Analysis of Water Hammer by Using Pipenet Software and Manual Methods

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***Abstract*—Water hammer is an unusual condition that frequently occurs in piping system. The impact of this condition including pipe rupture which can cause catastrophic accident. Therefore, analysis must be performed in preventing this matter where a few methods have been discovered. The first objective of this research is to observe several factors that can lead to water hammer problem. Meanwhile, the second objective is to discover the most effective method in mitigating the water hammer. The method used in this paper including the simulation of Pipenet as well as manual calculations. The results obtained in this research showed that only valve closure rate factor has reasonable results for both Pipenet simulation and manual calculation. Both methods proved that longer valve closure rate would result smaller surge pressure. Meanwhile, the other two factors which are pipe length and fluid flow rate, only Pipenet simulation gave more reliable results. Based on the result obtained via simulation, longer pipe length would produce smaller surge pressure. As for larger fluid flow rate, the surge pressure resulted became larger. A few methods in reducing the water hammer such as installation of surge tank, accumulator and pressure relief valve have been tested by using Pipenet simulation. Overall results showed that the surge pressure was successfully reduced although they were varied in reduction percentage. From this research, it was proven that pressure surge was affected by various factors and it was a crucial study that shall be done by engineer to avoid pipe rupture due to water hammer.**

***Keywords*— *Water Hammer, Surge Pressure, Pipenet Vision, Joukowsky expression, Allievi Charts and Expression*.**

I. Introduction

The water hammer which also called as pressure surge is a phenomenon that occurs in a closed conduit [1,2]. The water hammer will produce as the fluid inside the conduit experienced an abrupt change either the fluid is forced to stop or change its direction [1]. Besides, it also will occur due to pump starts or stops or the opening or closing of the valve that present in the system [1,3,4]. In addition, power failure will also cause water hammer since the electronic component will not functioning [3].

In short, almost all piping system will experience such examples that can lead to water hammer however, the water hammer phenomenon is not a usual conditions. Therefore, the engineers especially process engineers must perform surge analysis on the new piping system or if the system is required to have some modifications. Through analysis, the estimated surge pressure can be compared with the pipe strength to ensure the pipe failure will successfully prevented. Such analysis is more significant as the piping system involve hazardous service.

As for this paper, the surge pressure is analyzed by using both modern and conventional methods. The purpose is to make comparison between both methods. Furthermore, this research paper will identify more relevant method in analyzing the water hammer.

There are two objectives of this research paper which to investigate the surge pressure for several factors and to determine the most effective method that can reduce the surge pressure.

A few factors that can cause pressure surge have been identified through literature review. The common factor that will affect the surge pressure is the closure rate of valve where rapid closure will cause pipe rupture [3]. Meanwhile, a very slow valve closure will cause pipe implode [3]. The other factors that are observed in this paper including various pipe lengths and various flow rate of fluid.

Several ways identified can diminish the pressure surge phenomenon including the installation of extra devices into the system such as non-return valve, surge tank, air chamber and many others [5,6,7]. However, the methods analyzed in this paper only covered on the installation of surge tank, accumulator and pressure relief device.

II. METHODOLOGY

A. *Pipenet Vision 1.7 Simulation*

The first method used in this paper was Pipenet simulation. As it comes to simulation, the training manual provided must be read and fully understand. Firstly, the type of flow involved must be determined where in this case were the transient flow and thus the transient module being chosen for the whole process. Next, all the measurement unit and decimal places were specified and a pipe network was created on the schematic window. The properties of fluid, pipe and all the components in the system were determined and then the error in the system being checked by clicking on the green tick button as shown in the **Figure 1**. As no error showed,, the simulation can be started and there were two options in previewing the simulation results which in report or graphical form.

Figure 1:The Example of Toolbar Buttons in Pipenet

B. Manual Calculations

The manual calculation started with the speed of acoustic pressure wave, effective valve stroking time and valve closure rate determination as shown in Equation (1), (2) and (4) respectively [5].

$$s = \frac{1}{\sqrt{\frac{\gamma}{g}\left(\frac{1}{K}+\frac{1}{E}\frac{D}{t}\cdot C\right)}} \qquad ...(1)$$

Where,
s = acoustic pressure wave (m/s)
γ = liquid density (kg/m3)
g = gravity constant (m/s2)
K = liquid bulk modulus (Pa)
E = pipe material Young's modulus (Pa)
D = pipe inside diameter (mm)
t = pipe wall thickness (mm)
C = pipe constraint coefficient (usually 1.0)[5]

$$T_e = (T_e / T_v)^* T_v \qquad ...(2)$$

Where,
T_e = effective valve stroking time (s)
T_v = valve stroking time (s)

The α parameter was obtained by using Equation (3) where the value obtained will be used to find the ratio of T_e/T_v in a graph as shown in **Figure 2** [5].

$$\alpha = \left(\frac{A_v}{A_p}\right)^2 \cdot \lambda \cdot \frac{L_e}{D} \qquad ...(3)$$

Where,
α = a parameter to find T_e/T_v ratio
A_v = valve cross sectional area (m^2)
A_p = inside pipe diameter cross sectional area (m^2)
λ = 4f (f = Funning friction factor
L_e = pipeline equivalent length (m)

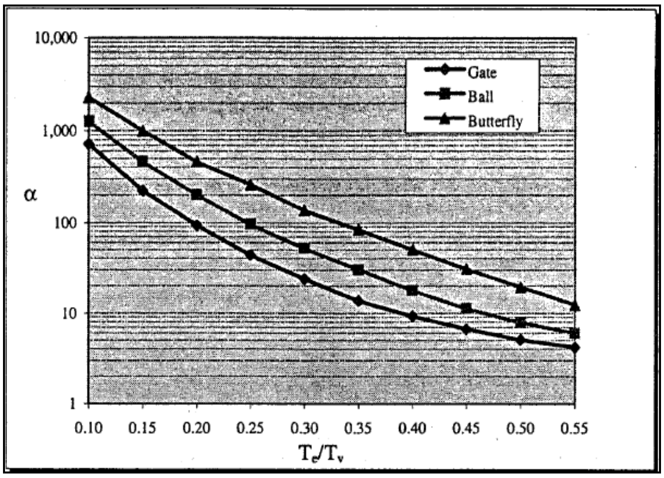

Figure 2 :The Chart Used for T_e Determination [5]

$$\mu = \frac{2L_a}{s} \qquad ...(4)$$

Where,
μ = required time for wave return back from the other end of pipeline (s)
L_a = pipe length (m)

By obtaining μ, the comparison can be made as follow:
$T_e > \mu$ = slow valve closure; use Allievi charts & expression
$T_e < \mu$ = rapid valve closure; use Joukowsky expression

<u>Allievi Charts and Expression (Slow Valve Closure):</u>

The related equations were expressed as in Equation (5), (6) and (7) [5]. However, the Equation (6) and (7) were used to find the ξ_M parameter in the charts to be inserted in Equation (5) [5].

$$H_{max} = H_0(1+\xi_M) \qquad ...(5)$$

Where,
H_{max} = maximum pressure surge (m)
H_0 = initial pressure head (m)
ξ_M = a constant parameter in Allievi Chart

$$\rho = \frac{sV}{2gH_0} \qquad ...(6)$$

Where,
ρ = pipeline constant
s = acoustic pressure wave (m/s)
V = initial velocity (m/s)
g = gravitational force (m/s^2)
H_0 = initial pressure head (m)

$$\theta = \frac{T_e}{\mu} \qquad ...(7)$$

Where,
θ = return number of pressure wave unti valve fully closed
T_e = effective valve stroking time (s)
μ = required time for wave return back from the other end of pipeline (s)

Referring to the Allievi Charts as per **Figure 3** until **Figure 5**, if the value of θ calculated is equal to or less than 1.0, Joukowsky expression must be used to determine the maximum pressure surge.

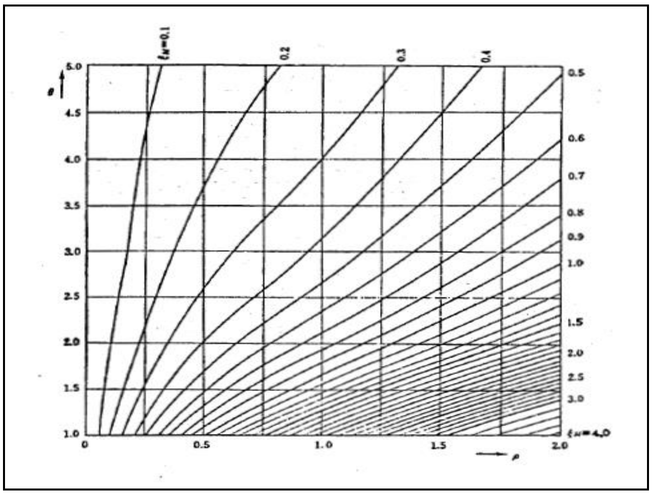

Figure 3: The Allievi Chart 1 [5]

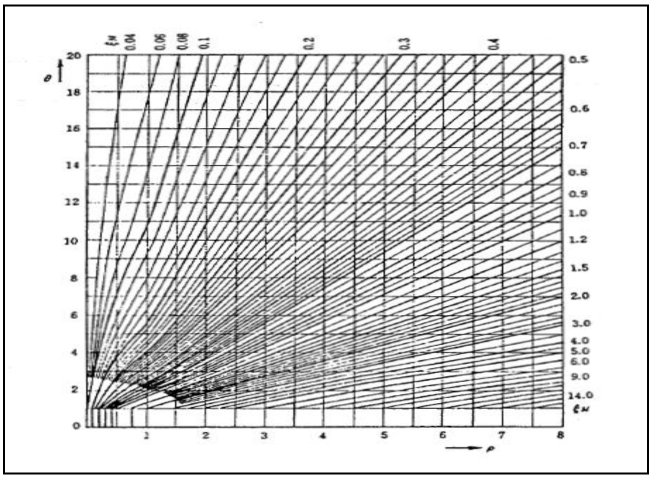

Figure 4: The Allievi Chart 2 [5]

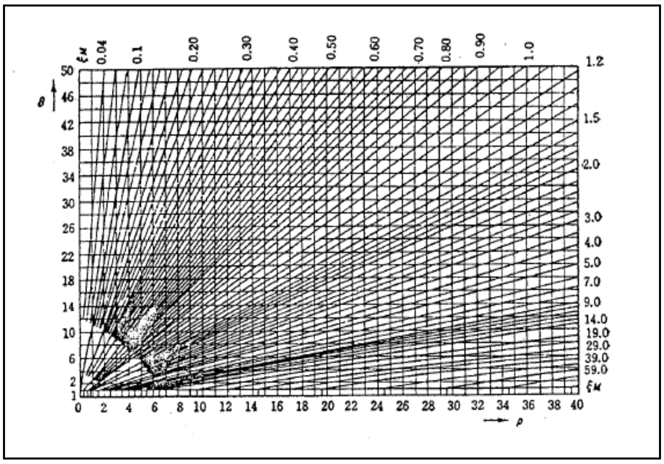

Figure 5: The Allievi Chart 3 [5]

Joukowsky Expression (Rapid Valve Closure):

The equation employed for Joukowsky expressions were shown as in Equation (8) and (9) as follow [5].

$$\Delta H = \frac{s(\Delta V)}{g} \quad \text{...(8)}$$

Where,
s = acoustic pressure wave (m/s)
g = gravitational force (m/s^2)
ΔV = change in velocity (m/s)

III. RESULTS AND DISCUSSION

A. The effects of pipe length on pressure surge

Pipenet Vision 1.7 Simulation:

The following **Figure 6, 7** and **8** showed the graphs obtained from the simulation of 5000 m, 6000 m and 7000 m pipe length. The other variables were kept constant. The maximum pressure surged obtained for 5000 m, 6000 m and 7000 m pipe was at 17.94 barg, 16.69 barg and 15.72 barg respectively. The time that recorded the maximum surge pressure is at 9.5 s, 11 s and 12.5 s according to increasing pipe length. For the time up to 500 s, the pressure inside the conduit kept oscillating regardless the pipe length as showed in **Figure 6, 7** and **8.**

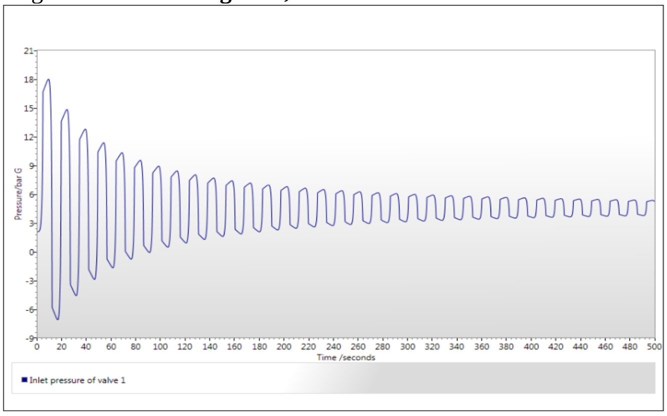

Figure 6: The Graph for 5000 m Pipe Length

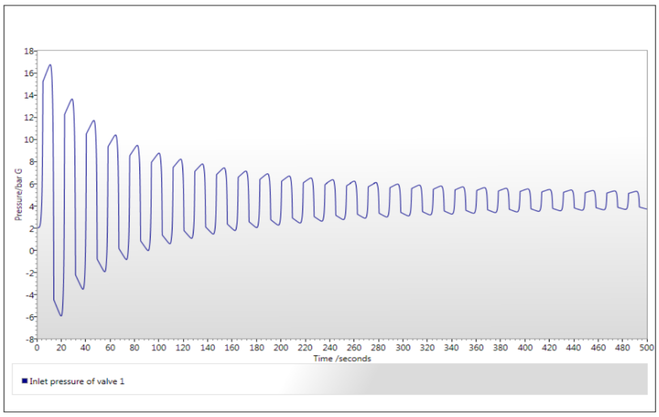

Figure 7: The Graph for 6000 m Pipe Length

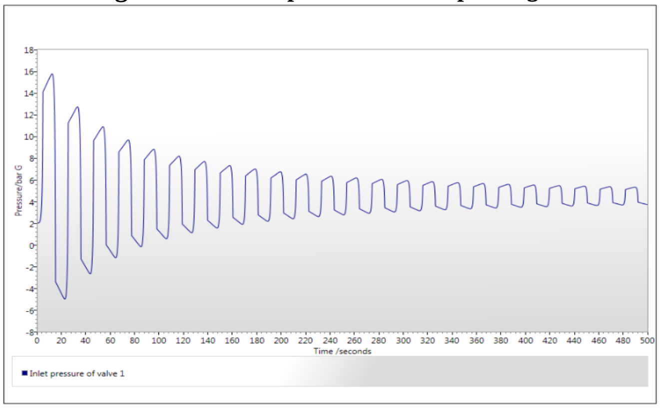

Figure 8: The Graph for 7000 m Pipe Length

Manual Calculations:

Table 1: Surge Pressure for Various Pipe Length

	5000 m	6000 m	7000 m
Joukowsky Surge Pressure (barg)	3.59E+01	3.59E+01	3.59E+01
Allievi Surge Pressure (barg)	NA	NA	NA

Note: NA = Not Applicable

Referring to **Table 1** above, the maximum surge pressure obtained for Joukowsky expression were same for all pipe length which at 3.59×10^1 barg. This due to the consideration of pipe length only in determining the effective valve stroking time, T_e, and the required time for wave return back from the other end of pipeline,µ. However, the surge pressure using Joukowsky expression did not taking these parameters into account. Thus, the surge pressure obtained kept constant for all pipe length since all the parameters in Equation (8) was having constant values.

The results for Allievi method were not applicable all pipe length since the closure rate for these cases which kept constant at 5s was classified as fast closure. This was determined as the T_e value obtained was relatively smaller than µ.

Pipenet and Manual Calculation Method Comparison:

Table 2: Comparison between Pipenet and Manual Method for Varied Pipe Length

	5000 m	6000 m	7000 m
PIPENET , barg	17.9413	16.6888	15.7168
JOUKOWSKY, bar	36.8526	36.8526	36.8526
JOUKOWSKY, barg	35.8526	35.8526	35.8526
Pressure Difference	17.9114	19.1639	20.1358
Percentage Difference (%)	49.9584	53.4518	56.1627

Referring to the above **Table 2**, the percentage difference obtained for 5000 m pipe length between the Pipenet results and Joukowsky expression was at about 50%. On the other hand, the percentage difference increased along with increasing pipe length which at 53% and 56% for 6000 m and 7000 m respectively. Therefore, the conclusion for various pipe lengths is longer pipe length can cause smaller surge pressure. However, some modifications on Joukowsky expression shall be made in future analysis to take into account the pipe length parameter.

B. The effects of valve closure rate on pressure surge

Pipenet Vision 1.7 Simulation:

The following **Figure 9, 10** and **11** showed the graphs obtained from the simulation of 10 s, 15 s and 20 s valve closure rates. All the other variables were kept constant. The maximum pressure surged obtained for 10 s, 15 s and 20 s valve closure rates were 16.16 barg, 15.73 barg and 15.35 barg respectively. The maximum surge pressure reached for 10 s, 15 s and 20 s valve closure rate was at 14 s, 17.2 s and 20.6 s respectively. This showed that when the valve closure rate longer, the time taken for the wave to achieve maximum surge pressure getting faster.

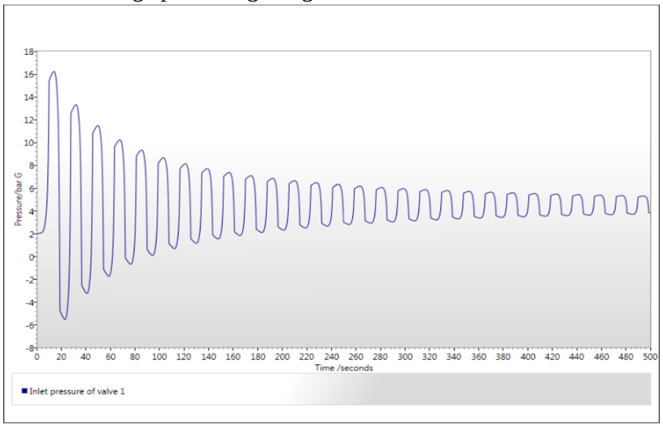

Figure 9: The Graph for 10 s Valve Closure Rate

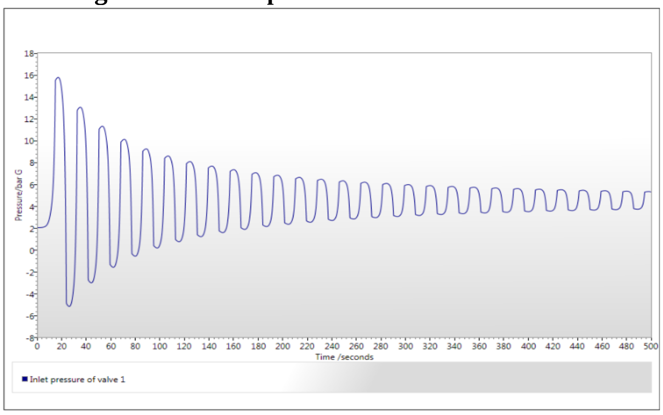

Figure 10: The Graph for 15 s Valve Closure Rate

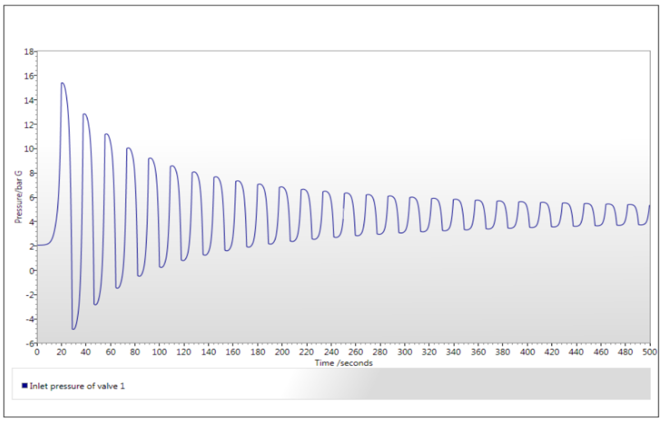

Figure 11: The Graph for 20 s Valve Closure Rate

Manual Calculations:

Table 3: Surge Pressure for Various Valve Closure

	10 s	15 s	20 s
Joukowsky Surge Pressure (barg)	3.59E+01	3.59E+01	3.59E+01
Allievi Surge Pressure (barg)	-	3.02E+01	2.81E+01

As for various valve closure rate, the results obtained as referred to **Table 3** above. The 10 s closure was classified as rapid closure since the comparison made between T_e and μ value found that the T_e is smaller than μ. On the other hand, the 15 s and 20 s closure rate were categorized as slow closure and thus the pressure surge can be obtained through Allievi charts and expression.

By applying Joukowsky method, the maximum surge pressure achieved for all cases were having a constant value of 35.9 barg. This was due to the determination of maximum pressure surge for this method neglected the valve closure rate.

Pipenet and Manual Calculation Method Comparison:

Table 4: Comparison between Pipenet and Manual Method for Varied Valve Closure

	10 s	15 s	20 s
PIPENET , barg	16.1636	15.7277	15.3482
JOUKOWSKY/ALLIEVI, bar	36.8526	31.1590	29.0817
JOUKOWSKY/ALLIEVI, barg	35.8526	30.1590	28.0817
Pressure Difference	19.6890	14.4313	12.7335
Percentage Difference (%)	54.9166	47.8507	45.3445

According to **Table 4** above, the manual method consists of a combination of Joukowsky and Allievi expression. This due to a constant value achieved for all valve closure as Joukowsky method used meanwhile, 10 s valve closure could not use the Allievi method. Thus, the surge pressure for 10 s was taken from Joukowsky method and the others were taken from Allievi method. The difference between results obtained from simulation and manual calculation for 10 s, 15 s and 20 s were about 55%, 48% and 45%. Therefore it can be concluded that longer valve closure time results lower surge pressure [3,5].

C. The effects of fluid flow rate on pressure surge

Pipenet Vision 1.7 Simulation:

The following **Figure 12, 13** and **14** showed the graphs obtained from the simulation of 100 m^3/hr, 200 m^3/hr and 300 m^3/hr fluid flow rates. The other variables were kept constant. The maximum pressure surged obtained for 100 m^3/hr, 200 m^3/hr and 300 m^3/hr fluid flow rates were 10.6 barg, 13.2 barg and 14.7 barg respectively. The results obtained from Pipenet simulation showed an increment in pressure surge as the flow rate of fluid increased. The pattern of the graph achieved via the simulation has different pattern compared to the graphs for the pipe length and valve closure rate analysis. This due to the adjustment of the flow rate in Pipenet Vision 1.7 cannot be simply entered the desired flow rate although there was option offered as the results obtained was showed as in **Figure 15**. According to training manual provided by Pipenet, a pump must be added to allow the different flow rate analysis.

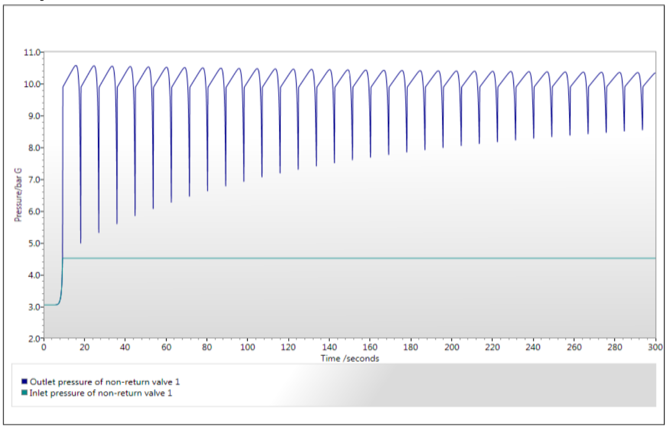

Figure 12: The Graph for 100 m^3/h of Fluid Flow Rate

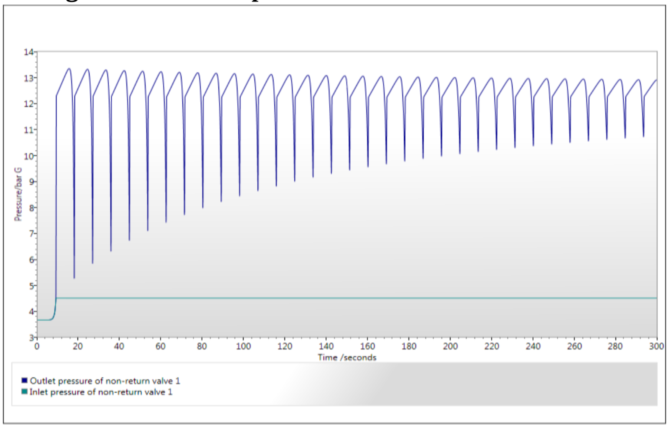

Figure 13: The Graph for 200 m^3/h of Fluid Flow Rate

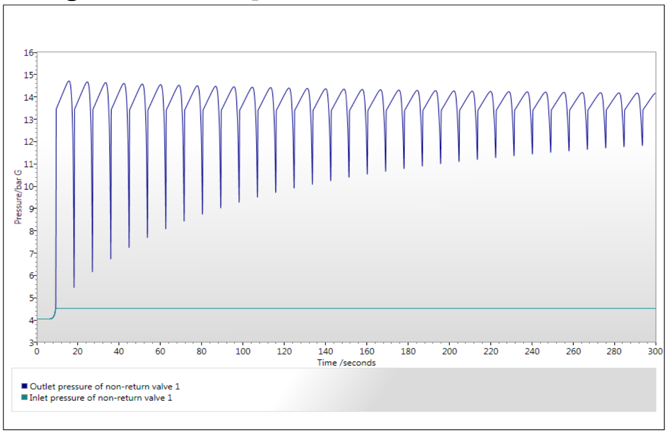

Figure 14: The Graph for 300 m^3/h of Fluid Flow Rate

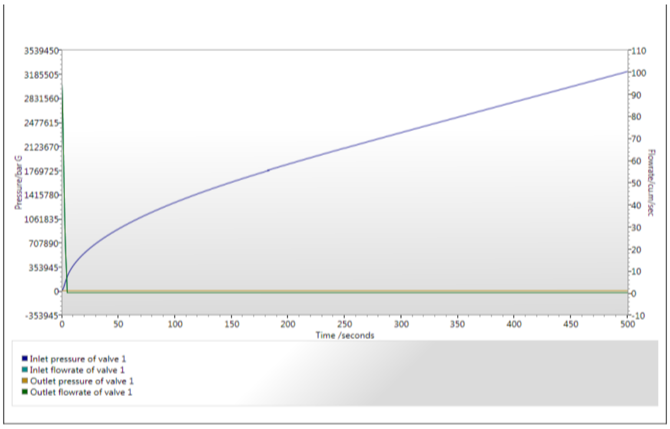

Figure 15: The Graph for 100 m^3/h of Fluid Flow Rate without Adding Pump

Manual Calculations:

Table 5: Surge Pressure for Various Fluid Flow Rate

	100 m^3/h	200 m^3/h	300 m^3/h
Joukowsky Surge Pressure (barg)	1.74E+01	3.59E+01	5.43E+01
Allievi Surge Pressure (barg)	NA	NA	NA

Note: NA = Not Applicable

Various fluid flow rate used has affected the fluid velocity where higher flow rate produced higher velocity. As for this case, only Joukowsky expression was applicable since the closure rate was kept constant at 5 s which classified as fast closure. Therefore, the pressure surge calculated will be affected with varied fluid velocity. Referring to **Table 5** above, the pressure surge obtained increase in accordance to increasing flow rate of fluid. The maximum flow rate of 300 m^3/h produced the maximum surge pressure which at about 54.3 barg. Meanwhile, the smallest flow rate of 100 m^3/h achieved the smallest value of surge pressure which aat 17.4 barg. Thus, it can be concluded that higher flow rate of fluid must have much more attention on surge analysis.

Pipenet and Manual Calculation Method Comparison:

Table 6: Comparison between Pipenet and Manual Method

	100 m^3/h	200 m^3/h	300 m^3/h
PIPENET , barg	10.5638	13.3052	14.7914
JOUKOWSKY, bar	18.4263	36.8526	55.2790
JOUKOWSKY, barg	17.4263	35.8526	54.2790
Pressure Difference	6.8625	22.5474	39.4876
Percentage Difference (%)	39.3802	62.8892	72.7493

Referring to **Table 6** above, both methods showed similar pattern in which the surge pressure experienced incremental as the fluid flow rate was increased. Although the results for manual calculation only dependent on the Joukowsky method, the expected results was obtained. The difference between manual method and simulation for 100 m^3/h, 200 m^3/h and 300 m^3/h was approximately at 40%, 63% and 73% respectively. Therefore, it can be concluded that the higher flow rate of fluid will cause higher pressure surge produced.

D. Ways in Mitigating the Pressure Surge

Pipenet Vision 1.7 Simulation:

The following **Figure 16, 17** and **18** showed the graphs obtained as the simulation for mitigating the surge pressure performed. The base condition was a system that having 5 s valve closure rate, 6000 m pipe length and 200 m^3/h of fluid flow rate. The whole results showed the reduction in pressure surge. All these methods were recommended in the Pipenet training manual and amongst the common mitigating steps in industry [7].

The first method used is installation of surge tank into the system where the result was showed in **Figure 16**. The maximum pressure obtained as a surge tank being installed only at 4.56 barg which decreased by approximately 73% as compared to surge pressure obtained from base case. The pressure obtained also more stable where a constant pressure value was obtained started from 350 s onwards.

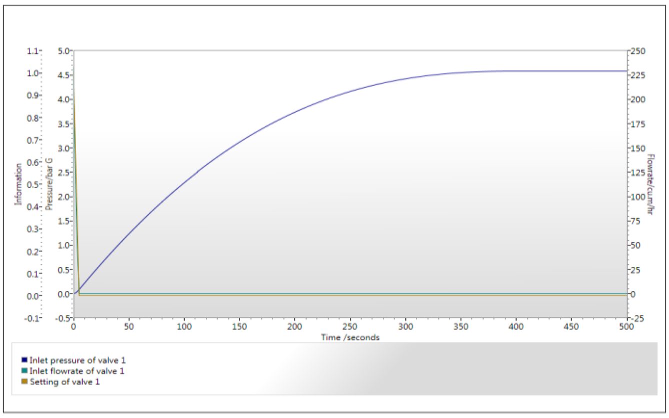

Figure 16: The Installation of Surge Tank into the System

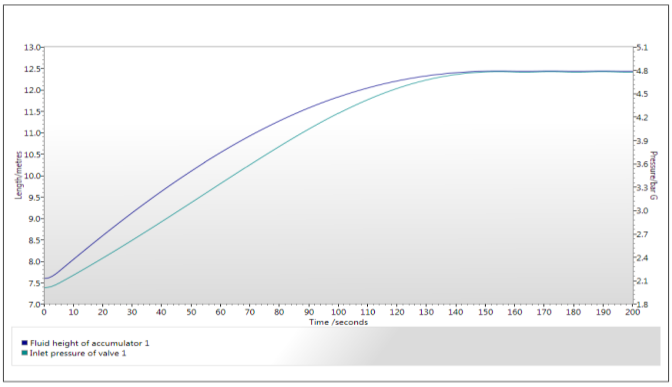

Figure 17: The Installation of Accumulator into the System

As for **Figure 17**, it showed the results as an accumulator being installed in the system. Referring to Figure, the maximum pressure recorded was at 4.85 barg which experienced about 71% reduction compared to the base case conditions. The pattern of pressure obtained also stable via the installation of an accumulator in the system.

For the last **Figure 18** showed the results achieved as a pressure relief valve installed into the system. The maximum pressure recorded for this case was about 13.03 barg. The pressure reduction experienced only at about 22% as compared to the maximum base case pressure. The pattern of the pressure obtained for this case was still unstable.

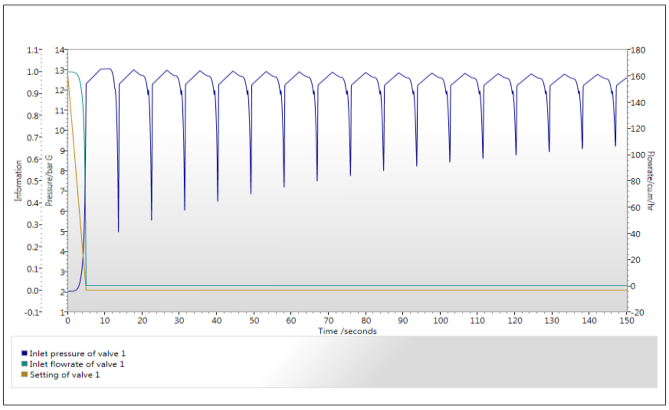

Figure 18: The Installation of Pressure Relief Valve into the System

A comparison has been made between these three options in reducing the surge pressure. The aspect compared was in terms of the effectiveness and the current price of each device. The results from the comparison were tabulated as in Table 8. Referring to the Table 8, the price of accumulator tank is cheaper than the price of surge tank at the same tank capacity. The performance between these two devices only has slight difference which around 70%. Therefore, it can be concluded that the accumulator tank is preferred since the cost was quite economical and at the same time have good performance in reducing the pressure.

Table 7: The Performance and Price of Each Device

	Surge Tank	Accumulator Tank	Pressure Relief Device
Performance (%)	72.68	70.94	21.93
Price (USD)	10,000 (16m^3)	5,000(16m^3)	50

IV. CONCLUSION

As a conclusion, the pipe length, valve closure rate and fluid flow rate were identified can affect the value of pressure produced in conduit. Based on the results obtained, shorter pipe will results in higher pressure surge. As for rapid valve closure, large pressure surge is produced inside the conduit. In terms of fluid flow rate, high pressure surge is produced which corresponded to higher flow rate of fluid. The best method identified that can significantly reduce the pressure surge with the most economical value is via the installation of accumulator tank.

ACKNOWLEDGMENT

Thank you to my supervisor, Mr Abdul Aziz Ishak, my internship supervisor, Mr Muhammad Farid Karim and Universiti Teknologi Mara for supports provided.

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