

# Experimental Study of Water Hammer Phenomena in Drinking Water Pipeline Distribution Using Video Camera Method

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**Abstract**— The huge energy potencies in the pressure release chamber on the drinking water pipeline distribution can be utilized by installing the micro hydropower turbine. The problem that may be occurred is the water hammer effect which is caused by sudden closure of a valve or malfunction of the turbine. Water hammer means a transient condition of fluid that is occurred while hydraulic operation. An initial steady state hydraulic flow suddenly changes because of valve off or clogging. This transient wave leads to a high pressure change dramatically that may damage the penstock, break the seal or break the turbine. Therefore prevention of water hammer phenomena should be taken in account properly. This research is an experimental study on micro hydropower turbine in the laboratory scale intended to provide solutions for reducing water hammer effect. The research is conducted to observe the effect of time closure of the valve to water hammer and the solution due to installation of bifurcation pipe as a release valve before the turbine inlet. This research proposes a simple method by using a video camera and slow motion playback to observe the water hammer effect, so that the pressure transient can be captured. This research resulted that the method using video camera and slow motion playback can be used effectively to visualize the pressure transient, and the water hammer effect can be reduced with the delaying of time closure of the valve. The bifurcation did not give significant result in reducing the water hammer effect compared to pipe with turbine without bifurcation. These results are also comparable with the theoretical calculation.

**Index Terms**— bifurcation pipe, drinking water pipeline, micro hydro, turbine, water hammer, valve closure, video camera.

## 1 INTRODUCTION

INDONESIA fulfills drinking water needs of its people through Water Companies (PDAM). Water supply systems including piping are managed by PDAM of each district and/or city. Water is delivered by large diameter steel pipelines into a hundred of small pipelines leading to residents. Generally, drinking water pipelines come from high head reservoir with high pressure that can be utilized for alternative energy resources by installing micro hydropower plant. Unfortunately, until today those potencies are allowed to simply fall apart on the pressure release chamber.

Micro hydropower plant is the best way to utilize those potencies. However, the development of micro hydro power plant (using a drinking water pipeline as a penstock) is constrained by the effect of water hammer (pressure shock) which is mainly caused by faulty system operation such as an instantaneous closure of the valve. The impacts of the water hammer are the rupture of pipes, pipe holders, pipe fittings, valves, and as well as turbines.

Water hammer has become an interesting assessment in applied hydraulics and mechanic fluid since ninetieth century. Theoretically, there are several methods to calculate or predict a maximum pressure change and the character of transient pressure due to water hammer. Ghidoui et.al (2005) gives a description of derivation from mass momentum equation and continuity equation. Together these equations provide a numerical solution that can be solved by using several appropriate software. The implementation of finite element method called Method of Characteristics (MOC) was conducted by Hariri [7]. The author compared transient pressure properties for different material and dimension of penstock as an economical consideration for the further. MOC is believed to be the simplest numerical method among the others after Sarma

[10]. It transforms the partial differential equation to be an ordinary differential equation and pressure change by varying a friction factor of the penstock. Furthermore, for calculating the pressure change occurred due to water hammer, the simple empirical formula after Joukowski in Ghidaoui et.al [3] can be used.

This research is a laboratory scale experiment which reflects to PDAM pressured drinking water pipeline as a penstock for micro hydropower plant. The test rig was designed using PVC pipe 3 inch in diameter, equipped by a ball valve with a same diameter. Briefly, pressure change that is occurred due to water hammer effect was observed by using manometers which is installed along the penstock. Each manometer will describe a changing in static pressure of inner surface of the penstock. The simple empirical formula known as Joukowski formula in Ghidaoui [3] is playing a role as a comparison.

## 2 RESEARCH METHODOLOGY

### 2.1 Research Design

This research aims to describe the water hammer characteristics in PDAM pipeline (penstock of micro hydropower plant), represent by the test rig in laboratory. This research proposes a solution to reduce water hammer, by varying a time closure of the valve from 1 second until 10 seconds (gradual closure). Meanwhile, the measurement of pressure change was performed by using manometer. This device was installed in 4 point of observations along the penstock; point A, B, C and D. This research also provides the new method in observing water hammer using video camera. At the time the valve is closed (1 second, 2 seconds, etc.) any movement of mercury

inside the manometer will be simply recorded by this video camera.

Then, the character of transient flow which is represented by movement of mercury will be clearly visible in slow motion video playback. Each peak point can be marked and then depicted in X and Y coordinates by using Microsoft Excel. This method will be implemented in three conditions; free penstock, penstock with cross flow turbine installation and penstock with turbine together with bifurcation pipe installation. The most important objective in this research is to obtain a description of water pressure change due to the water hammer with a variation of time closure of the valve in the penstock, including the maximum and minimum pressure occurred.

The impact of variation time closure of the valve from 1 second until 10 seconds (gradual closure) in reducing pressure change will be revealed as the experimental results which are being compared with the theoretical one. The reliability of video camera recording method also will have shown as trend lines from comparison graphs that revealed (see 2.3). The results of video camera indicates that the maximum and minimum pressure change in all of points A, B, C and D and also the pressure change at every experimental condition.

## 2.2 Test Rig Explanation

The test rig installation was begun with elbow and PVC pipe (penstock) assembling (Fig.1). Those have a same diameter from the inlet of reservoir to the valve. PVC assembling process is using PVC glue to ensure there is no leakage occurred on the fitting pipe (penstock).

This installation is continued with valve assembling. The valve that used in this experiment is ball valve and has the same diameter with the PVC penstock. The ball valve is the most appropriate one for this research, due to the convenience in closing it with the variety of time i.e. 1 second until 10 seconds closure.

Fig. 1 shows the main concept of experimental device installation. It contains of reservoir (number 1), PVC elbow 45° (number 2), PVC pipe as penstock with 3inch in diameter and 3,5 meters in length (number 3), PVC elbow 45° at the bottom (number 4) and ball valve 90° shut-open with 3 inch in diameter (number 5). Bifurcation pipe then was being installed next to the valve.

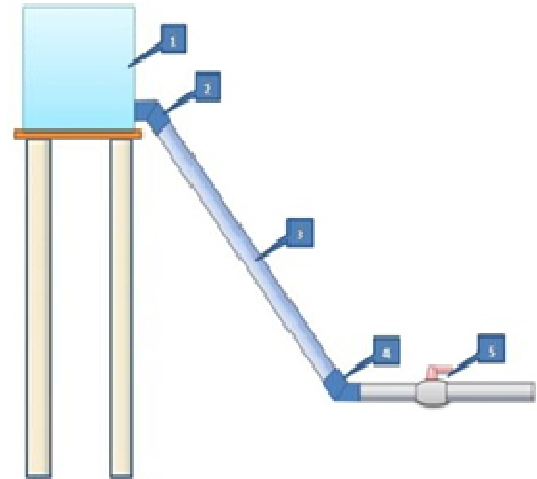


Fig.1 Test rig in laboratory

As stated above, manometer was installed in PVC penstock (number 3) for 4 point of observations which were made within 25 cm in distance respectively. The observation activity is explained by these pictures below:

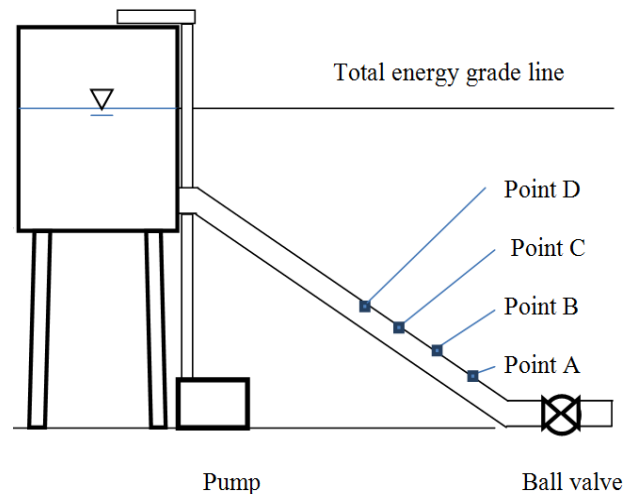


Fig.2 Points of pressure change observation in test rig



Fig.3 Manometers (with mercury) to observe the pressure change

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Fig.4 Ball valve with 90° shut-open

### 2.3 Observation Using Video Camera

Observation by using a video camera is the simplest method in describing the changing of pressure change (water hammer). As explained before, water hammer is simulated by varying the time closure of a valve gradually from 1 second until 10 seconds and the camera will be stand by during the experiment to capture manometer movement. That the character and peak of the pressure change of each time closure which are clearly visible in video playback, is the advantage of this method.

Validity of this method to described the water hammer character can be explained statistically when it is being compared with the theoretical results. Regression will create a 'power trend line' and the coefficient of correlation will indicate the effect of gradual valve closure in reducing the water hammer effect. The regression and the coefficient of correlation can be calculated from formula from Sudjana [11] as stated below:

$$Y = ax^b \tag{1}$$

$$\log a = \frac{\sum \log Y_i}{n} - b \frac{\sum \log X_i}{n} \tag{2}$$

$$b = \frac{n(\sum \log X_i \log Y_i) - (\sum \log X_i)(\sum \log Y_i)}{n(\sum \log^2 X_i) - (\sum \log X_i)^2} \tag{3}$$

$$R^2 = \frac{((n)(\sum XY) - (\sum X)(\sum Y))^2}{(n(\sum X^2) - (\sum X)^2)(n(\sum Y^2) - (\sum Y)^2)} \tag{4}$$

In which:

$Y_i$  = Value of each point in Y axis

$X_i$  = Value of each point in X axis

$R^2$  = Coefficient of correlation

$a, b$  = Constant

### 2.4 Water Hammer Theoretical Calculation

The experimental results must be compared by theoretical calculation to get an idea how the water hammer phenomena occurred. Moreover, in the real situation it is required to predict the maximum and minimum pressure caused by water hammer. Theoretical study refers to maximum pressure change (water hammer), total pressure acquired by the pen-

stock, length of the penstock, water velocity, water density, discharge; total head and speed of propagation that must be known from the beginning.

Water hammer problem could be a complex calculation by considering every aspects which are involved on it, such as change in flow structure from laminar to fully turbulent, and pressure oscillations. Basically, water hammer ( $P$ ) is greatly influenced by speed of propagation ( $a$ ), water velocity in pipe ( $v$ ), water density ( $\rho$ ), total head ( $H$ ) and cross section area of penstock ( $A$ ). Meanwhile, the magnitude of pressure rise ( $\Delta P$ ) depends on the valve time closure ( $t$ ).

Before water hammer occurred, speed of wave propagation can be written as an initial form in Ghidaoui [3]:

$$\frac{1}{a^2} = \frac{d\rho}{dP} + \frac{\rho}{A} \frac{dA}{dP} \tag{5}$$

Meanwhile, mass and momentum equation and continuity equation for 1D water hammer are:

$$\frac{g}{a^2} \frac{\partial H}{\partial t} + \frac{\partial v}{\partial x} = 0 \tag{6}$$

$$\frac{\partial V}{\partial t} + g \frac{\partial H}{\partial x} + \frac{\tau_w \pi D}{\rho A} = 0 \tag{7}$$

Since this research examines the water hammer effect for gradual closure of the valve ( $t > 2L/a$ ) those two equations above should be derived into a Joukowski formula, written as:

$$\Delta P = \rho L v / t \tag{8}$$

Head increase for each point is:

$$\Delta H = \pm \Delta P / (\rho g) \tag{9}$$

Meanwhile, water velocity  $v$  in (7) can be calculated from an energy equivalent concept using Bernoulli equation which is stated in Potter (2008):

$$\frac{P_1}{\rho g} + \frac{v_1^2}{2g} + z_1 = \frac{P_2}{\rho g} + \frac{v_2^2}{2g} + z_2 \tag{10}$$

Where:

$P_1$  = Pressure of point 1 (Pa)

$v_1$  = Velocity of point 1 (m/s)

$z_1$  = Elevation of point 1 (m)

$P_2$  = Pressure of point 2 (Pa)

$v_2$  = Velocity of point 2 (m/s)

$z_2$  = Elevation of point 2 (m)

## 3. RESULTS AND DISCUSSION

### 3.1 Validity of Video Camera Method for Pressure Change Observation

Validity of video camera method is necessary to ensure that the data of pressure change which are captured is trusted and reliable. Generally the video camera method is valid if it meets these following conditions:

- The video camera method is able to show both maximum and minimum pressure change clearly.
- The video camera method can trace events started from the beginning valve closure towards the end of pressure change.
- The observed values which are captured by video camera are comparable with the theoretical calculation results. For the example the maximum value.

Regarding to this research, video camera which is used can fulfill those requirements above as evidenced by graph below:

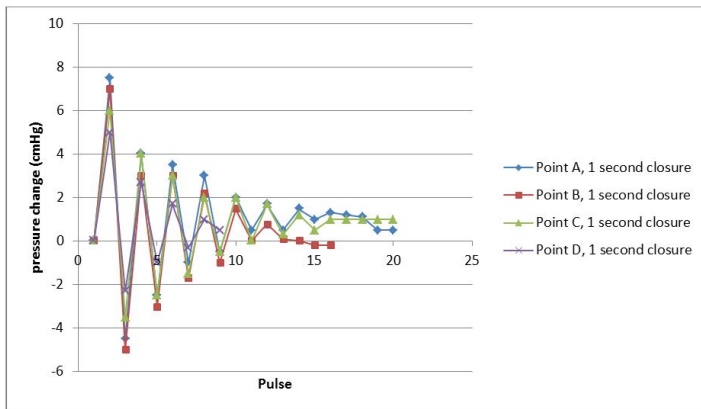


Fig.5 Maximum and minimum value and the trace of pressure change

This Fig.5 leads to an understanding that the water hammer characteristic in piping system can be shown by using a manometer and video camera recording method.

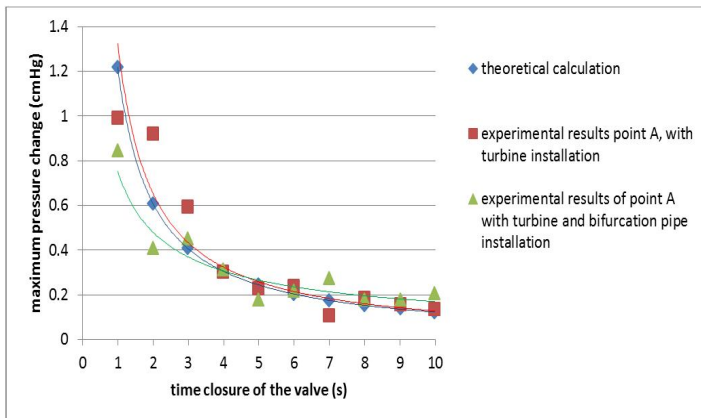


Fig.6 Comparison between experimental results and theoretical calculation

Both Fig.5 and Fig.6 indicate that the video camera method in this research fulfills three main requirements of validity.

TABLE 1  
LIST OF EACH TREND LINE IN FIGURE 6

Nu	Result trend line	Regression	Coefficient of correlation (R <sup>2</sup> )
1	Theoretical Results	$y = 1.2166x^{-1}$	1
2	Experimental Results point A with turbine	$y = 1.3225x^{-1.017}$	0.8812
3	Experimental Results point A with turbine and bifurcation pipe	$y = 0.7521x^{-0.649}$	0.852

and bifurcation pipe		
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Those high coefficients of correlation once again show the affectivity of recording method with video camera and manometer in describing water hammer characteristics. Recording method is also helpful for researcher to determine the peak value of pressure transient both in the laboratory and in the field.

### 3.2 Observation Results of Water Hammer without Turbine and Bifurcation Pipe Installation (Free Penstock Condition)

All of the graphs in this section are the observation results that showed the mercury movement in manometer which is captured by the camera as a sign of water hammer. These data were obtained by simulating time closure of the valve from 1 second until 10 seconds.

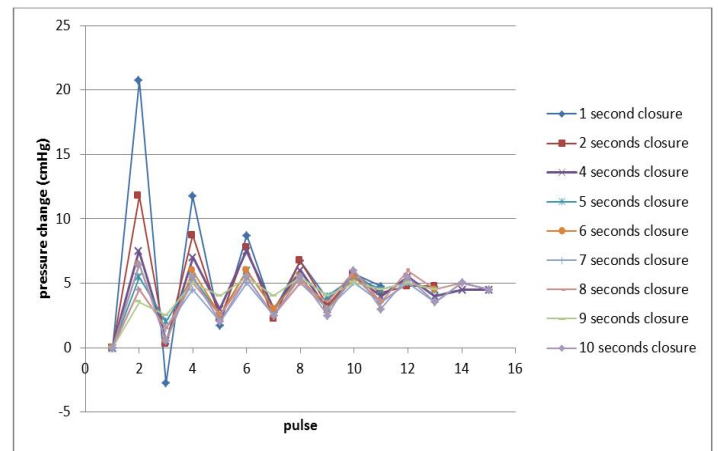


Fig.7 Water hammer characteristic for point A (free penstock condition)

The rest of pressure in Fig.7 is not turning back to the initial condition. This phenomenon occurred due to natural pressure in reservoir which is always getting larger.

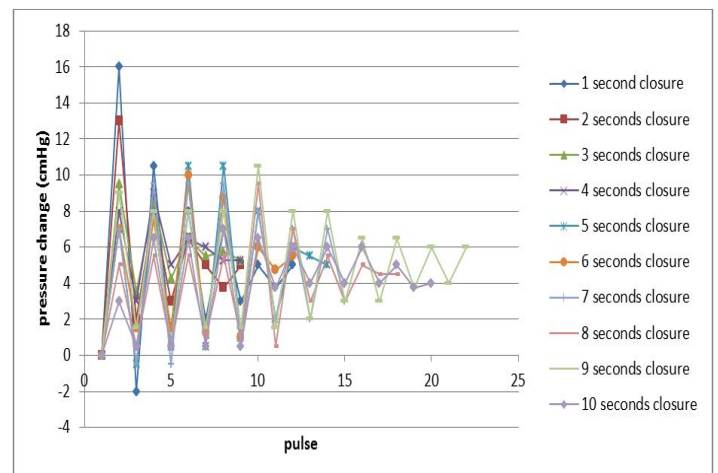


Fig.8 Water hammer characteristic for point D

In this research the period of oscillation is neglected, because this research is focusing on the observation of the maximum and minimum pressure change also the character of depletion of it. As the consequence, each X axis in every oscillation graph doesn't show the oscillation period but it pro-

vides number of pulse occurred while water hammer. From Fig.7 and Fig.8, can be concluded that the maximum pressure change becomes lower for each point of observation as it is getting further away from the valve ( $\Delta H$  point A >  $\Delta H$  point B >  $\Delta H$  point C >  $\Delta H$  point D). Those graphs also provide evidence that the gradual valve closure gives a significant effect in reducing the water hammer. The faster time closure of the valve, the greater pressure occurred. The greatest pressure occurs at the valve closing of 1 second, 2 seconds, and 3 seconds respectively. For 10 seconds valve closure the maximum pressure is decreasing until 68.3% in point A, 75.6% in point B, 60% in point C and 60.3% in point D compared to 1 second time closure.

### 3.3 Observation Results of Water Hammer with Cross Flow Turbine Installation

This experiment aims to get the water hammer effect due to turbine installation. Turbine installation directly gives a resistance to water which flows inside the penstock and it leads to the discharge reduction.

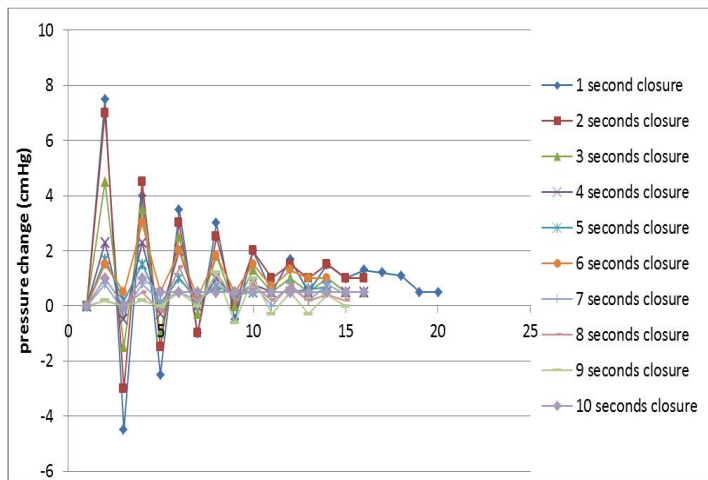


Fig.9 Water hammer characteristic in point A (when turbine is installed)

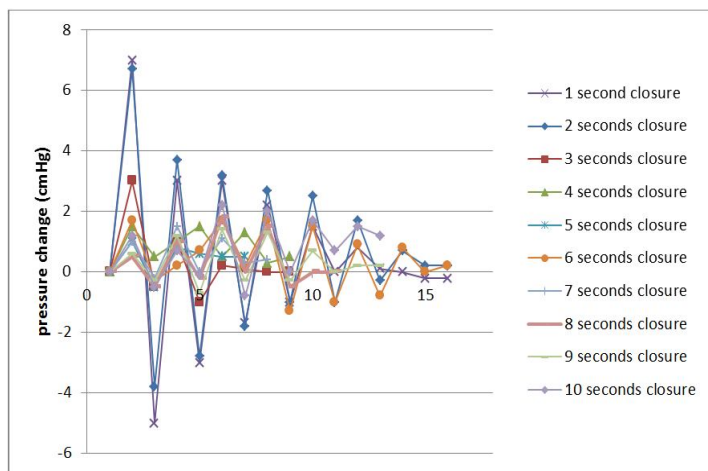


Fig.10 Water hammer characteristic for point B (when turbine is installed)

Turbine installation evidently reduces the water hammer effect in the penstock compared to free penstock condition by similar time closure. Fig.9 shows the maximum delta head pressure in point A is 7.5 cmHg. This value is much far below

the maximum value when the turbine doesn't exist, which is 20.75 cmHg.

Meanwhile, Fig.10 indicates the maximum pressure change in point B is 7 cmHg. This phenomenon leads towards verification that the delta head pressure is directly influenced by water velocity inside the pressured pipe.

### 3.4 Observation Results of Water Hammer with Cross Flow Turbine and Bifurcation Pipe Installation (20% opening)

Bifurcation pipe was installed between cross flow turbine and valve (see Fig.1). This branch pipe is 20% opened among its cross sectional area. This installation leads to minor hydraulic losses and velocity reduction. The results of this experiment will show the significance reducing of water hammer compared to free penstock condition. Nevertheless, it doesn't have significant difference compared to penstock with turbine without bifurcation pipe.

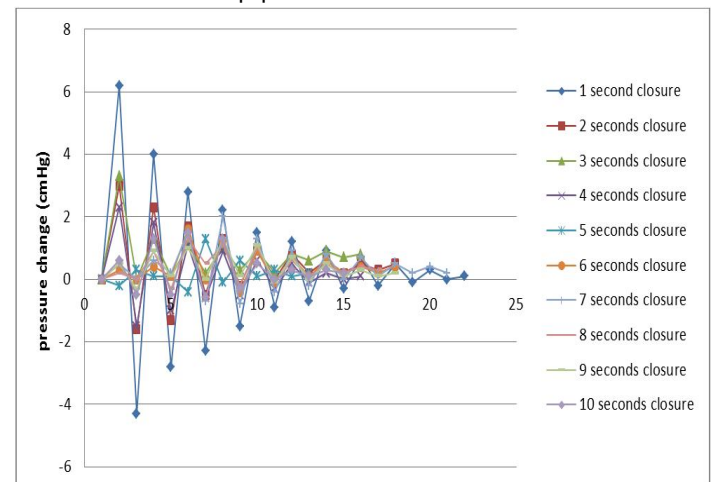


Fig.11 Water hammer characteristic for point A (with turbine and bifurcation pipe installation)

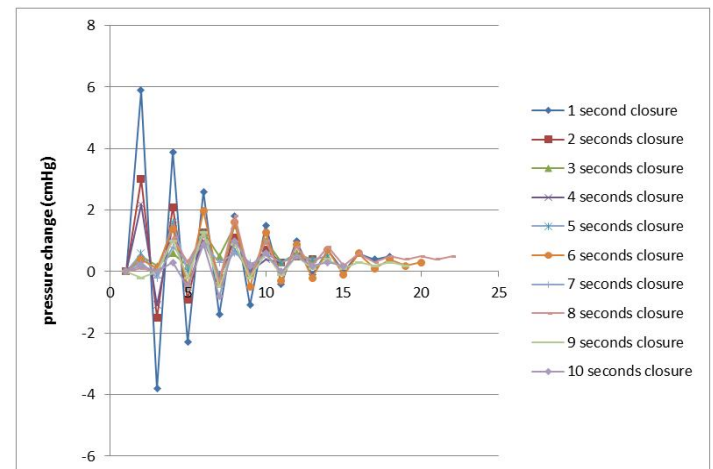


Fig.12 Water hammer characteristic for point B (with turbine and bifurcation pipe installation)

It can be ensured that the pressure in this section (with turbine and bifurcation pipe) is much lower than the pressure value without turbine (free pipe). Fig.11 indicates the highest pressure change in point A is 6.2 cmHg. This is slightly adrift

below the value with turbine installation without bifurcation pipe, which is 7.5 cmHg. Here, bifurcation pipe installation makes only 17.33% in water hammer reduction.

Fig.12 shows the highest one in point B is 5.9 cmHg. It is similar to the previous results; it creates a small difference from value with turbine installation without bifurcation pipe (7 cmHg). Now, bifurcation pipe installation acquires only 2% in water hammer reduction. In this case, the small percentage predicted might caused by a small opening of bifurcation pipe, which is 20% from its cross sectional area.

### 3.5 Theoretical Calculation of Water Hammer

According to (7) and (8), theoretical results can be compared with the experimental one by knowing pipe and hydraulics specification. For the experimental results, the peak values for each time closure must be determined first before they are being compared with experimental. It is easier for time closure 1 second until 3 seconds, because the values of pressure rise are directly visible after the valve is closed. Another case for 4 seconds until 10 seconds, the value of pressure is more influenced by the 'human error' in closing the valve.

This section purposed to get an idea about the comparison between theoretical water hammer and experimental results. Other words, how the experiment results are considered from the theory's perspective. Another reason is to describe the reliability of water hammer observation by using a video camera method with gradually closure of the valve.

#### 3.5.1 In Free Pipe Condition

By using (8) and (9), the highest pressure change for each time closure is possible to be calculated correctly. This condition provides discharge 31.45 l/s and velocity is 6.9 m/s. The comparison between theoretical and experimental is stated below:

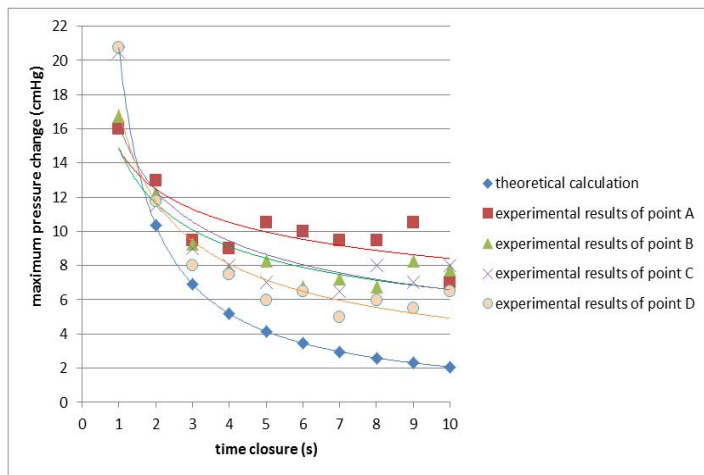


Fig.13 Comparison of theoretical and experimental results for water hammer peak values in free pipe condition

Fluctuation of pressure change was occurred in all of point of observations. Fig.13 indicates that increasing in distance between the points (25 cm) provides a clear influence to the declining of pressure change due to water hammer. Nevertheless, the values of pressure change are relatively higher than the theoretical one. This because of a high velocity of water flows in the penstock. This phenomenon cannot be clearly ex-

plained yet.

TABLE 2  
LIST OF EACH TREND LINE IN FIGURE 13

Nu	Result trend line	Regression	Coefficient of correlation (R <sup>2</sup> )
1	Theoretical Results	$y = 20.759x-1$	1
2	Experimental Results point A	$y = 14.796x-0.245$	0.66
3	Experimental Results point B	$y = 14.881x-0.353$	0.811
4	Experimental Results point C	$y = 16.274x-0.393$	0.7292
5	Experimental Results point D	$y = 17.157x-0.542$	0.865

Compared with the theoretical calculation, the experimental results made large disparities especially from 4 seconds until 10 seconds. The largest disparity in average was made by point A on 9 seconds closure with 8.19 cmHg. Point A's trend line stays in the highest position, followed randomly by point B, C and the last one D. Overall, the coefficient of correlation value stays high which is directly signed that the gradual closure of the valve reduces water hammer clearly.

#### 3.5.2 With Crossflow Turbine Installation

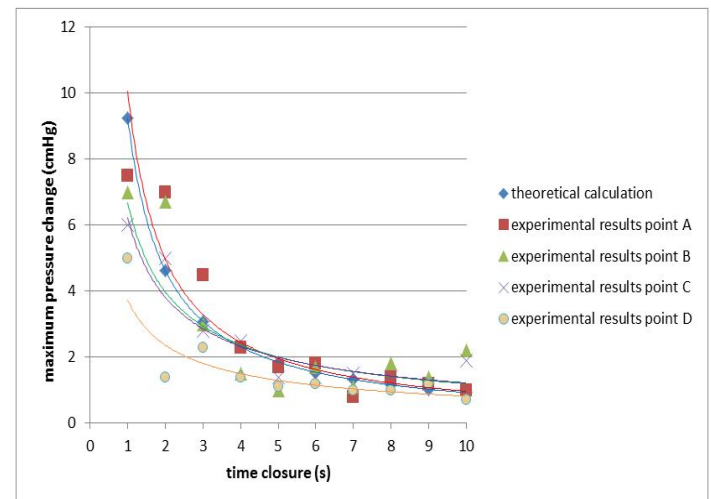


Fig.14 Comparison of theoretical and experimental results for water hammer peak values with crossflow turbine installation

Moreover, Fig.14 shows that valve closure delay provides a significant effect to reduce pressure change due to water hammer, for each point of observation. Fig.14 indicates in point A, the pressure values are spread normally, without any significant disparities. The theoretical results (blue line) have a regression in power trend line with R<sup>2</sup> value of 1. Trend line of experimental result for point A is drawn by  $y=10.051 x (^-$

1.017). It is supported by the highest value of  $R^2$ , which is 0.8812. This correlation value is high; it means that the observation results in this point have proved that valve closure delay gives a significant influence in reducing the water hammer effect.

Point B shows a fluctuating pressure value, especially in 2 seconds and 10 seconds time closure. In 2 seconds the pressure is too high from theoretical result, which pressure change is 6.7 cmHg from its initial. It is getting lower dramatically in 5 seconds closure, which is 1 cmHg. Another is slightly shifted from a trend line. Even the value of  $R^2$  in point B (0.6387) is the lowest among the others, but it is still large enough to show the significant decreasing trend line.

TABLE 3  
LIST OF EACH TREND LINE IN FIGURE 14

Nu	Result trend line	Regression	Coefficient of correlation ( $R^2$ )
1	Theoretical Results	$y = 9.2462x-1$	1
2	Experimental Results point A	$y = 10.051x-1.017$	0.8812
3	Experimental Results point B	$y = 6.6751x-0.748$	0.6387
4	Experimental Results point C	$y = 6.2332x-0.709$	0.8404
5	Experimental Results point D	$y = 3.7336x-0.659$	0.7847

By using (1) the regression of trend line is easily determined. Meanwhile, (4) is very helpful to find the coefficient of correlation as shown in Table 2.

Overall, experimental results presentation for each point of observation seems spread evenly. Point A as the nearest spot to the valve provides the closest trend line to the theoretical. It is followed by the next point which is sequentially getting further to theoretical trend line. Statistically, the coefficient of correlation for each trend line of point of observation is high. It confirms the fact that the highest pressure will be acquired by the closest point to the valve. In other words, the delaying in the valve closure provides a significant effect in reducing pressure change. It also affirms that water hammer observation with gradually valve closure by using video camera is one of a feasible method that could be directly implemented in the field.

### 3.5.3 With Crossflow Turbine Installation and Bifurcation Pipe (20% opening)

Another condition, when the bifurcation pipe is being installed together with the turbine discharge is becoming 11 l/s and velocity is 2.4 m/s. Similar to the previous calculations, theoretically pressure change (peak values) for each time closure can be determined by using equation (7) and equation (8).

Clearly in this case, water hammer effect is reduced due to decline of water velocity. The comparison between theoretical and experimental results is stated below.

Fig.15 indicates a better data distribution for each point of observation. Point A, gives the highest value pressure change in biggest portion, almost in every time closure of the valve.

The lowest correlation is found in experimental results point B. The  $R^2$  value is 0.7521. This means that the contribution of time valve closure delays to the decreasing of water hammer effect is only 75.21%, the rest depends on another factor. However, since  $R^2$  extends from 0 to 1, the correlation of these two variables is still large. From the previous observation results including "with crossflow turbine installed" condition, the coefficient of correlation ( $R^2$ ) has showed a satisfying high value. Practically, the delaying of time valve closure is significantly reducing the pressure change and the results can be drawn graphically in power trend line.

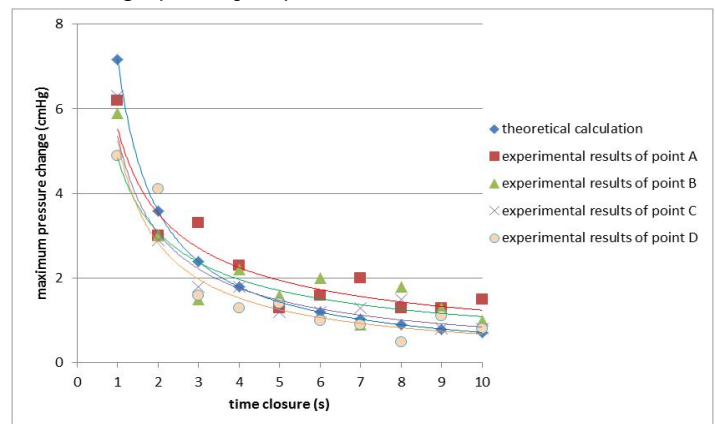


Fig.15 Comparison of theoretical and experimental results for water hammer peak values when cross flow turbine and bifurcation pipe are being installed

TABLE 4  
LIST OF EACH TREND LINE IN FIGURE 15

Nu	Result trend line	Regression	Coefficient of correlation ( $R^2$ )
1	Theoretical Results	$y = 7.1736x-1$	1
2	Experimental Results point A	$y = 5.533x-0.649$	0.852
3	Experimental Results point B	$y = 4.8367x-0.648$	0.7521
4	Experimental Results point C	$y = 5.3595x-0.803$	0.907
5	Experimental Results point D	$y = 5.2421x-0.889$	0.852

When they are being compared with the theoretical, the experimental results spread surrounding. Point A's trend line stays in the highest position, followed uniformly by point B, C and D.

## 5. CONCLUSIONS

1. This research has confirmed that the method using video camera can be implemented to observe the water hammer effect (pressure change) in the laboratory scale satisfactorily.
2. Pressure change due to water hammer can be reduced by lengthening valve closure time (gradual closure of the valve), and the reduction can be explained clearly through power trend line controlled by coefficient of correlation and also match to the theoretical calculation results.
3. Pressure change due to water hammer was decreased significantly by installing the bifurcation pipe before turbine. So, this method can be implemented in order to minimize the dangerous of water hammer effect on micro hydro-power plant.

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## 6. RECOMMENDATIONS

This research might be continued; to describe the cause of large disparities between experimental results and theoretical calculation in determining pressure change especially in free penstock condition, to observe the period of oscillation using video camera method and also to find out the appropriate solution to reduce water hammer effect using energy valve.

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