-1.711) = 21.237 m

α = arctan (10/425) = 1.236 deg

β = arctan (10.752/425) = 1.389 deg

Suppose elevation of air vessel = 2.257 m = H_B

So, $L = L_0+L_1 = (21.237 - 2.257)\left(\frac{\cos\alpha}{\sin(\alpha+\beta)}\right) = 414.44$ m

Based on preliminary calculation of air vessel volume 5.572 m^3, it will be installed at several locations in the system. The installed locations are in front of valve, behind check valve and optimal location. The pressure results after installing air vessel at several locations are shown in Figures A.4, A.6, A.7, A.9, A.10.

1) Air vessel installed behind the check valve (L<414.44)

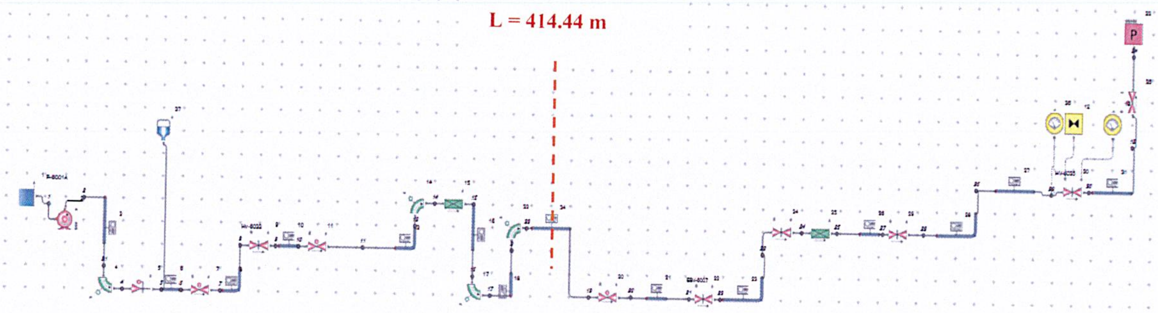

Figure A.3. Location of air vessel is behind the check valve.

After installing the air vessel at behind check valve and the system ran at steady state for 300 seconds. Then, HV1 valve was rapidly closed within 5 seconds (red line). The peak pressure at closed valve HV1 (blue line) was generated to 20.56 bar but it was still higher than allowable pressure which is 18.7 bar.

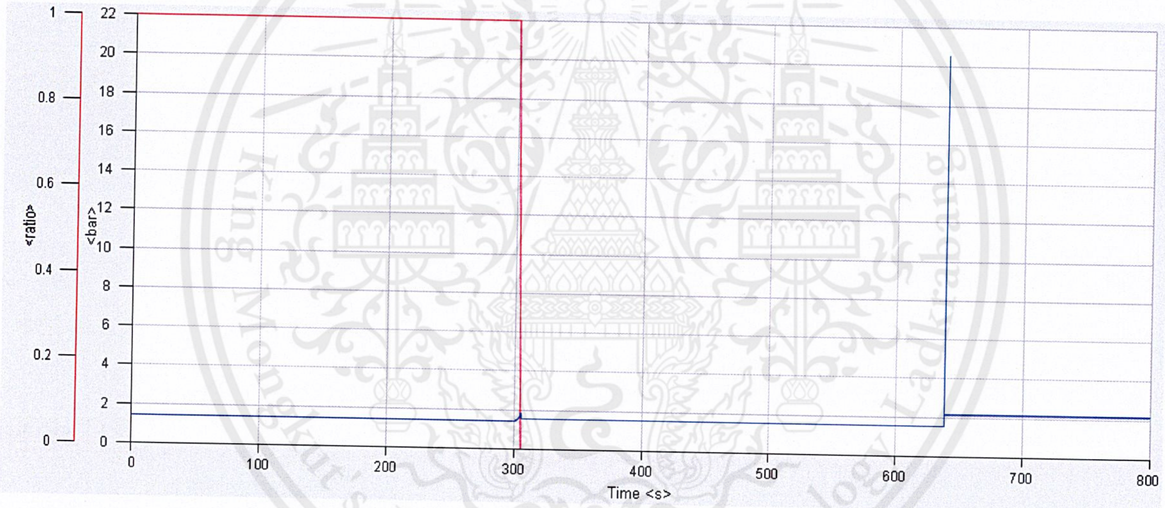

Figure A.4. Pressure profile at upstream HV1 after installing the air vessel behind check valve.

2) Air vessel installed at protection distance (L ≈ 414.44 m) from pump

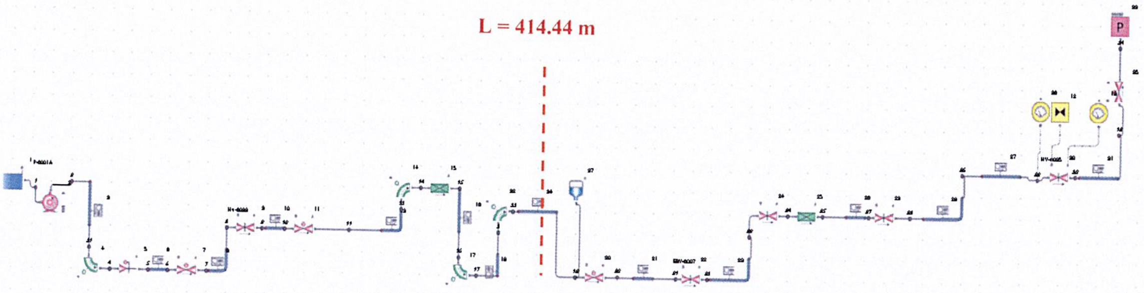

Figure A.5. Location of air vessel is at optimal location.

After installing the air vessel at optimal location and the system ran at steady state for 300 seconds. Then, HV1 valve was rapidly closed within 5 seconds (red line). The peak pressure at both valve HV1 and highest point of this system (blue line) was generated to 4.79 and 5.81 bar, respectively which is acceptable pressure.

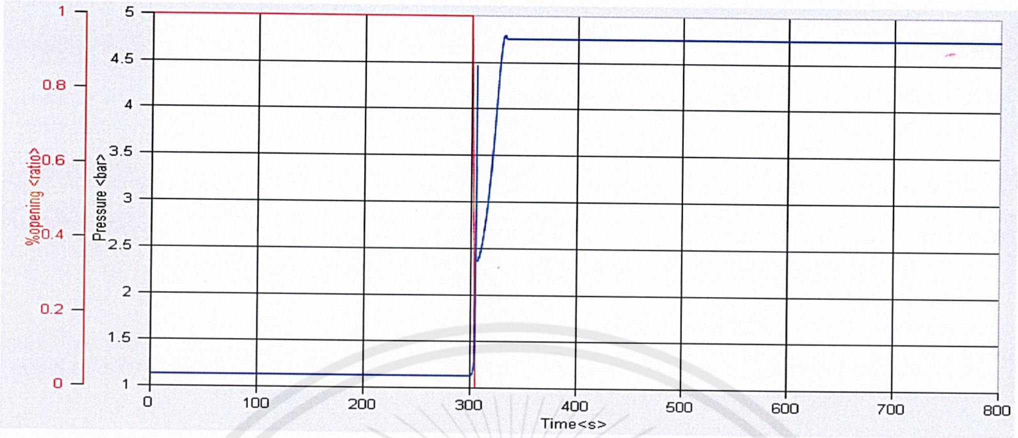

Figure A.6. Pressure profile at upstream HV1 after installing the air vessel at optimal location.

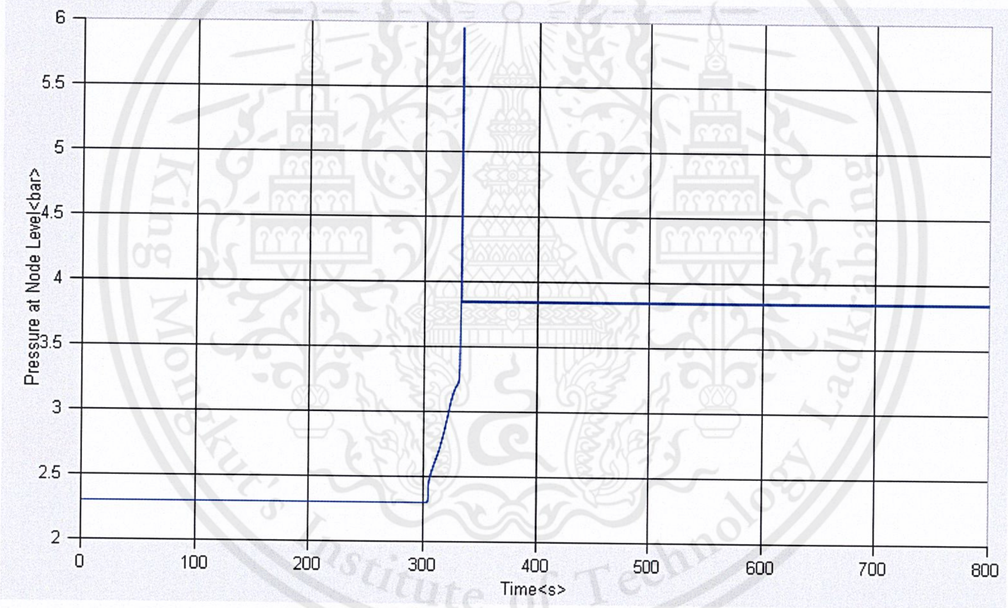

Figure A.7. Pressure profile at highest point after installing the air vessel at optimal location.

3) Air vessel installed in front of closed valve (L>414.44)

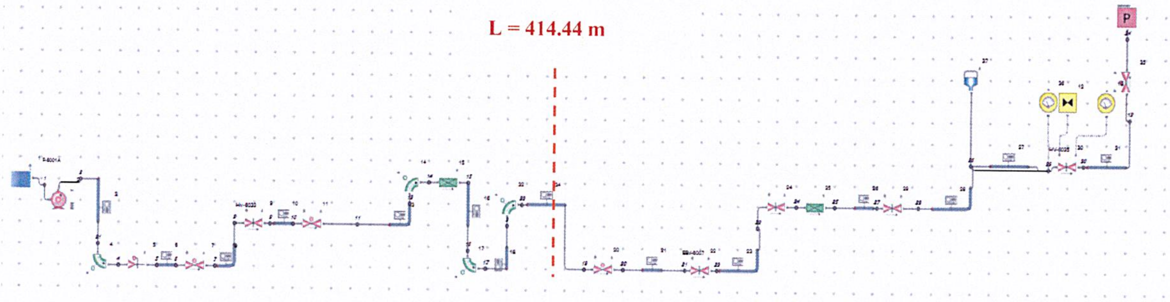

Figure A.8. Location of air vessel is in front of closed valve.

After installing the air vessel in front of closed valve the system ran at steady state for 300 seconds. Then, HV1 valve was rapidly closed within 5 seconds (red line). The peak pressure at valve HV1 (blue line) was generated to about 14 bar which is acceptable pressure. However, the peak pressure at highest point of this system exceeded the allowable pressure.

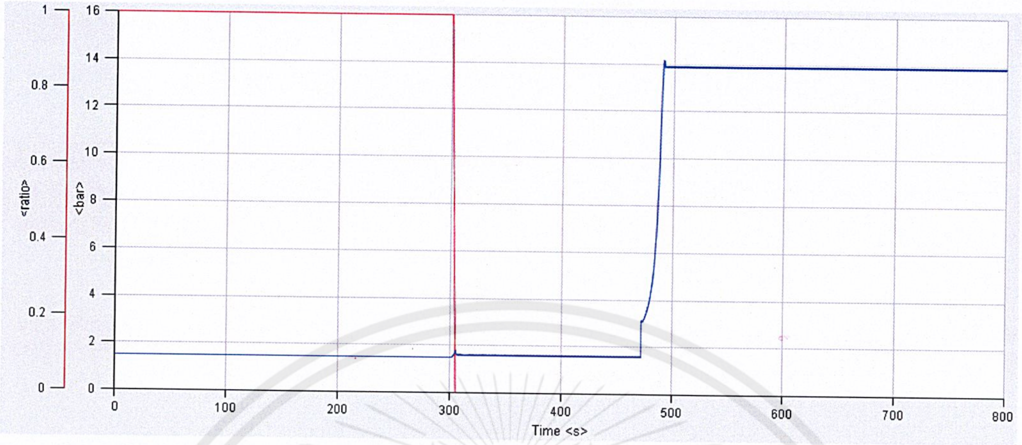

Figure A.9. Pressure profile after installing the air vessel at upstream HV1.

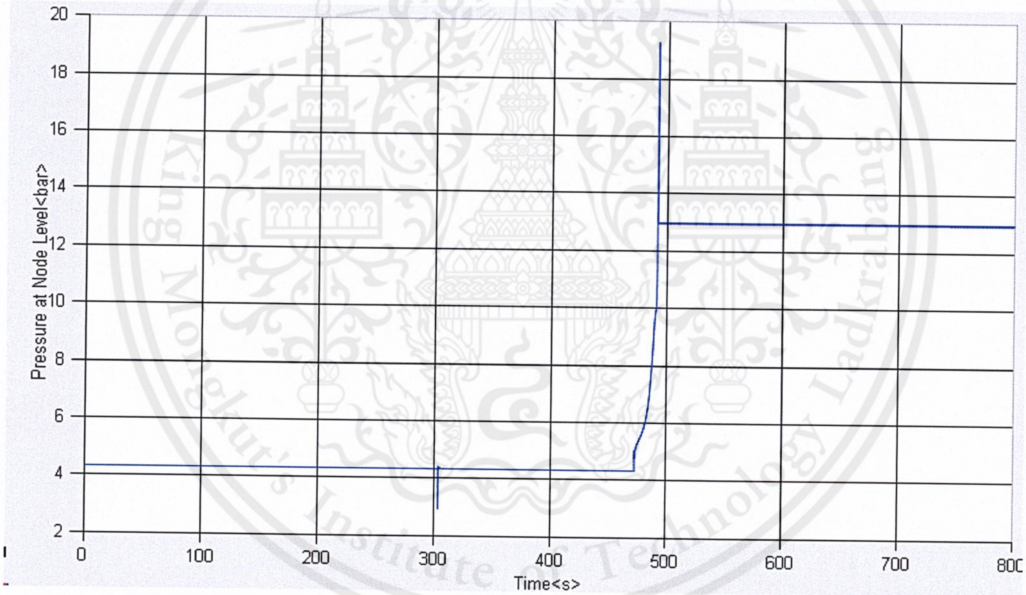

Figure A.10. Pressure profile at highest point after installing the air vessel at upstream HV1.

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