H405

Pipe Surge and Water Hammer

User Guide

TecQuipment has taken care to make the contents of this manual accurate and up to date. However, if there are any errors, please let us know so we can rectify the problem.

TecQuipment supply a Packing Contents List (PCL) with the equipment. Carefully check the contents of the package(s) against the list. If any items are missing or damaged, contact TecQuipment or the local agent.

DB/BW/0123

TECQUIPMENT

Symbols Used in this Manual

NOTE		*Important information*
CAUTION		*Failure to carry out this instruction could cause damage to the apparatus, other equipment, personal property, or the environment.*
WARNING		***Failure to carry out this instruction could cause personal injury.***

Contents

TECQUIPMENT

H405

Pipe Surge and Water Hammer

User Guide

Introduction

Figure 1 H405 Pipe Surge and Water Hammer

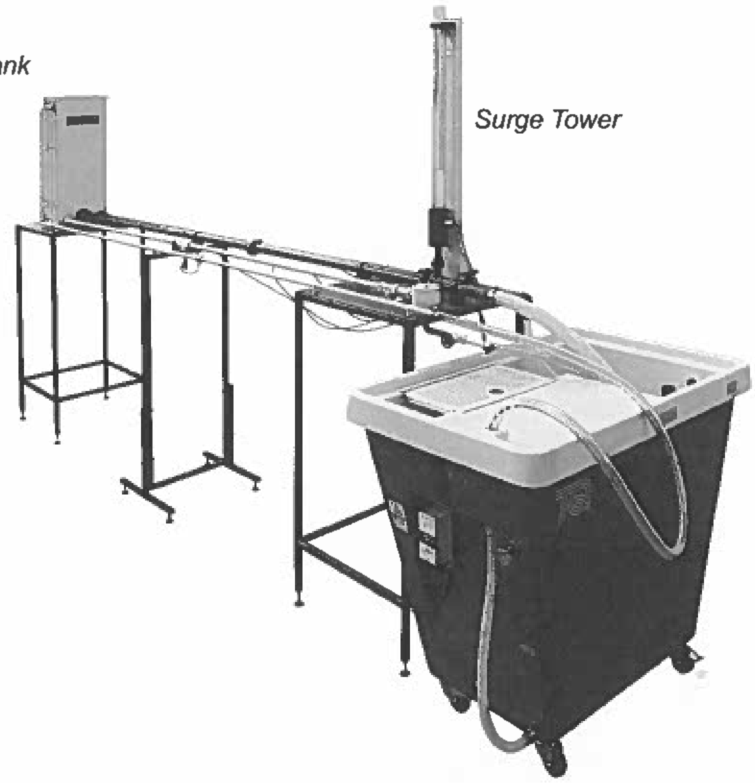
Most dictionaries define surge as 'a sudden or transient increase'. In fluid mechanics, pipe surge is a sudden increase in fluid 'head' or pressure, caused by a change in fluid velocity in the pipe. Opening and shutting a valve quickly can produce pipe surge, as can sudden changes in the speed of a pump. Determined by the liquid properties, its flow and how quickly the change happens, the surge amplitude may be large. It may be enough to cause damage, breaking pipework and other parts of the fluid path.

Water hammer is the name given to the audible transient pressure wave or 'shock wave' created as a liquid quickly decelerates (comes to a sudden stop) against a surface, such as a water flow against the sudden closure of a valve or tap. As its name suggests, water hammer most often occurs in water, but may also occur in other fluids.

Pipe surge and water hammer are both important areas of study in fluid mechanics, as both can cause damage to a fluid system. Therefore, engineers must understand why they happen and understand how to allow for them in their designs.

TecQuipment's Pipe Surge and Water Hammer equipment (H405) allows students to create and measure both these aspects of fluid mechanics. The experiments and theory in this guide help students understand how to predict the possibly damaging pressures involved, while learning how to allow for them.

Description



Pipe Surge and Water Hammer (H405) - Shown with H1D Volumetric Bench (not included)

The equipment works with TecQuipment's Digital Hydraulic Bench (H1F) or an existing Volumetric Hydraulic Bench (H1D)(not included). The bench supplies and measures the flow during experiments. However, any clean water supply and measurement system of the correct pressure and flow may be used (refer to **Technical Details**).

Figures 4 and 5 show the two main arrangements. They both use the Header Tank (reservoir) fitted with an inlet pipe and float valve. For good engineering practice, the Header Tank has an internal overflow. Two separate test pipes, one for surge and the other for water hammer, lead from the Header Tank. The water leaving both pipes exits to the measuring tank of a Hydraulic Bench.

The pipe surge experiment creates relatively low pressures, so uses durable plastic pipe and fittings. The downstream end of the surge test pipe has a vertical, clear plastic 'Surge Tower'. A control valve just downstream of the surge tower allows the user to set an initial flow rate along the pipe. A sudden closure of the valve (see Figure 2) generates a surge made visible by a rise in the water in the tower. A pressure transducer at the base of the Surge Tower connects to TecQuipment's VDAS® mkII equipment to display the pressure changes during the surge. A scale alongside the Surge Tower allows users to see the maximum height (head) of the surge for reference.

NOTE

The surge sensor is 225 mm above the centreline datum of the surge pipe, so it cannot measure the full height of water in the surge tower. However, when selecting the pipe surge experiment, VDAS® channel 1 allows for this and automatically adds this value to the trace.

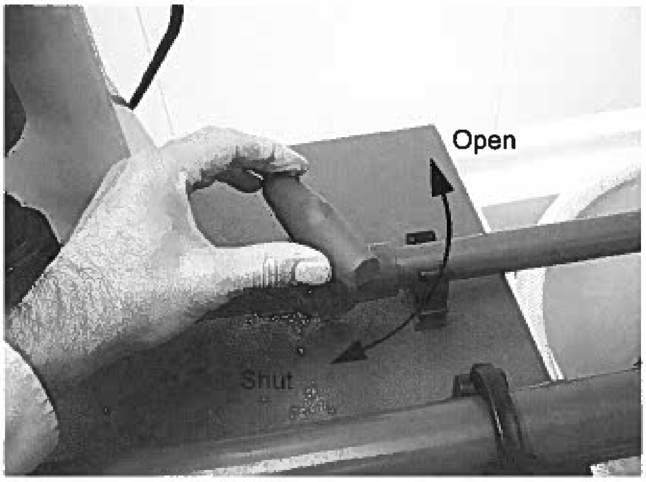


Figure 2 Surge Valve

The water hammer experiment creates relatively high transient pressures, so uses a metal pipe and fittings which can withstand the pressures. The downstream end of the water hammer pipe has a special quick-closing valve, followed by a hand-operated flow control valve. The quick-closing valve has an internal spring that tries to shut the valve. This helps the user to shut the valve more quickly, for best results. A Valve Rest (see Figure 3) helps to keep the quick-closing valve open while the user sets the flow rate.

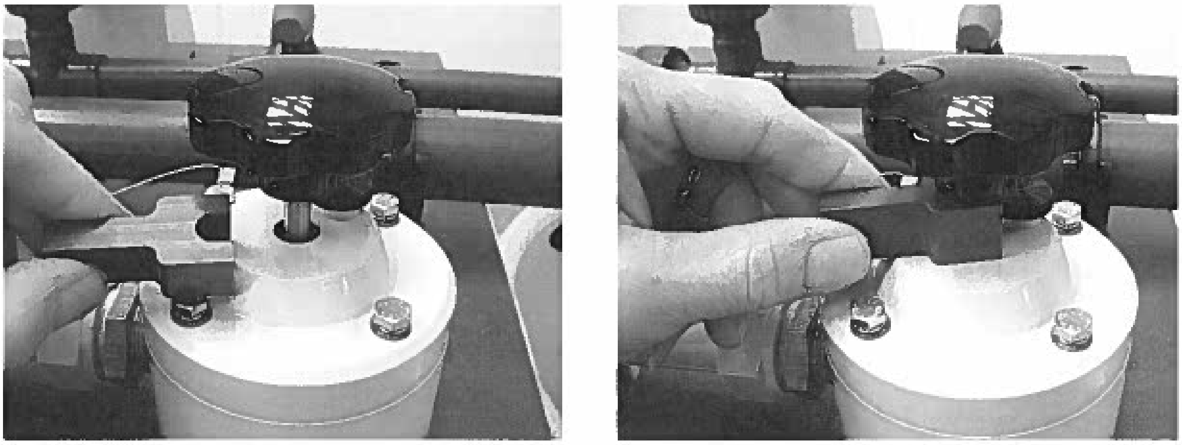


Figure 3 Valve Rest

The flow control valve allows the user to set the flow rate before generating the water hammer. Shutting the quick-closing valve causes a pressure wave, which travels upstream. Two pressure transducers in the pipe connect to TecQuipment's VDAS® mkII equipment to display the pressure changes at two different positions along the pipe. The distance between the transducers is important, as it allows the user to measure the velocity of the pressure wave travelling back along the pipe.

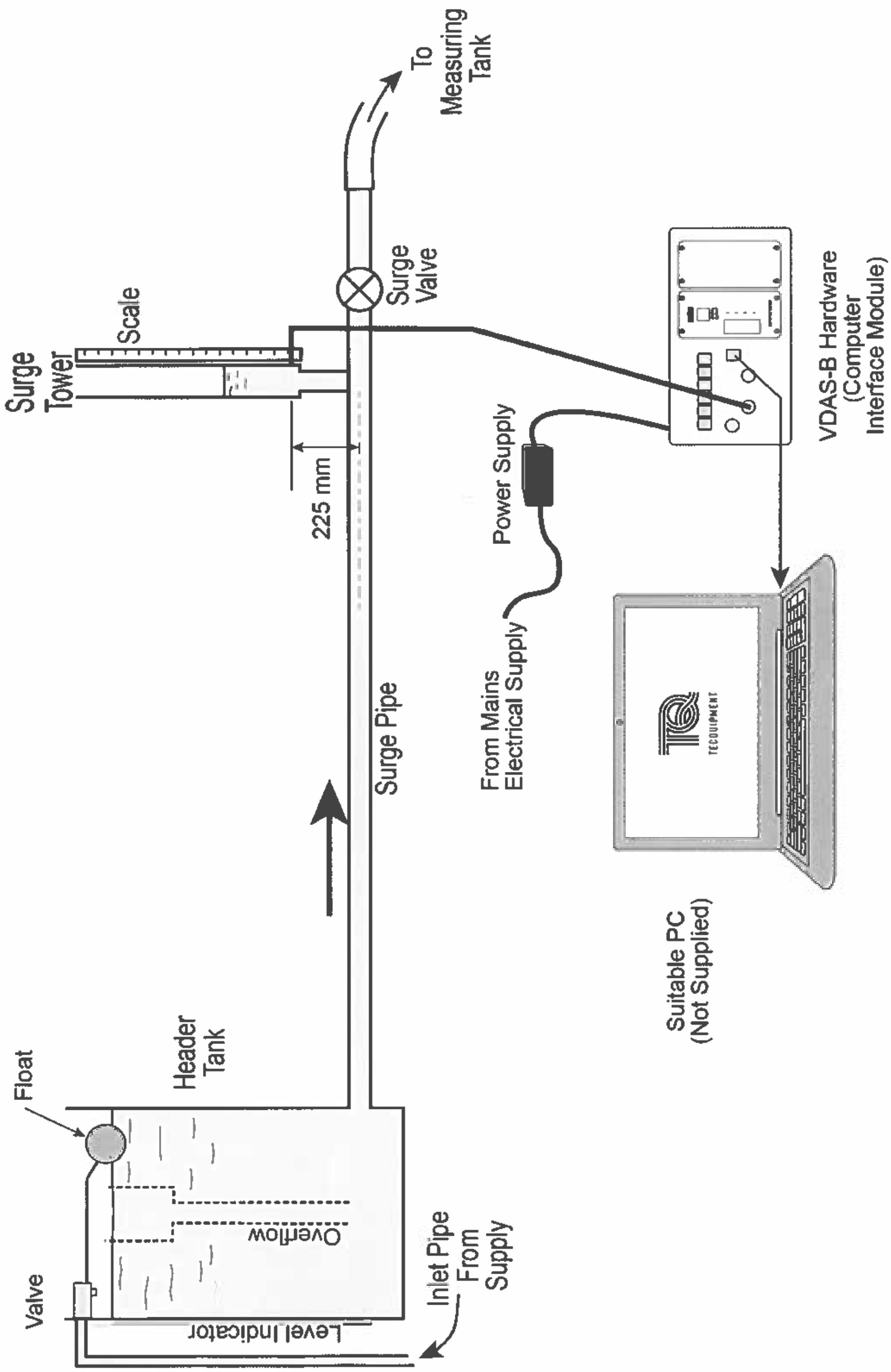


Figure 4 Setup For Pipe Surge Experiments

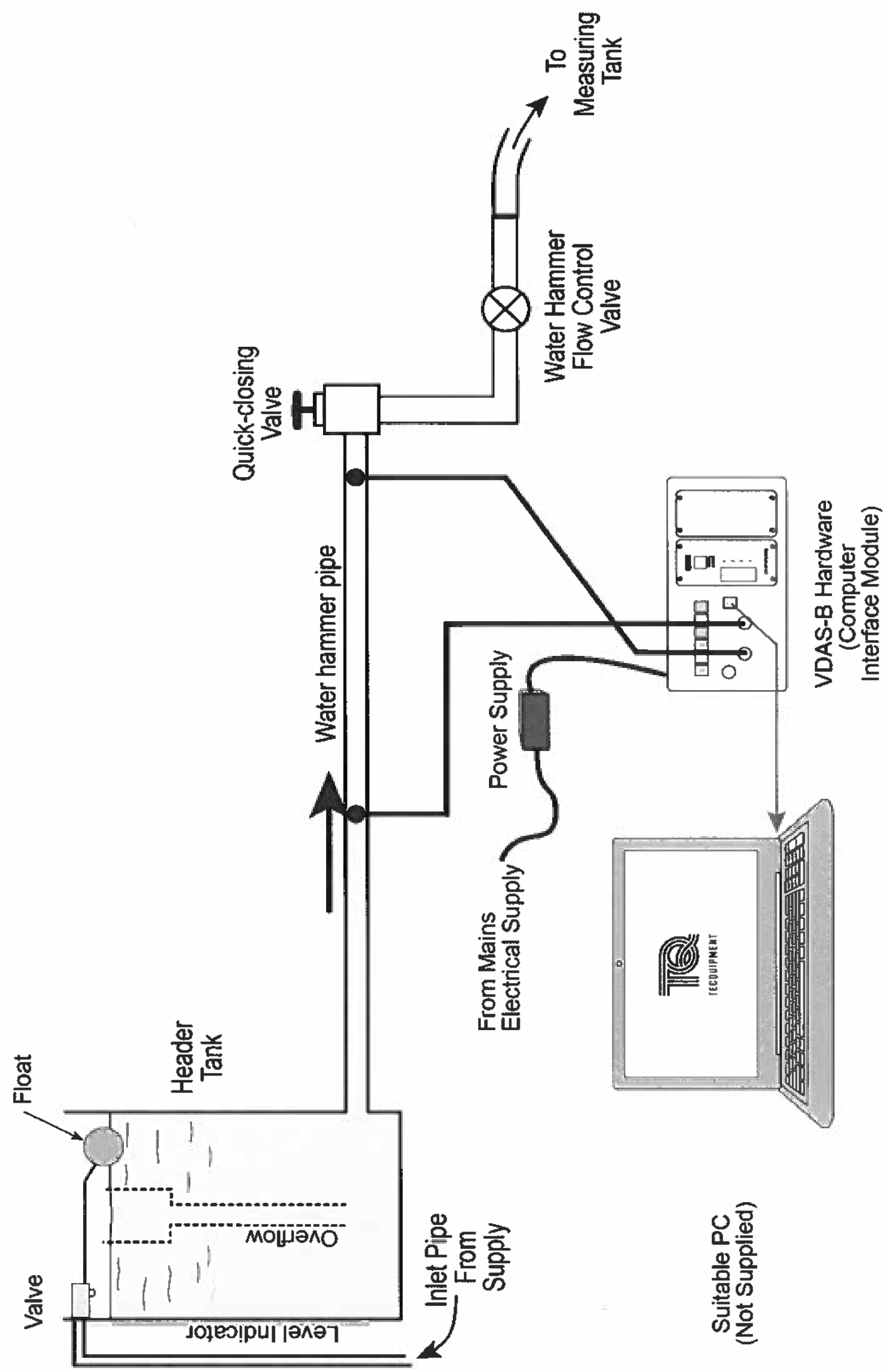


Figure 5 Setup For Water Hammer Experiments

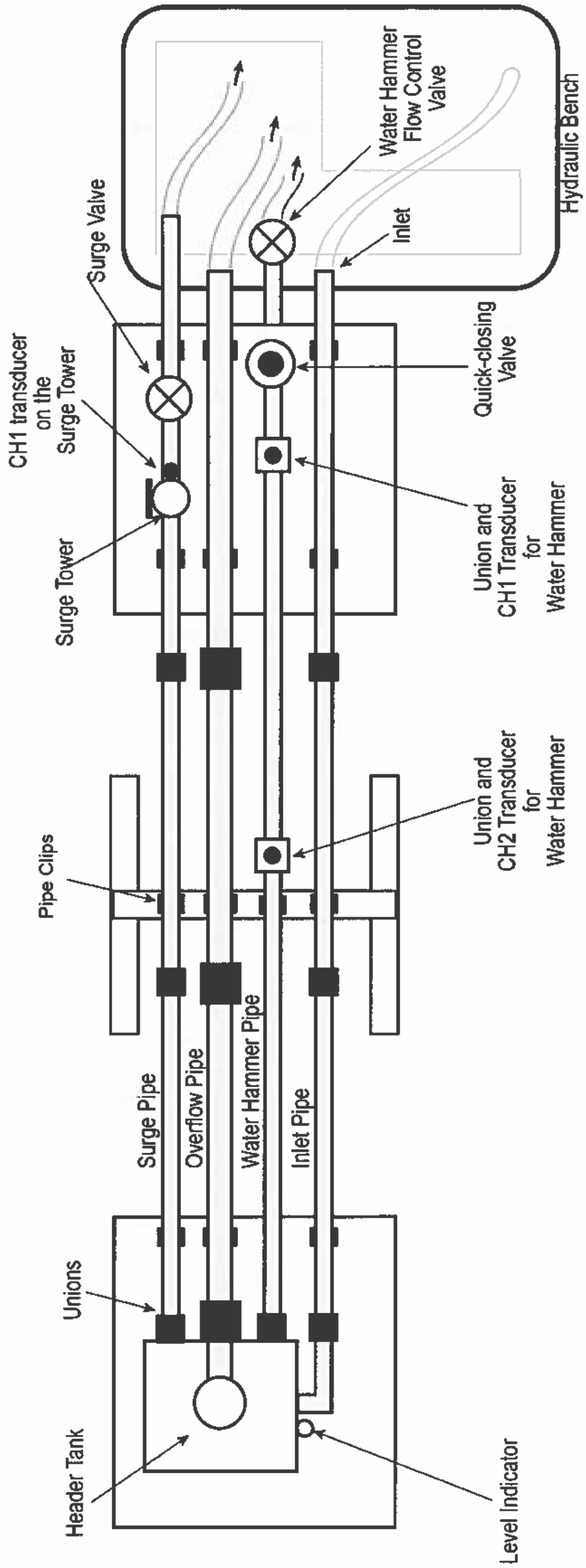
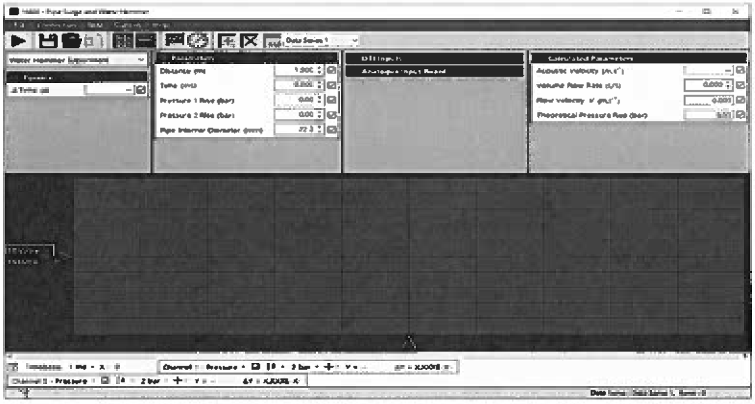


Figure 6 Plan View

Versatile Data Acquisition System - VDAS® (mkII)



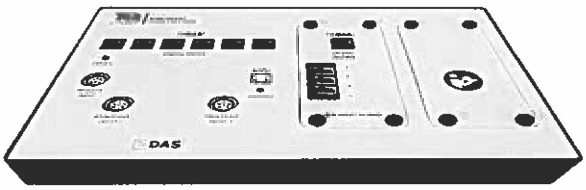


Figure 7 The VDAS® Hardware and Software

TecQuipment's VDAS® (mkII) is an ***essential*** extra for the Pipe Surge and Water Hammer (H405). It is a two-part product (Hardware and Software) that will:

- Display traces of the pressure changes
- Automatically log data from experiments
- Automatically calculate data
- Save time
- Reduce errors
- Create charts and tables of data
- Export the data for processing in other software

NOTE *A suitable computer (not supplied) will be needed to use TecQuipment's VDAS®.*

Technical Details

Item	Details
Assembled size and weight	Main Parts: 3850 mm long x 630 mm wide x 2400 mm high and 100 kg
Water supply needed	Minimum 0.8 $l.s^{-1}$ and head of 3 m Do not exceed 2 bar.
Pressure Transducers	Pipe Surge: 1 x 100 mbar transducer Water Hammer: 2 x 30 bar transducers
Water Hammer Pipe	Material: Hard-drawn Brass Young's Modulus E: 103 x 10^9 $N.m^{-2}$ (103 GPa) Inner Diameter D: 22.2 mm Wall Thickness t: 1.6 mm Cross sectional area A: 0.387 x 10^{-3} m^2 Approximate distance between transducers: 1.5 m
Surge Supply Pipe	Length L between reservoir and surge tower 3 m Inner Diameter: 21.1 mm Cross sectional Area A_P: 0.3497 × 10^{-3} m^2
Surge Tower	Inner Diameter: 44.5 mm Cross sectional Area A_S: 1.5553 × 10^{-3} m^2 Maximum Measurement Height: 950 mm above pipe centreline
Header Tank	Maximum Measurement Height: 700 mm above pipe centreline

Table 1 Technical Details

Noise Levels

The noise levels recorded at this apparatus are lower than 70 dB (A).

Installation and Assembly

The terms **left**, **right**, **front** and **rear** of the apparatus refer to the operators' position, facing the unit.

NOTE *Follow any regulations that affect the installation, operation and maintenance of this apparatus in the country where it is to be used.*

TecQuipment pack the equipment in several parts for transit, so it must be assembled. Find a suitable area in the laboratory to fit the equipment. It must have a stable, level floor that can resist minor water spills. Refer to the **Technical Details** for assembled sizes.

Using Figure 1 as a guide:

1. Set the three frames level on the ground using the adjustable feet supplied.
2. Remove the header tank from its position underneath its frame and re-use the four fixings to refit it on the top of the frame (see Figure 8). Note the rubber mat under the tank.

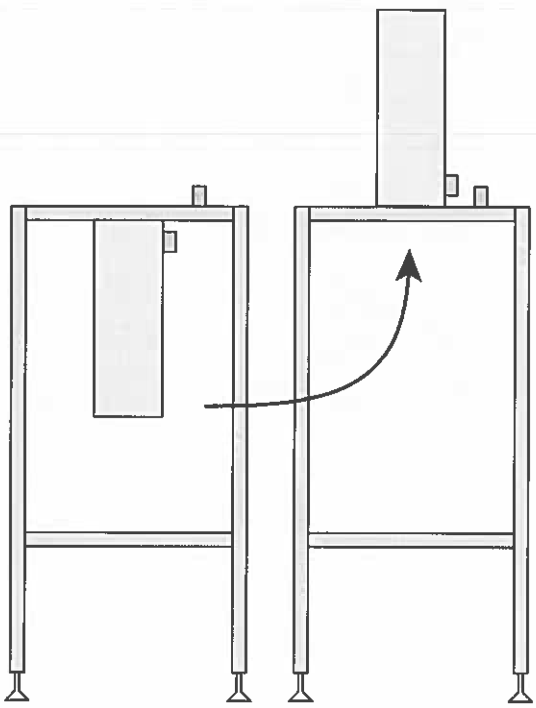


Figure 8 Unbolt Header Tank from Under Frame and Re-use the Fixings to Refit it On Top of the Frame

3. Mount the four pipes into the relevant positions as shown in Figure 6 and tighten all unions. TecQuipment pack the sections of each pipe together to avoid errors. If the pipes do not fit correctly, the wrong section is being used.
4. Note the 'olives' on each fitting of the metal pipes. Take care with these fittings and do not damage the olives.

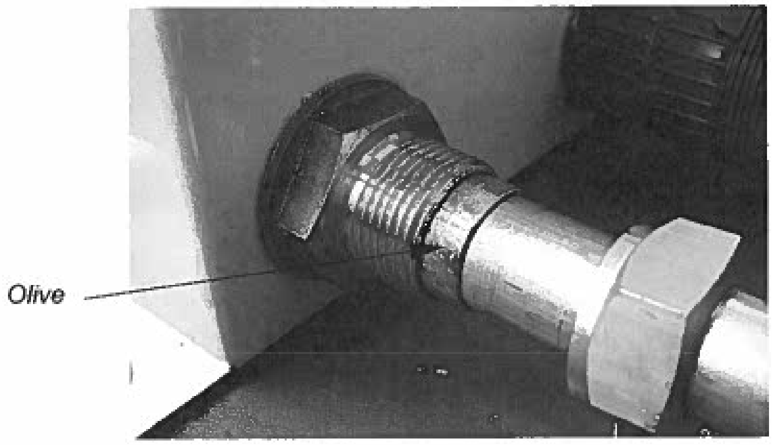


Figure 9 Metal Pipe Fittings

5. Note that the surge tower has a support bracket. Fit the bracket to the top of its support stand (see Figure 10). Leave the fixings loose to allow adjustment to align with the surge tower.

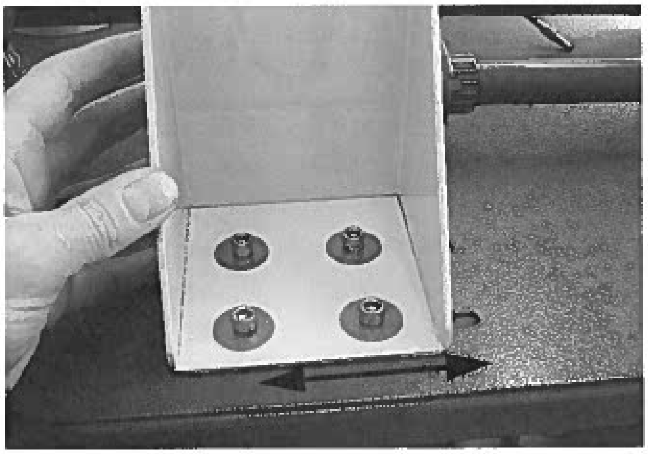


Figure 10 Fit the Bracket of the Surge Tower

6. Fit the bottom of the surge tower to the surge pipe and make sure the clamp of its bracket holds the top of the surge tower. See Figure 11. Tighten the support stand fixings.

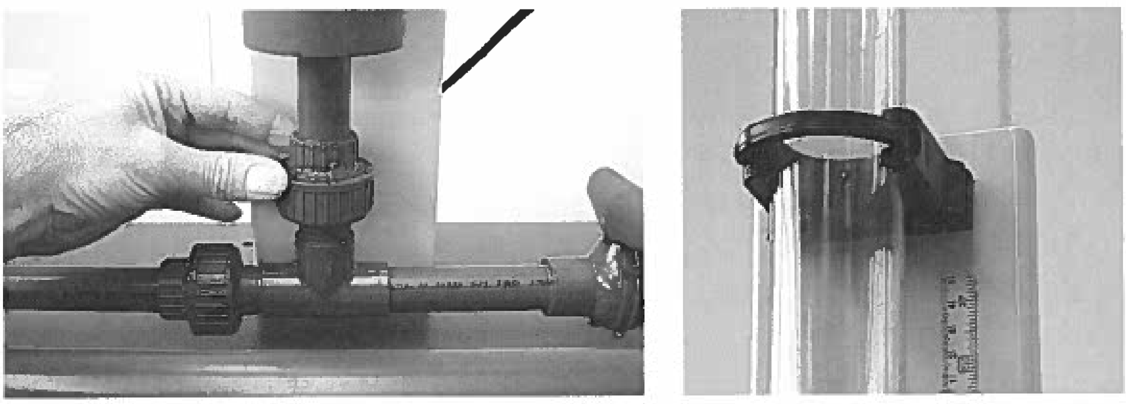


Figure 11 Fit Surge Tower to Surge Pipe and Fix the Clamp

7. Fit the metal water hammer outlet pipe assembly to the underside of the quick-closing valve, so that it faces outwards from the frame (see Figure 12).

Figure 12 Rotate the Water Hammer Outlet Pipe to face Outwards as Shown

8. Put the Hydraulic Bench under the ends of the pipe as shown in Figure 1 and 6.
9. Use the fittings supplied to connect the Hydraulic Bench supply hose to the inlet pipe.
10. Connect the short piece of large diameter tube to the overflow pipe assembly.
11. Fit the two water hammer transducers to their positions on the metal pipe. Make sure they have their sealing rings attached and screw them in carefully by hand. DO NOT USE ANY TOOLS.

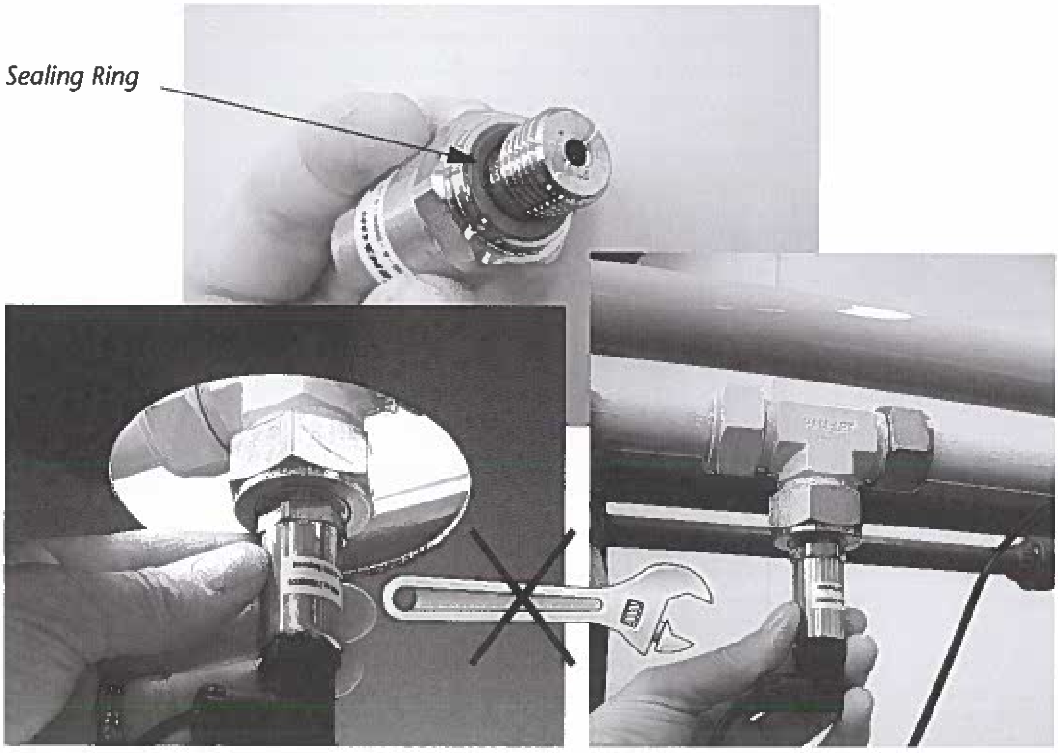


Figure 13 Fit the Transducers

12. Check that all pipes are level and evenly supported. Adjust the frame feet as required.

Note: The level of the equipment can be checked later by shutting the pipe surge and water hammer valves. With the Hydraulic Bench on full flow allow the header tank to reach its maximum level. Now check that the water level in the header tank is the same as that in the surge tower.

13. Run water through the equipment and check for leaks.
14. Fit the lid to the reservoir (see Figure 14).

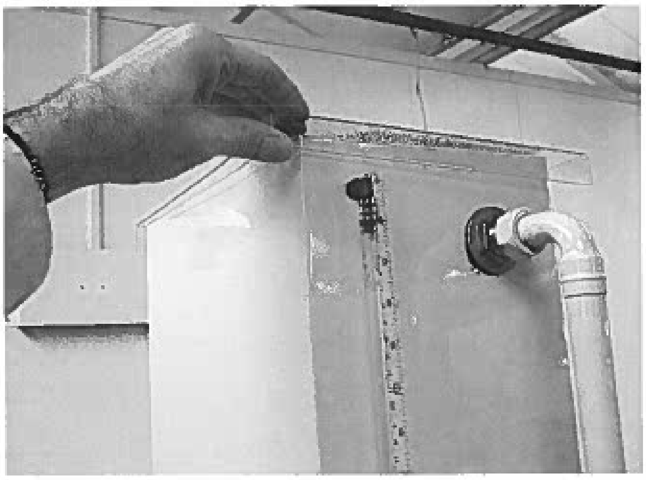


Figure 14 Fit the Lid to the Reservoir

15. Connect and set up VDAS® mkII as shown in Figures 4 or 5.

WARNING *Keep the VDAS® interface and the computer as far away from the Hydraulic Bench as possible (determined by the length of the transducer cables), to avoid any small splashes of water.*

Theory

Notation

Symbol	Meaning	Units
A, A_S and A_P	Cross sectional Area, and of surge tower and supply pipe	m^2
a	Acoustic velocity	m/s or $m.s^{-1}$
D	Diameter	m
E	Elastic Modulus	Pa
F	Force	Newton
f	Frequency of oscillation	Hz
g	Acceleration due to gravity	m/s^2 or $m.s^{-2}$
h	Pressure head of liquid	m (or mm where shown)
h_f	Head loss due to friction	m (or mm where shown)
K and K'	Bulk Modulus and Effective Bulk Modulus	N/m^2 or $N.m^{-2}$
L	Length	m
m	Mass of liquid	kg
$\dot{m}$	Mass flow rate	kg/s or $kg.s^{-1}$
p	Pressure	Pa or N/m^2 or $N.m^{-2}$
Q	Volume Flow	m^3/s (or $l.s^{-1}$ where shown)
R	Area ratio	A_S/A_P
S	A distance	m (or mm where shown)
t	Thickness	m
T	Period of time	s
V	Velocity	m/s or $m.s^{-1}$
ρ	Density	kg/m^3 or $kg.m^{-3}$

Table 2 Notation

Unit Conversions

Pressure

1 bar = 100000 Pa = 100000 $N.m^{-2}$

With water at density 1000 $kg.m^{-3}$, 1 m head (h) of water = 0.1 bar = 10000 Pa = 10000 $N.m^{-2}$

Flow Volume and Velocity

The volume of flow of liquid along a pipe is equal to the product of the flow velocity V and area A of the pipe.

Q = AV so V = Q/A

Pressure Changes in a Simple Pipeline

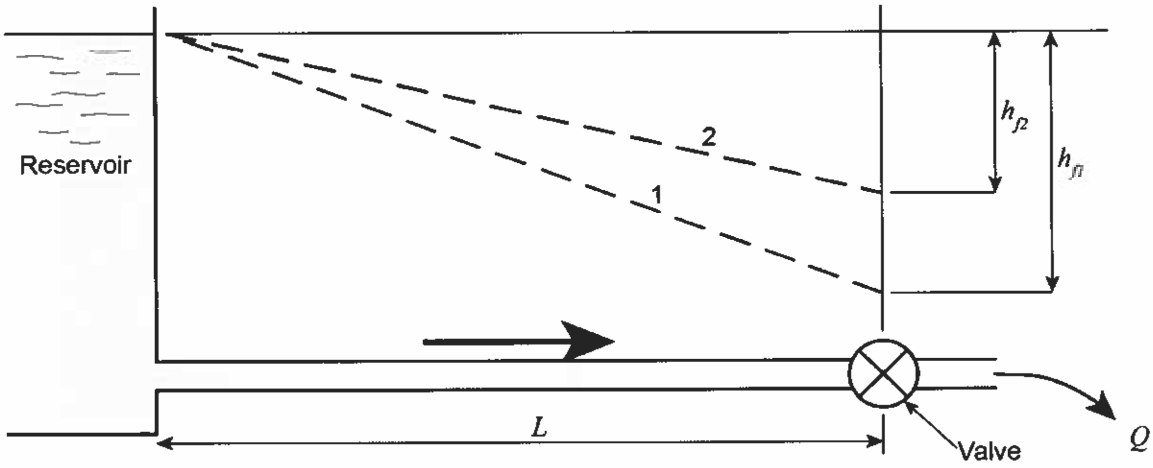


Figure 15 A Simple Pipeline

Consider the uniform pipeline of Figure 15, supplied from a reservoir at a constant level. A valve at the downstream end regulates the flow. For any fixed valve setting which produces flow rate Q_1, the steady-state distribution of pressure along the pipe (usually expressed as piezometric head) is typically as shown by the hydraulic gradient 1. The piezometric head drop due to friction, h_{f1}, depends on the characteristics of the pipe and the valve setting. For some other setting of the valve, giving some other steady flow rate Q_2, the piezometric head drop would have some other value, h_{f2}.

Adjusting the valve changes the flow velocity, which creates pressure changes. If more time is taken to change the valve setting than the time needed for a wave to travel length L of the pipe, then the water contained in the pipeline may be treated as a homogeneous, incompressible whole. The transient behaviour is then referred to as 'surge'. If, however, the same or less time than the transit time of an acoustic wave is taken, the water cannot be regarded as a homogeneous whole. These changes move along the pipe as a pulse and travel at the speed of sound or 'acoustic' velocity. This pulse is called a 'pressure surge'.

We now have to take into account the slight change of density of water which occurs across the pressure wave, and the change in speed of flow caused by passage of the wave. A comparatively small change in flow velocity produces a very high pressure difference across the wave, creating the 'water hammer'.

Pipe surge and water hammer are very important concerns when planning the supply lines of hydropower stations. In these lines, the water may travel for long distances, along a pipeline or tunnel, from the supply reservoir to the water turbine. To cope with variations in electrical demands, the lines have some means of flow regulation, such as variable gates at a turbine inlet. In severe conditions, the electrical load may be suddenly rejected. This means that the electrical generator no longer absorbs and converts the power developed by the turbine. Unless a control system shuts the gates quickly, the turbine and generator could rapidly overspeed, with potentially disastrous results. However, rapid gate closure causes severe deceleration of the large mass of water in the long supply pipeline, with the associated danger of extremely high pressure rise.

Using a Surge Tower

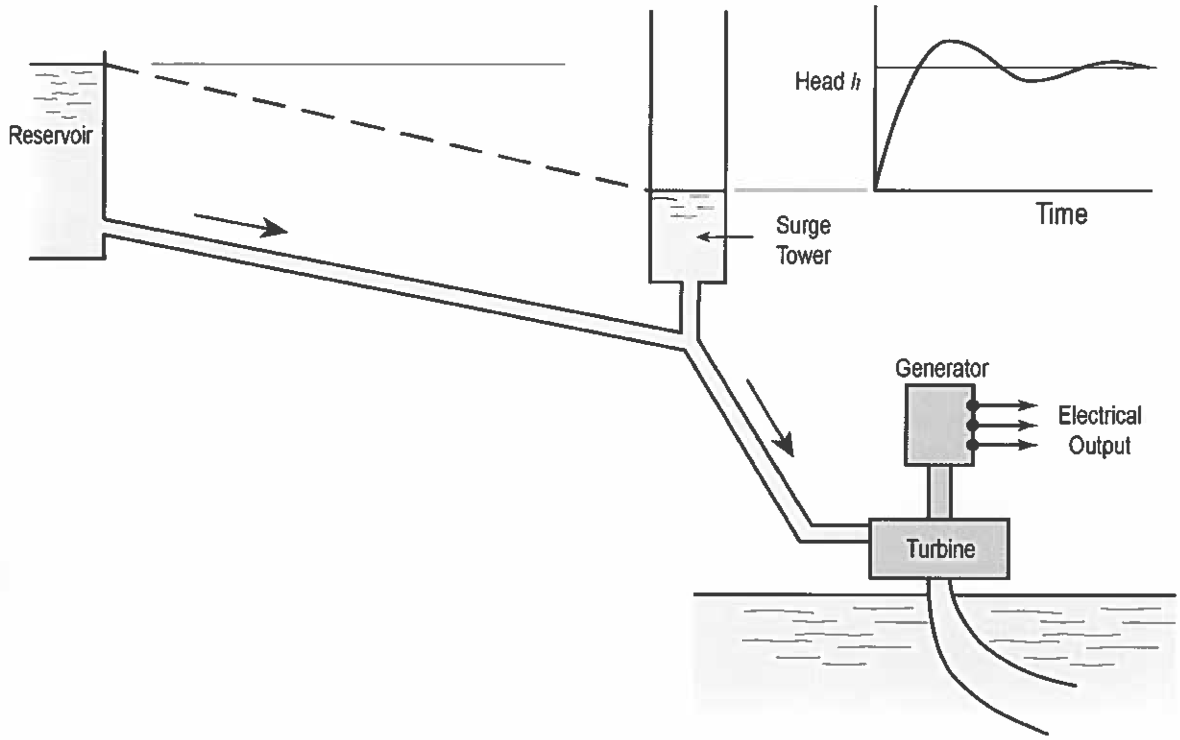


Figure 16 Schematic Arrangement of Water Supply to a Hydropower Station

Figure 16 shows one method of solving the problem of surge - by fitting an open-topped surge tower, as near to the turbine as possible. The short length of pipeline between the surge tower and the turbine is liable to water hammer. It has to be strong enough to withstand this severe condition. The longer length of pipeline between the reservoir and surge tower, however, is subject only to much milder effects. When the turbine gates shut suddenly, water continues to flow from the reservoir along the pipeline, but now enters the surge tower instead of passing to the turbine. The water level in the tank rises steadily, but its rate decreases as the motion decelerates. As shown in Figure 16, this gives a damped oscillation. For a short time the head in the section of the pipeline upstream of the surge tower is slightly greater than that in the supply reservoir. When the turbine restarts, or if demand increases, the water level in the surge tower temporarily drops, while the flow in the long pipeline gradually accelerates.

Note that Figure 16 shows greatly exaggerated differences in water levels between the reservoir and surge tower. Any loss of head between the reservoir and the turbine reduces the overall efficiency of the hydroelectric plant. Therefore, the pipeline is usually proportioned so that, under normal operating conditions, there is only a small loss of overall head.

Pipe Surge - Assuming No Friction

NOTE

Friction in the pipework affects the measured results. The additional theory needed to allow for friction is very complex and needs computer analysis for accurate results. For this reason, this guide only shows the basic theory, which should produce good results with reasonable accuracy.

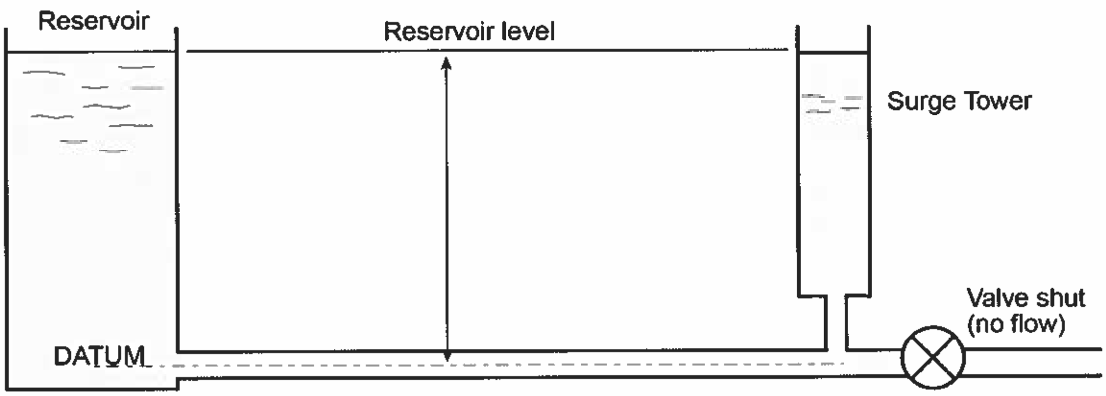


Figure 17 Static State - No Flow

In a static state condition ***with no flow***, the water level in a surge tower should match the level in its supply reservoir (Figure 17).

In a ***steady state condition with flow*** (Figure 18), the level in the surge tower will be lower than that in the reservoir, due to a frictional loss along the supply pipe. The flow in the supply pipe determines the amount of steady state head loss, or 'differential head loss'. A greater flow gives a greater head loss.

More flow = more head loss

Head Loss = Reservoir Level - Steady State Surge Level

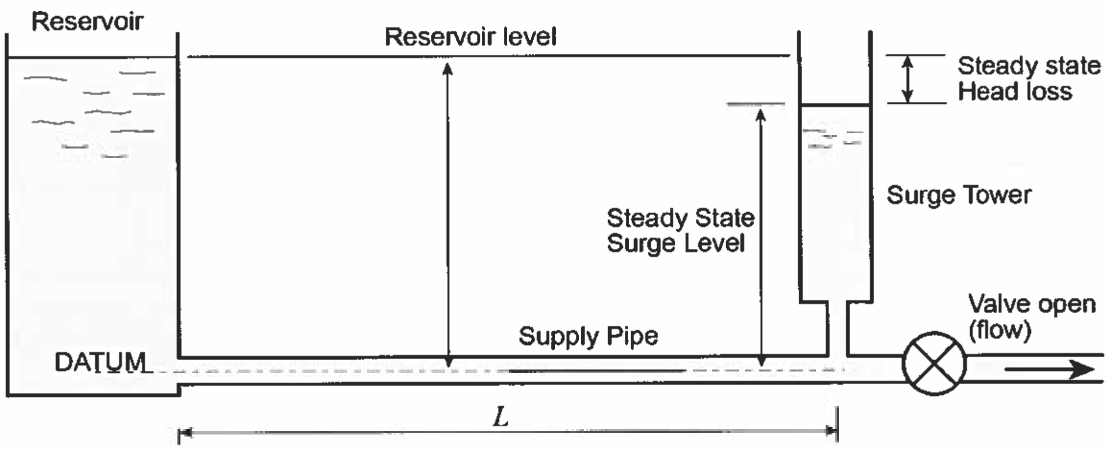


Figure 18 Steady State - with flow

A chart of the steady state head loss against the flow rate at different flow rates should show that the relationship is not linear, giving a curve that obeys a power law with an exponent of approximately 1.75 (see Figure 19). The equation for the chart will then be of the form: $Y = mx^{1.75}$.

NOTE *Refer to textbooks or other TecQuipment products for more detailed theory of pipe friction and differential head loss.*

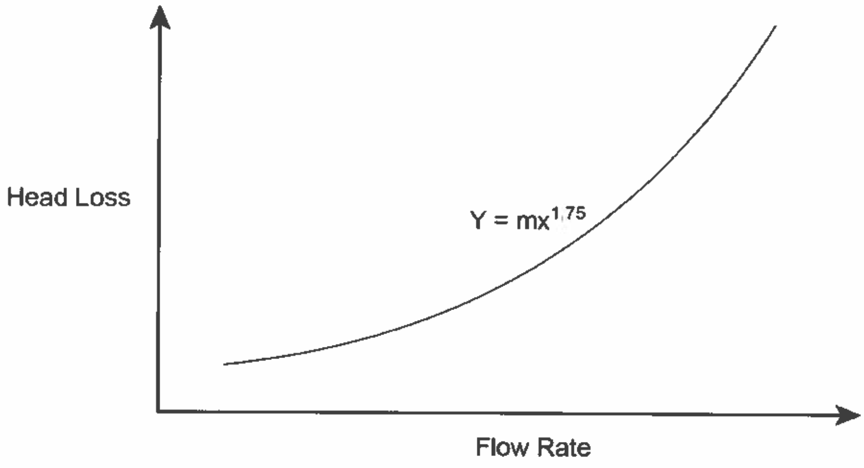


Figure 19 Pipe Friction Chart

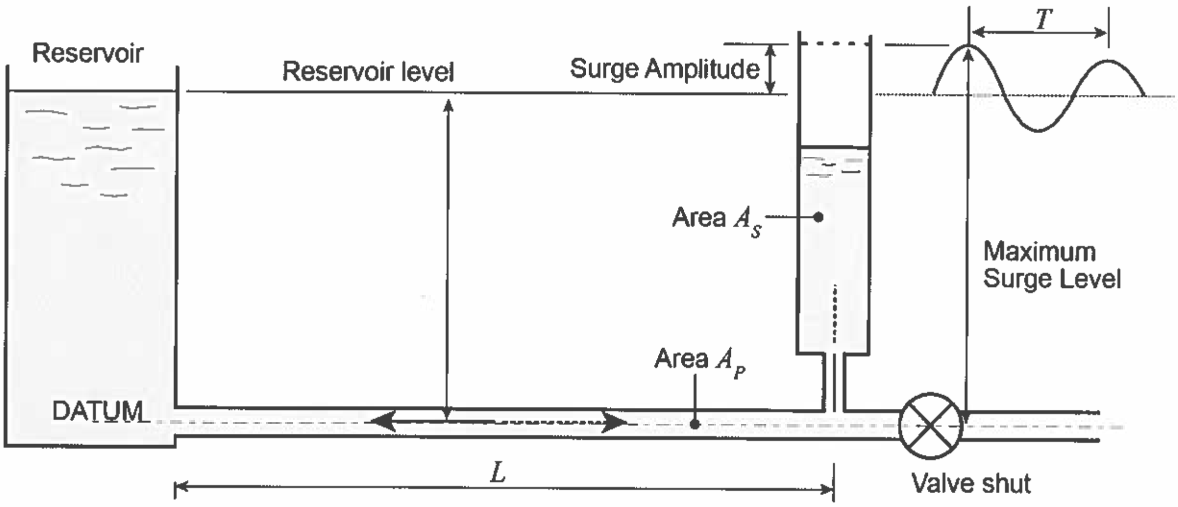


Figure 20 Surge Oscillations

When something happens downstream that causes a complete flow blockage in the surge supply pipe, such as shutting a valve quickly, the initial energy of the flow of water causes the head of water in the surge tower to rise. This is the function of the surge tower - to prevent this sudden energy rise from creating pressure spikes that could damage the system.

The water in the surge tower rises to a new 'maximum surge height level' or amplitude above the reservoir level and determined by the energy in the initial flow (its velocity) before the blockage. A greater initial flow gives a greater surge height.

Higher initial flow rate = higher surge

As the surge height reaches its maximum amplitude, it then transfers back to flow velocity going backwards down the supply pipe towards the reservoir.

Surge Amplitude = Maximum Surge Level - Reservoir Level

The water level in the surge tower then drops to a level below that of the reservoir, so the surge height reaches a minimum value, negative with respect to reservoir level.

The cycle then repeats, causing the surge height to oscillate at a given frequency (f), centred around the reservoir level. This is an example of simple harmonic motion (SHM).

The time period (T) of the oscillations from the area and length of the supply pipe and the surge tower can be calculated,

$$T = 2\pi\sqrt{\frac{LR}{g}} \tag{1}$$

or

$$f = \frac{1}{2\pi}\sqrt{\frac{g}{LR}}$$

Where

$$R = \frac{A_S}{A_P}$$

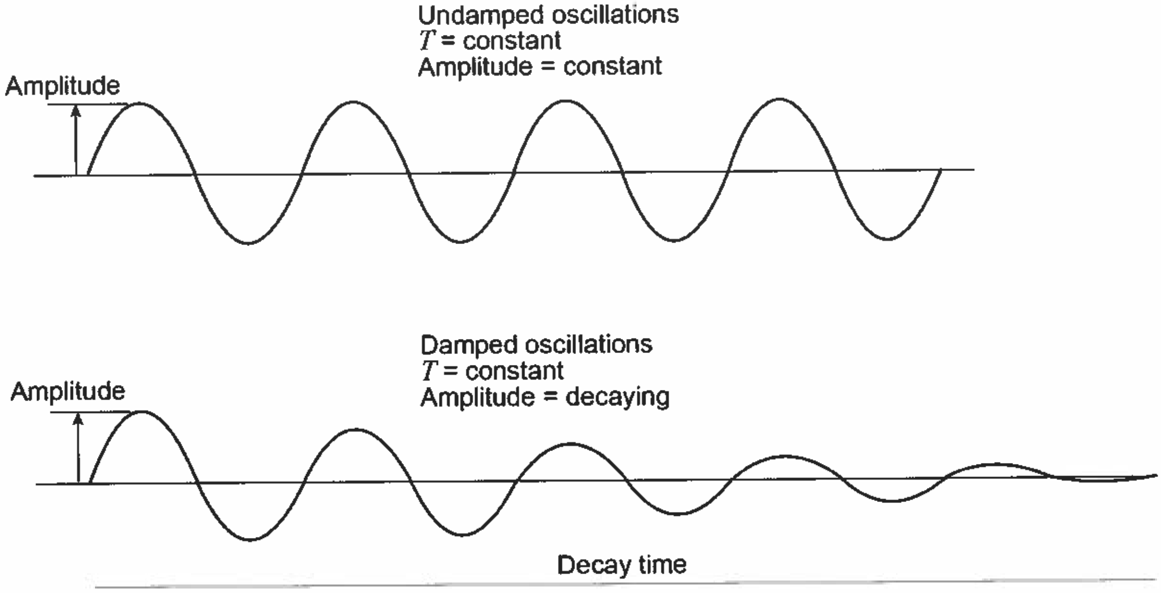


Figure 21 Oscillations

If there where no friction in the pipe system, the oscillation would continue indefinitely at its given frequency, time period and amplitude. However, in a real system the pipe friction causes a 'damping' of the amplitude of the oscillations until they eventual settle back to the reservoir height. This is an example of ***damped oscillations*** (see Figure 21). Note - the friction does not affect the time period T.

So, from this, it can be seen that pipe friction will affect the maximum amplitude of the surge height and how fast the oscillation decays until the system settles back to the reservoir height.

Pipe friction = damping, affecting maximum surge height and decay time

Because the oscillations follow simple harmonic motion, the initial velocity (before the surge) with SHM theory can be used to predict the maximum amplitude of the surge, using:

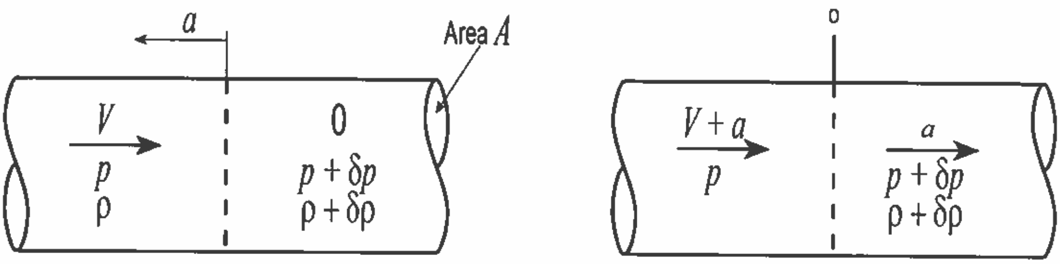
$$Amplitude = V\sqrt{\frac{L}{gR}} \qquad (2)$$

Where amplitude, velocity, length and g are in SI units of metres.

However, this equation will only work accurately for systems with little or no pipe friction.

Water Hammer

As already mentioned, water hammer is generated by the passage of a pressure wave along the pipe. Figure 22(a) shows the wave, travelling upstream at acoustic velocity 'a', generated by sudden closure of the valve at the downstream end of the pipe. Ahead of the wave, the water still flows with undisturbed velocity V, and behind the wave the flow is reduced to rest.



a) As seen by a stationary observer

b) As seen by an observer travelling with the wave

Figure 22 Pressure Wave in a Pipeline

To help understand the motion if it is seen as an observer (O) travelling with the wave, as shown in Figure 22(b). The observer sees flow approaching the wave with speed $V + a$, and leaving it with speed a. Suppose that the pressure rises from p to $p + \delta p$ through the wave and that the increment of pressure increases the density of the water from ρ to $\rho + \delta\rho$. The relationship between pressure increment and density change is expressed in terms of the bulk modulus K of the water as follows:

$$\frac{\delta p}{\delta\rho/\rho} = K \qquad (3)$$

Now the equation of mass continuity across the wave is:

$$\dot{m} = \rho A(V+a) = (\rho + \delta\rho)Aa$$

in which $\dot{m}$ is the mass flow rate.

From this we obtain:

$$\frac{\delta\rho}{\rho} = \frac{V}{a} \qquad (4)$$

Noting that $V \ll a$, the mass flow rate approximates closely to:

$$\dot{m} = \rho A a \qquad (5)$$

Also the momentum equation is:

$$\{p-(p+\delta p)\}A = \dot{m}\{a-(V+a)\}$$

which simplifies to:

$$\delta pA = \dot{m}V$$

Substituting for $\dot{m}$ from Equation 5, this reduces to:

$$\delta p = \rho aV \text{ or } dh = \frac{aV}{g} \qquad (6)$$

Substituting in Equation 3 for $\delta\rho$ from Equation 6 and for $\frac{\delta\rho}{\rho}$ from Equation 4 leads to the result:

$$a = \sqrt{\frac{K}{\rho}} \qquad (7)$$

This gives the acoustic velocity, a, in terms of the physical properties K and ρ of the water. The pressure rise, δp, across the wave may then be found from Equation 6. Note that δp is proportional to the velocity V.

A commonly accepted value of bulk modulus K for water is:

$K = 2.15 \times 10^9$ N.m^{-2}

and for density ρ is:

$$\rho = 1000 \text{ kg.m}^{-3}$$

Substituting these values into Equation 7, the theoretical acoustic velocity is:

$$a = 1470 \text{ m.s}^{-1}$$

From the equipment, the acoustic velocity will be the ratio of the distance travelled from one sensor to the other, divided by the time taken to travel that distance, so

$$a = \text{distance travelled/time taken}$$

From Equation 6 we see that:

$$\delta p = 1000 \times 1470\ V \text{ N.m}^{-2} = 1.47 \times 10^6\ V \text{ N.m}^{-2} = 14.7\ V \text{ bar}$$

$$dh = 150\ V \text{ m water}$$

where V is the velocity in m.s^{-1}.

Note that water hammer can generate extremely high pressure differences, even for a small change in flow velocity. In Equation 6, therefore, the symbols δp and dh are usually replaced by Δp and Δh, showing finite pressure and head increments, rather than small ones.

So:

$$\Delta p = \rho aV \text{ or } \Delta h = \frac{aV}{g} \qquad (8)$$

These high values arise because the ratio of bulk modulus K to density ρ is large, leading to a high acoustic speed. The presence of a few air bubbles in the water would greatly reduce the effective bulk modulus, because of the much greater compressibility of the air. However, the overall density would reduce only slightly. Therefore, the acoustic velocity, and the resulting water hammer pressure, would be greatly reduced. It is therefore important in this experiment to ensure that all air pockets are flushed out of the pipe.

The elasticity of the pipe wall also reduces the effective bulk modulus of the water. It may be shown that the effective bulk modulus K' of water, when contained in a pipe of diameter D and wall thickness t, is given by:

$$\frac{1}{K'} = \frac{1}{K} + \frac{D}{tE} \qquad (9)$$

where E is the Young's modulus of the pipe material. So, for better accuracy in estimating the acoustic velocity, the effective modulus K' should be used in place of K in Equation 7.

So

$$a = \sqrt{\frac{K'}{\rho}} \qquad (10)$$

Comparing Water Hammer and Surge Pressures

The pressure produced by a pipe surge is, in comparison with that produced by water hammer, generally small. For example, consider a 3 m run of pipe along which the flow velocity is V m.s^{-1}. Suppose the motion decelerates uniformly to rest over a period of 0.1 seconds. Then the differential head caused by this deceleration is Δh = 3.1 V m water, which is only about 2% of the effect of water hammer in the same pipe. Note, however, that the pipe length comes into consideration of surge. If the pipe were, say, 3 km long, then the deceleration time would have to be 100 seconds to give the same result.

Experiments

Useful Notes

Two People

TecQuipment recommend that at least two people do to the experiments. One person to use VDAS® and the other to measure flow rate and adjust the valves.

Splashes of Water

This apparatus uses water and may splash some onto the top of the Hydraulic Bench. Be prepared for small splashes of water.

WARNING *Make sure the hands are dry before using VDAS® and the computer.*

Experiment 1 - Pipe Surge

Aims

To compare the measured surge height and oscillation period with theoretical predictions.

Procedure

1. Setup the equipment as shown in Figure 4.
2. Shut the surge valve and the water hammer flow control valve.
3. Fully open the water supply valve on the Hydraulic Bench and start its pump. The Header Tank (reservoir) will fill to its maximum of around 610 mm, which may vary between each product.
4. Note the level on the vertical scale at the Surge Tower. It should be similar to the level at the reservoir (+/- 5 mm). If it is not, then recheck the level of the equipment.
5. In VDAS®, select the H405 layout, then select the Pipe Surge experiment. Check that the Surge Tower and Surge Pipe details in VDAS® are as shown in the Technical Details. If not, then adjust the values in VDAS®.
6. Click on the 'Initiate Communications with Device' toolbar button. Check that the channel 1 trace of VDAS® indicates a similar value as that shown on the scale next to the surge tower (+/- 10 mm).

NOTE *The scale next to the Surge Tower is not calibrated and only for guidance. Use the value shown in VDAS® for the results and calculations.*

The surge sensor is around 225 mm above the centreline datum of the surge pipe, so it cannot measure the full height of water in the surge tower. However, when selecting the pipe surge experiment, VDAS® channel 1 allows for this and automatically adds this value to the trace.

7. In VDAS® click on the 'Terminate Communications with Device' toolbar button

8. Carefully open the Surge Valve, allowing a small flow to pass along the Surge Pipe into the measuring tank of the Hydraulic Bench. Adjust the Surge Valve until the Surge Tower water level becomes steady at roughly 550 mm as shown on its scale. This is the 'Steady State Surge Level' and should be lower than the 'Reservoir Level'.
9. Allow up to a minute for the flow to stabilise and recheck the Steady State Surge Level remains at roughly 550 mm.
10. Use the Hydraulic Bench to measure the volume flow rate leaving the end of the surge supply pipe.
11. In VDAS®, click on the 'Initiate Communications with Device' toolbar button and enter the Volume Flow Rate, Reservoir Level and Steady State Surge Level shown on the channel 1 trace.
12. Hover the mouse cursor over the trace or use the vertical cursors to measure this value.

    VDAS® automatically calculates the flow velocity and subtracts the Steady State Surge Level from the Reservoir Level to find the head loss along the supply pipe at each flow rate.
13. Shut the surge valve as quickly as possible. VDAS® will show the oscillations.
14. In VDAS®, wait at least 90 seconds for the oscillations to reduce to zero. The flow has stopped so the surge level should return to the same value as the reservoir noted in step 4.
15. Press the 'Terminate Communications with Device' toolbar button.
16. A trace similar to that shown in Figure 24 should be seen. If necessary, use the Scroll Bar under the Trace Window to see the complete decaying waveform as in Figure 23.
17. Use the cursors in VDAS® to measure the Period and Maximum Surge Height of the trace. Enter these values into VDAS® and record the data.

    VDAS® automatically subtracts the Reservoir Level from the Maximum Surge Height, giving the Surge Amplitude.
18. Click on the damping model tool button and select the underdamped model. Click on the 'Fit Data' button. VDAS® will fit the trace to a viscous damping model, confirming that the damping caused by the pipe friction is similar to that created by viscous damping.

NOTE

For correct damping calculations, the VDAS® software trace window needs to show a complete and valid set of oscillations. See the notes in the VDAS® damping model fitting dialogue box.

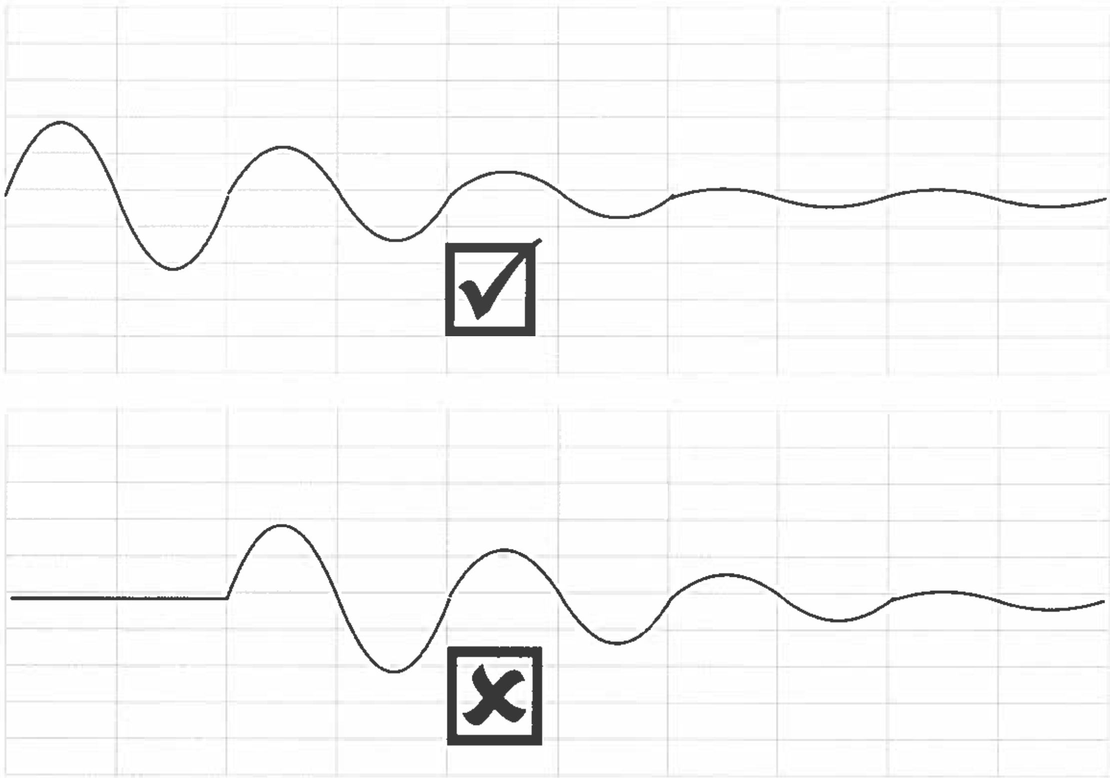


Figure 23 Good and Bad examples of Oscillation Traces

19. Repeat the experiment with progressively lower Steady State Surge Levels of roughly 500 mm, 450 mm, 400 mm, 350 mm and 300 mm.

20. After use, turn off and disconnect all electrical and water supplies. Open all the valves to drain out any water from the apparatus.

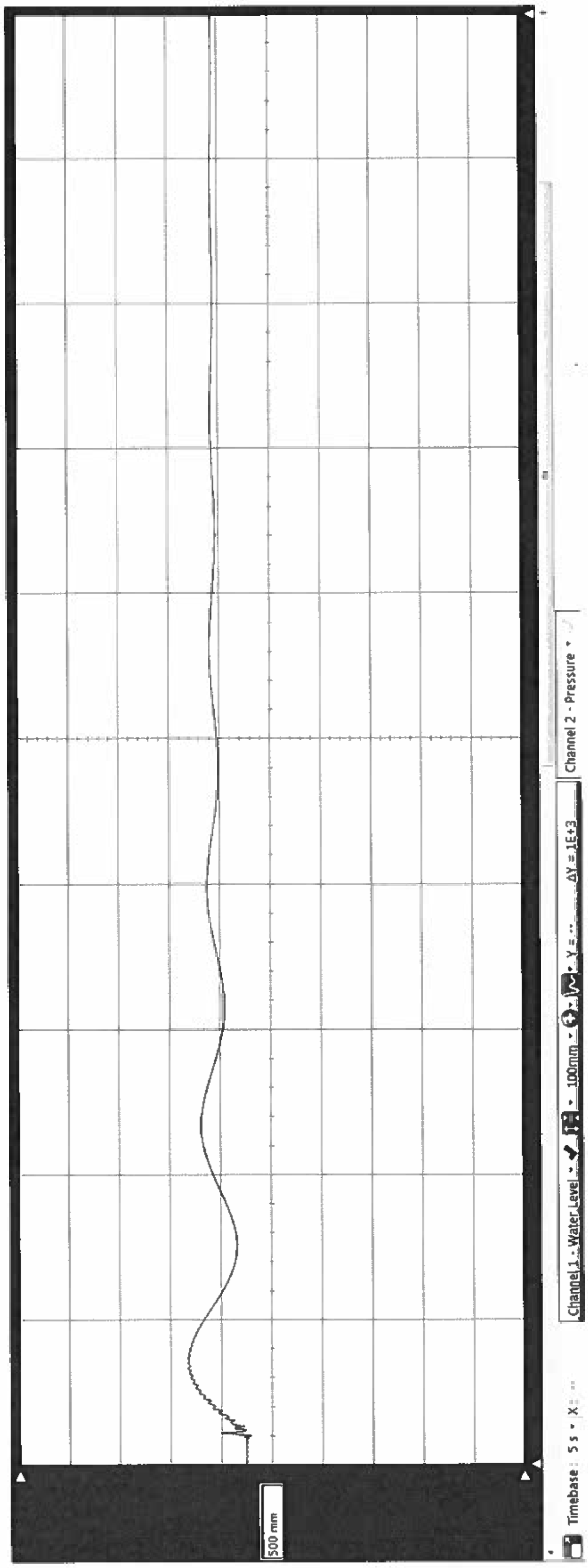


Figure 24 A Typical VDAS® Pipe Surge Trace

Results Analysis

Create a chart of head loss (vertical axis) against volume flow rate to see the effect of the pipe friction. If possible, calculate the equation of the curve and compare it with the curve shown in the theory.

Compare the theoretical time period with the measured time period. Compare the results at the highest and lowest flow rates to see that flow rate or steady state surge level has no effect on the period.

VDAS® uses measured flow velocity to calculate the theoretical frictionless surge amplitude for each set of results.

Create a chart of surge amplitude (vertical axis) against volume flow. Add both the theoretical and measured results for comparison and comment on the differences.

Experiment 2 - Water Hammer

Aims

To compare the measured amplitude of pressure with theoretical predictions.

To calculate the speed of the pressure surge along the pipe.

Procedure

1. Setup the equipment as shown in Figure 5.
2. Shut the surge valve and the water hammer flow control valve.
3. Fully open the water supply valve on the Hydraulic Bench and start its pump to fill the reservoir to its maximum height of approximately 610 mm.
4. Insert the valve rest tool to keep the quick-closing valve open.
5. Shut the water hammer flow control valve.
6. Undo the thumbscrew on the quick-closing valve a few turns to allow a few drops of water to pass out. This helps to bleed any traces of air from the valve (see Figure 25). Any small air pockets will provide a pressure cushion which will produce lower pressures, so they must be removed for best results. Re-tighten the thumbscrew.

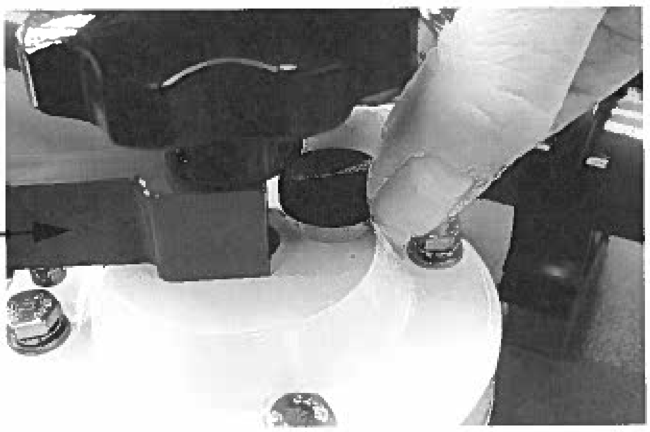


Figure 25 Use the Thumbscrew to Bleed The Water Hammer Quick-closing Valve

7. Fully open the water hammer control valve to give maximum flow.
8. Use the Hydraulic Bench to measure the flow rate from the water hammer pipe.
9. In VDAS®, click on the 'Initiate Communications with Device' toolbar button and enter the Volume Flow Rate. Also check that the pipe details match those shown in the Technical Details. If not, adjust the values in VDAS®.
10. While holding the quick-closing valve up, remove the resting tool.
11. Quickly press down plunger on the top of the quick-closing valve. The water in the pipe will make a hammer noise. VDAS® will capture the trace and show a small box saying that sampling has stopped. Click 'OK'. The trace will show the passage of the acoustic wave past each of the pressure transducers.

12. Figure 26 shows a typical trace. If the the trace is completely different, restart VDAS®, hold the quick-closing valve up for roughly 5 to 10 seconds, then press it down again.

13. Use the cursors in VDAS® to measure the time between the rising edges of the traces of channel 1 and 2 to see the time taken for the pressure to move from one transducer to the other. Enter this value into VDAS®.

    VDAS® automatically calculates:

    - The acoustic velocity using the measured time and distance between sensors.
    - The flow velocity using the water hammer pipe diameter and the volume flow rate.
    - The theoretical pressure amplitude using the theoretical acoustic velocity and water at a density of 1000 $kg.m^{-3}$.

14. After use, turn off and disconnect all electrical and water supplies. Open all the valves to drain out any water from the apparatus.

Results Analysis

Compare the theoretical and measured acoustic velocity and pressure amplitude.

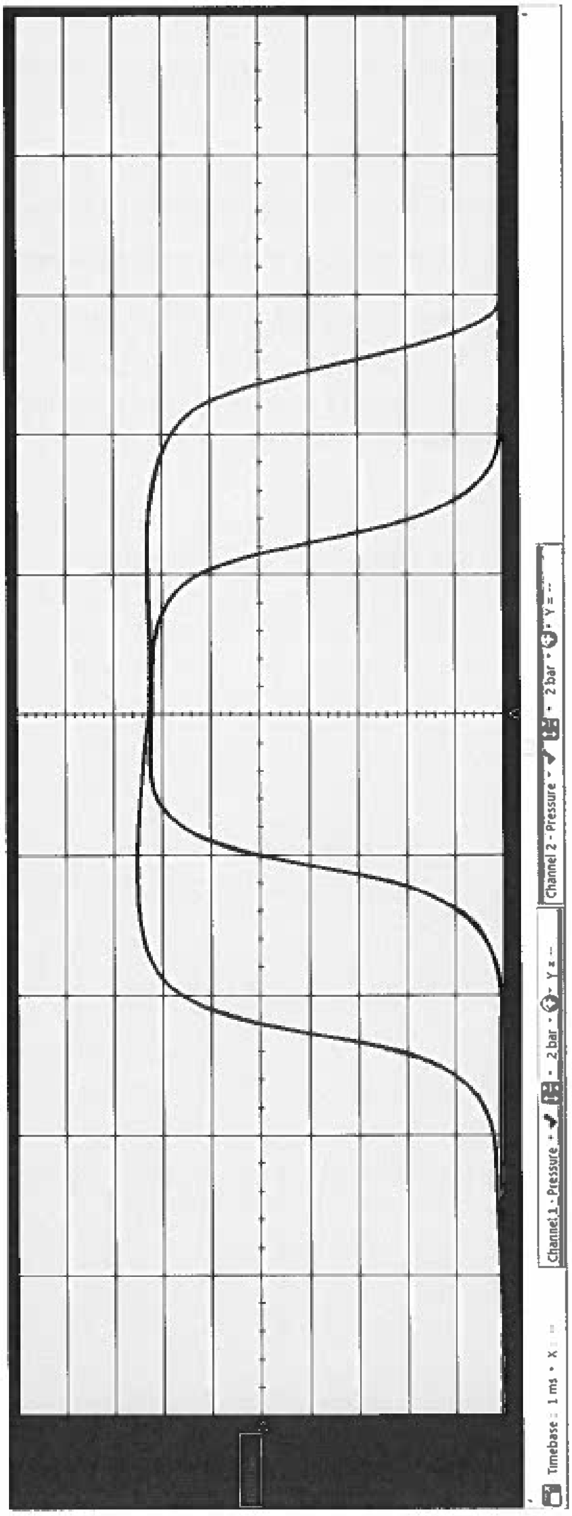


Figure 26 Typical Water Hammer Trace

Typical Results

All results are for reference only. Actual results may differ slightly.

Experiment 1 - Pipe Surge

Surge Pipe Cross-sectional Area A_P: 0.350 x 10^{-3} m^2 Surge Tower Cross-sectional Area A_S: 1.555 x 10^{-3} m^2 A_S/A_P: 4.44285 Surge Pipe Length L: 3 m									
Steady State Surge Level (mm)	Reservoir Level (mm)	Head loss (mm) (Reservoir Level - Surge Level)	Volumetric Flow Rate ($l.s^{-1}$)	Flow Velocity ($m.s^{-1}$)	Maximum Surge Height (mm)	Measured Amplitude (m) (Maximum Surge Height-Reservoir Height)	Measured Period (s)	Theoretical Period (s)	Theoretical Frictionless Amplitude (m)
547	600	53	0.138	0.395	667	0.067	8.12	7.33	0.104
504	592	88	0.188	0.538	667	0.075	8.04	7.33	0.141
447	575	128	0.243	0.695	667	0.092	8.16	7.33	0.183
402	572	170	0.277	0.791	667	0.095	8.28	7.33	0.208
348	565	217	0.320	0.914	667	0.102	8.16	7.33	0.240
306	562	256	0.350	1.000	667	0.105	8.16	7.33	0.263

Table 1 Typical Results

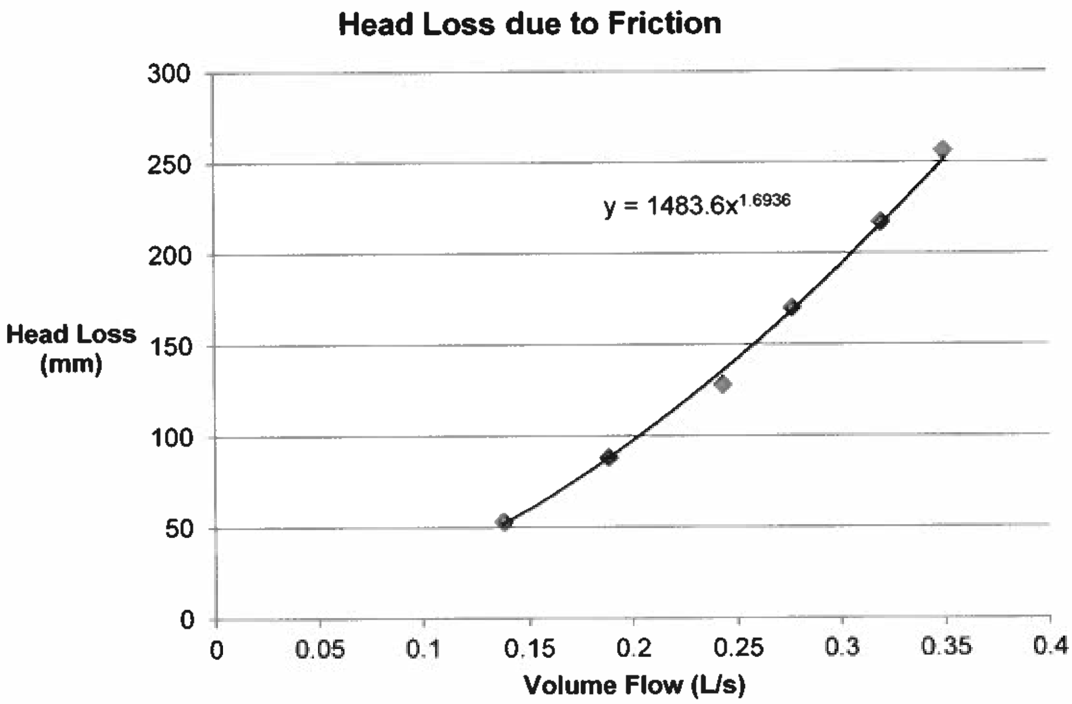


Figure 27 Typical Results

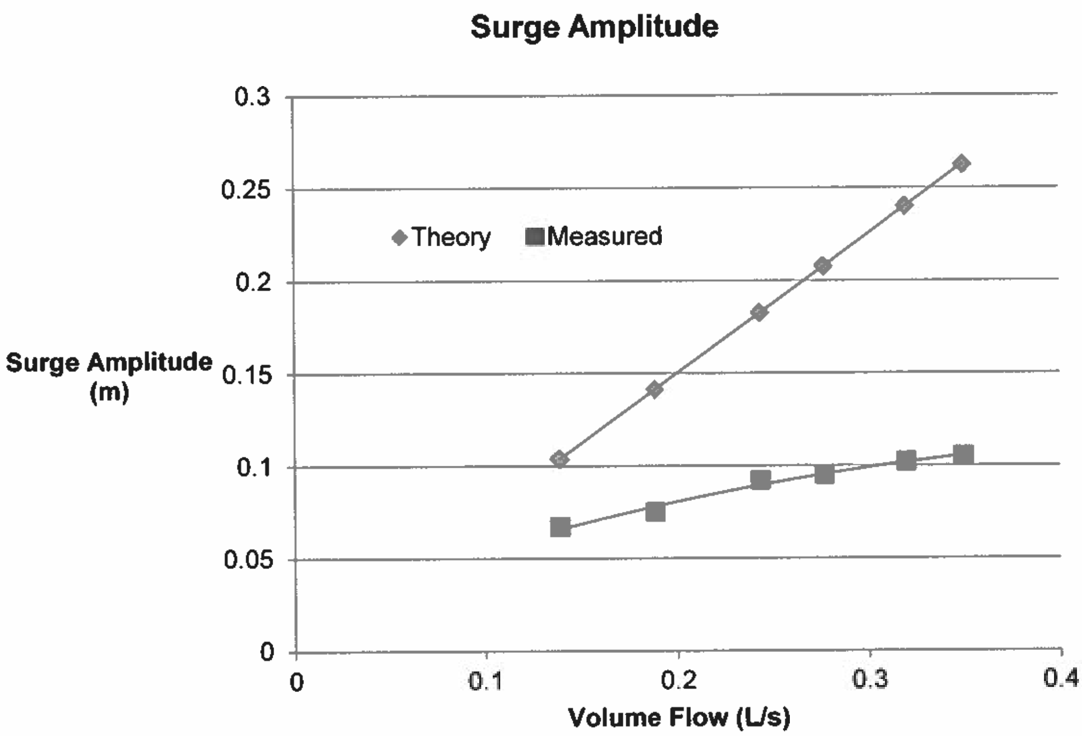


Figure 28 Typical Results

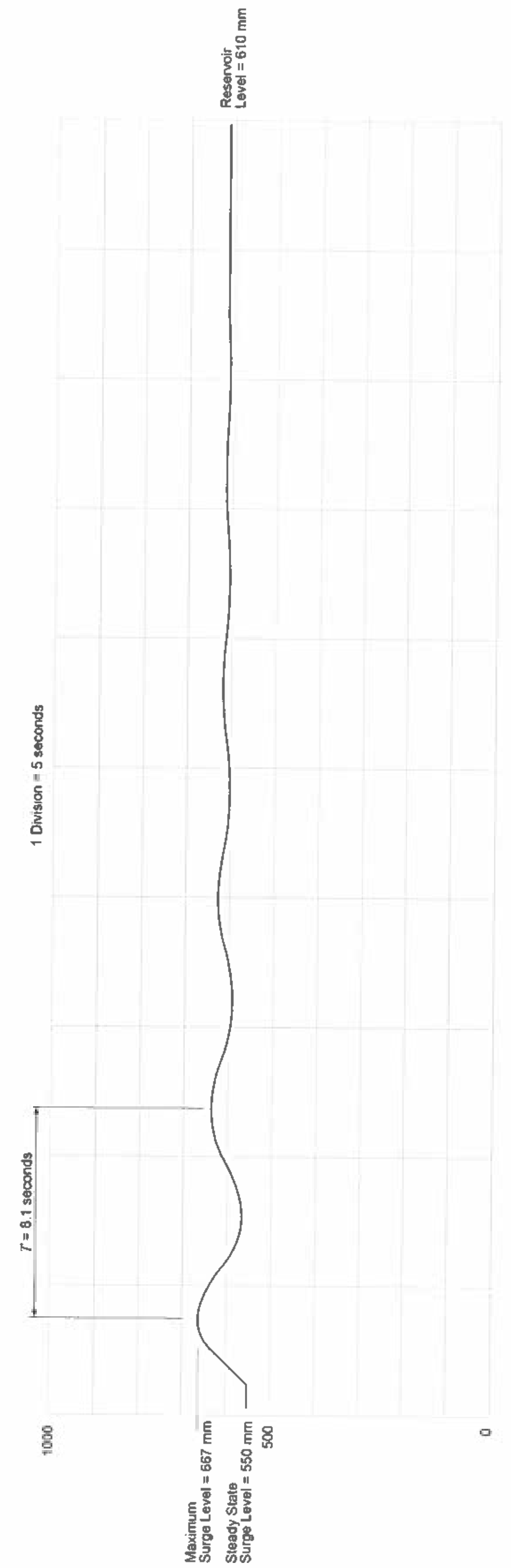


Figure 29 Typical Results

Typical time period calculation:

$$T = 2\pi\sqrt{\frac{LR}{g}}$$

$$R = A_S/A_P = 0.001553/0.000349 = 4.45$$

$$L = 3\ m$$

$$T = 2\pi\sqrt{\frac{3 \times 4.45}{9.81}} \quad so\ T = 7.33$$

Typical theoretical amplitude calculation:

$$= V\sqrt{\frac{L}{gR}}$$

$$V = 0.395\ m.s^{-1}$$

$$= 0.395\sqrt{\frac{3}{9.81 \times 4.45}} \quad = 0.103\ m$$

Conclusions

When the outlet valve from the surge pipe is suddenly shut, the water level in the surge tower moves up and down with a damped oscillation. The maximum amplitude depends on the flow velocity up to a certain point. The physical properties of the system limit the amplitude so that it can only ever reach a certain level once the flow has reached a given value. Flow rates above this value have no effect on surge amplitude, shown as a levelling out of measured amplitude.

The theoretical surge amplitude is based on an ideal frictionless system, so it continues upwards linearly. The actual amplitude is subject to the pipe friction, so the difference between theory and actual results becomes greater with flow due to the power law of the pipe friction.

The head loss due to friction chart shows a power of 1.69 which is acceptably near to 1.75, proving the power law of pipe friction.

The pipe friction causes a rapid damping of the oscillations, so that the surge tower level returns to the reservoir height within a few seconds (less than one minute) of the initial surge conditions.

The calculated time period of oscillation should agree well with the measured time period and should prove that flow or surge height does not affect period.

Experiment 2 - Water Hammer

Theoretical Calculation of Acoustic Velocity

Nominal bulk modulus of water, $K = 2.15 \times 10^9$ N.m^{-2}

D = 22.2 mm (0.0222 m)

t = 1.6 mm (0.0016 m)

A = 0.387 x 10-3 m^2

E = 103 GPa = 103 x 10^9 N.m^{-2}

$$\text{Effective bulk modulus } K'\text{:} \quad \frac{1}{K'} = \frac{1}{K} + \frac{D}{tE} \text{ so}$$

$$\frac{1}{K'} = \left\{\frac{1}{2.15 \times 10^9} + \frac{0.0222}{0.0016 \times 103 \times 10^9}\right\}$$

$$\frac{1}{K'} = 4.65x10^{-10} + 0.0222/164800000 = 6 \times 10^{-10}$$

$$K' = 1.67 \times 10^9 \ N.m^{-2}$$

$$\text{Acoustic velocity: } a = \sqrt{\frac{K'}{\rho}} = \sqrt{\left(\frac{1.67 \times 10^9}{1000}\right)}$$

$$a = 1290 \ m.s^{-1}$$

Measured Acoustic Velocity

a = distance travelled/time = 1.5 m/1.2 ms = 1250 m.s^{-1}

Theoretical calculation of Pressure Amplitude

Pressure rise across wave: $\Delta p = \rho a V$

Assuming water density at 1000 kg.m^{-3}, then $\Delta p = 1000 \times 1290 \times V$

$\Delta p = 1.29 \times 10^6 \times V$ N.m^{-2} = 12.9 V bar

Volume flow rate = 0.458 l.s^{-1} or Q = 0.000458 m^3.s^{-1}

Initial velocity, $V = \frac{Q}{A} = \frac{0.000458}{0.000387}$ = 1.18 m.s^{-1}

Theoretical pressure rise, Δp = 12.9 x 1.18 = 15.2 bar

Measured Pressure Amplitude

(Figure 30) shows typical pressure traces. They show a time delay between the two pressure transducers of approximately 1.2 ms. They show a maximum pressure recorded at the first transducer of approximately 15 bar, and around 14.5 bar at the second.

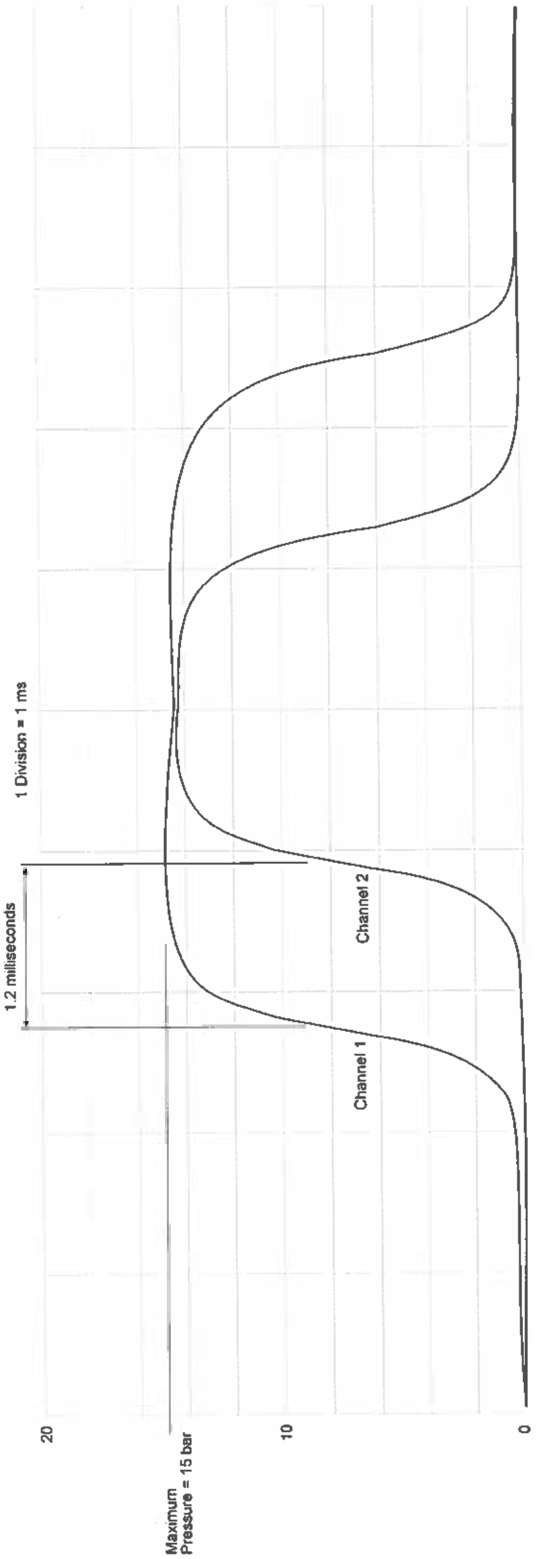


Figure 30 Water Hammer Pressure Traces

Conclusions

The experiment on water hammer confirms that sudden closures at the pipe exit generate high pressures. The transit time of the pressure wave over the distance between transducers indicates a measured acoustic velocity similar to the theoretical value. The measured maximum pressure rise is slightly less than the theoretical value, but some frictional pressure losses around the pipe and the transducer fittings can be expected.

The maximum pressure recorded by the channel 1 sensor (nearest the quick-closing valve) remains for around 3 ms. During this time, the pressure wave travels upstream to the pipe inlet, and a reflected wave, which releases the pressure, moves back down the pipe, arriving just under 5 ms after the first onset of the pressure pulse.

Further Work

The simple analysis as shown ignores the various physical properties of the system, especially pipe friction. Using the measured head loss, students can use more advanced methods to analyse the system to predict the amplitude of the damped surge oscillations.

Maintenance, Spare Parts and Customer Care

Maintenance

Regularly check all parts of the apparatus for damage, renew if necessary.

When not in use, store the apparatus in a dry, dust-free area, covered with a plastic sheet. If the apparatus becomes dirty, wipe the surfaces with a damp, clean cloth. Do not use abrasive cleaners.

Regularly check all fixings and fastenings for tightness, adjust where necessary.

NOTE *Renew faulty or damaged parts with an equivalent item of the same type or rating.*

Spare Parts

Check the Packing Contents List to see what spare parts we send with the apparatus.

If technical help or spares are needed, please contact the local TecQuipment agent, or contact TecQuipment direct.

When asking for spares, please tell us:

- Contact name
- The full name and address of the college, company or institution
- Contact email address
- The TecQuipment product name and product reference
- The TecQuipment part number (if known)
- The serial number
- The year it was bought (if known)

Please give us as much detail as possible about the parts needed and check the details carefully before contacting us.

If the product is out of warranty, TecQuipment will advise the price of the spare parts for confirmation.

Customer Care

We hope our products and manuals are liked. If there are any questions, please contact our Customer Care department:

Telephone: +44 115 954 0155

Fax: +44 115 973 1520

Email: **customer.care@tecquipment.com**

For information about all TecQuipment products visit: **www.tecquipment.com**