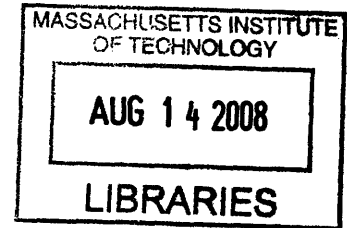


Physically Modeling and Mathematically Simulating
Pressure Transients in Transfer Lines

by

Matthew S. Humbert



SUBMITTED TO THE DEPARTMENT OF MECHANICAL ENGINEERING IN
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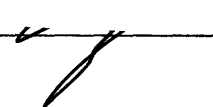
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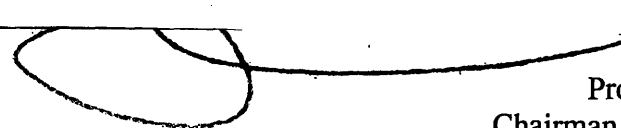
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Matthew S. Humbert

Submitted to the Department of Mechanical Engineering
on May 9, 2008 in partial fulfillment of the
requirements for the Degree of Bachelor of Science in
Mechanical Engineering

Abstract

Characterizing transient flow is not a trivial venture. It provides an excellent challenge for a senior mechanical engineering lab class. This project aimed at developing a new physical system for such a class based on the benefits and short comings of the previously used physical system.

A physical system was developed to vary key parameters, such as run length and pipe diameter. Pipe diameter was previously not a variable parameter. The physical system was designed to help the operator's intuition in developing a mathematical model for said system. The design incorporated solenoid valves and clear pipe. In contrast to the previous system that used ball valves and copper pipe. These features were chosen so that those using the system could neglect human error and visually inspect the flow. The system was designed to increase variation between runs so that a more robust model could be developed. The flexibility of the physical system allows for the examination of more complex flows than the previous system.

The mathematical model that was developed characterized the flow reasonably well. The unsteady Bernoulli equation was implemented with major and minor losses. The model revealed several aspects of the physical system that were not immediately obvious from the data. The unpredicted aspects of the physical system were the fluctuation in tank pressure over the test duration and the correlation between tank pressure and the loss coefficient of the main solenoid valve. The higher the pressure the lower the loss coefficient across the valve. The mathematical model did not account for losses that increase as the water air interface moves through different fittings. This was a major shortcoming of the mathematical model that was developed.

Thesis Supervisor: Douglas P. Hart
Title: Professor of Mechanical Engineering

Introduction

Surge flow and pressure transients can appear in many pipe systems and should be a consideration in the design of such a system. The specific situation that was modeled in this project is that of a transfer line. The physical concept of the transfer line is a high pressure tank with a drain valve that has a run of pipe connecting it to a drain or low pressure tank that has an inlet valve. A schematic of the system is presented in Figure #1.

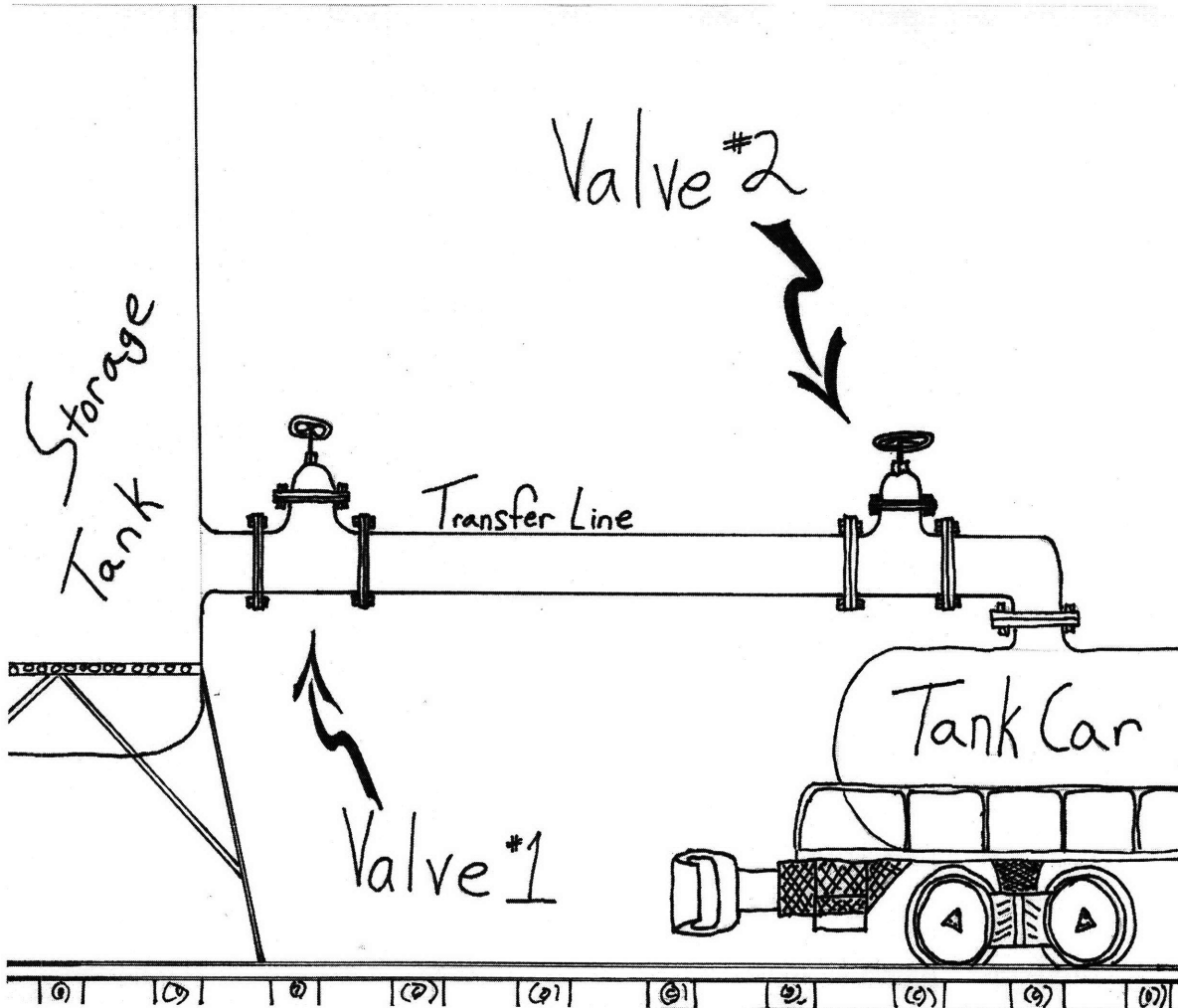


Figure #1: This is a schematic of a pipe system that will exhibit a transient response when valve #2 is opened before valve #1. The storage tank represents the liquid in a high pressure state. While the tank car represents a low pressure side.

The goals of the this project were to physically and mathematically model pressure transients in pipe systems resembling those of Figure #1 for a mechanical engineering lab class. There had been a previous version of this system that was used for the class. The original only used one diameter pipe and had only two different lengths of run. The goal of the new model was to expand the run section of the model while simplifying the less critical aspects of the high pressure and low pressure ends.

There were several design issues that needed to be considered to build a physical model of a transient response system. The main parameters that were difficult to vary in the previous model were run length and pipe diameter. To accomplish wider variation of these parameters while maintaining a relatively small footprint for the setup a common supply and drain manifold system was chosen as the base design. Figure two shows the new system. What is not shown is the high pressure tank and it's associated valving.

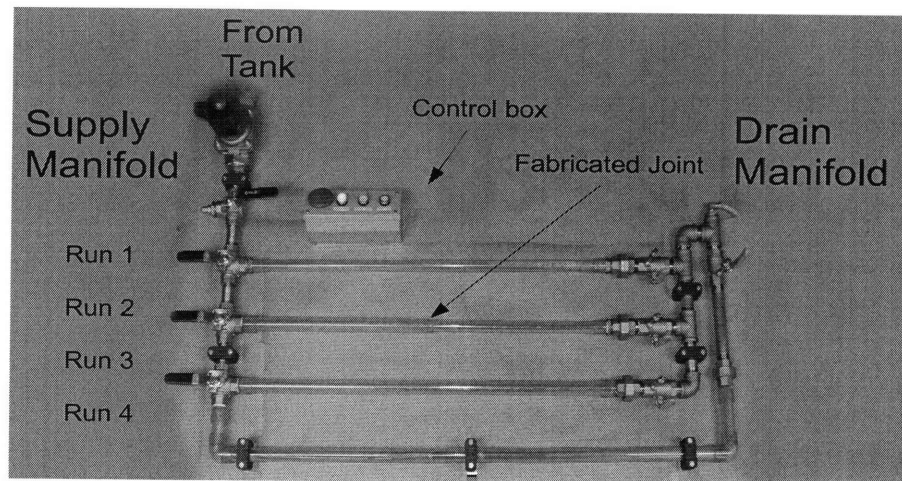


Figure #2: A photo of the new system. The high pressure supply and drain are marked as well as the control box for regulating the high pressure tank. The custom fabricated joint is also indicated.

The previous system was shaped like a "U". There was a valve and pressure sensor located at the bottom of the "U" with the inlet at one leg and another valve and pressure sensor at the other. To use the long run the valve at the bottom of the "U" was left open. To use the short run this valve was closed and the pressure measurements were taken at that valve. The previous system was made completely out of copper pipe, inhibiting the user from directly observing the flow. While the previous system produced good data, the new system is a better learning tool. The new system allows for more varied data collection and should allow the user to characterize the flow more easily by focusing on the more important aspects of the system.

Physical System Supply Manifold

The main component of the physical system is the inlet manifold. The supply manifold controls how the system operates. There are three main components of the supply manifold. They are the initiating solenoid valve, the air water selector valve, and the run selector valves. Each component was chosen based on its flow characteristics. Figure three shows the supply manifold.

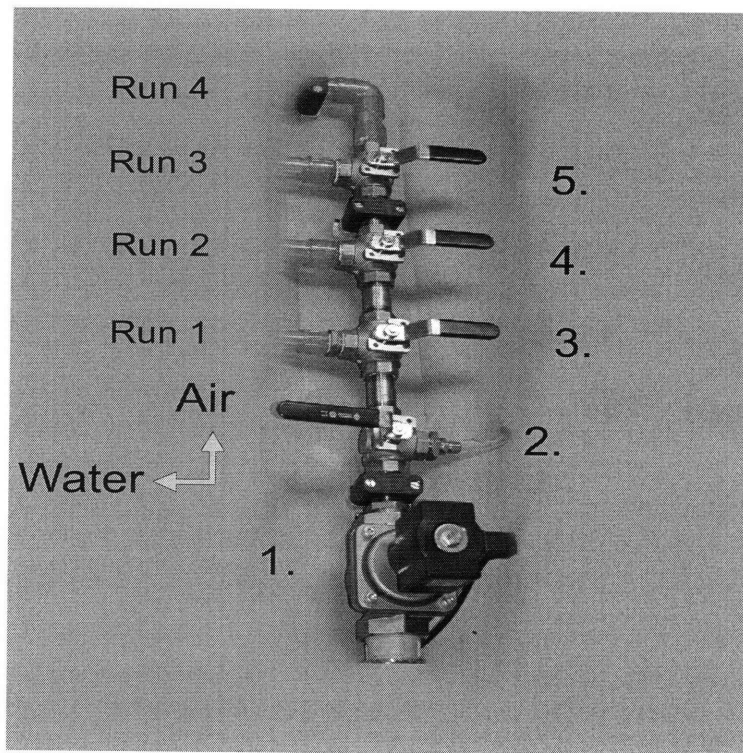


Figure #3: The supply manifold. This picture shows;

1. The main solenoid valve
2. The air water selector valve with arrows indicating which position is air and which is water.
3. Run 1 selector valve
4. Run 2 selector valve
5. Run 3 and 4 selector valve

The main solenoid valve is the backbone of the system. It is what will start the water flow through the run. Solenoid valves by design, have rather torturous flow patterns. They are rather similar to globe valves. In order to reduce the amount of loss across the solenoid valve in this system the largest diameter solenoid valve that was available was used. This valve was characterized by a coefficient of volume of 55.2 gallons per minute at 1psi difference across the valve with a fluid at 60°F that has a specific gravity of 1. This number represents an inverse of the standard loss coefficient for a valve. The actual loss coefficient will be calculated in the mathematical model section. When choosing the valve for this project the larger valves had higher coefficient's of volume but increased pipe size lead to increased total size. The largest practical valve was a two inch piston acting valve.

Another requirement of the main solenoid valve was that it shut even when there was no pressure differential across it. The zero pressure differential requirement stems from the operating conditions of the system. The main solenoid valve will be opened, the transient will be recorded and the solenoid valve released. The pressure differential when the main solenoid valve is released will thus be zero across the valve.

The main solenoid valve was also chosen to be actuated by 120VAC or wall voltage. Wall voltage was chosen to actuate all the solenoid valves because it doesn't require an additional transformer. Piston acting valves were chosen as the preferred actuation method because it was thought to be faster acting than indirect acting valves. There was no speed specifications on the manufacturers supplied data. Actuation speed was taking into consideration because in the ideal system the valve is open instantly. This will be discussed more in the mathematical model section.

The second most important valve to the system is the air water selector valve. The intake manifold has four, three-way, "T" flow selector valves. The first of which, down stream from the main solenoid valve, is the water air selector valve. This valve will determine if the runs will get air or water. In one orientation this valve will supply the manifold with pressurized air, for purging or calibrating the sensor. In this valves second orientation it will provide a straight path for the water coming from the main solenoid valve to flow through to get to the intake manifold. The pressurized air is connected directly to the valve so that when the selector valve is in the air-to-manifold position the air will be flowing into the manifold. Because the main solenoid valve is upstream from the air-water selector valve the system will be at atmospheric pressure when the drain is open and the water-air selector valve is in the water position.

Further down the intake manifold, after the air-water selector valve, are the run selector valves. There are three of them that select between four different runs. In their normal orientation they allow flow to pass through them down the manifold. The valve is in it's normal orientation when the handle is perpendicular to the manifold. When the handle is parallel to the

manifold the valve will direct the flow out of the manifold, down the run that that selector valve is attached to. The handles needed to be shortened after installation so that they wouldn't interfere with each other. They were shortened by approximately two inches. Only one run can be selected at a time. If two valves are positioned such that they both select a run from the manifold than the run closest to the main solenoid valve will be active.

The order of the runs along the manifold was very important due to their different volumes. The manifold was constructed out of one inch copper pipe. Dimensions for all parts will be included in the appendix. The runs start at the main solenoid valve. The runs are ordered one through four starting at the main solenoid valve. They are in increasing order of volume. The first run uses three quarter inch pipe. It has the smallest volume. The second run has about fifteen inches of one inch pipe then fifteen inches of three quarter inch pipe. The third and fourth runs use one inch pipe. The fourth run is much longer than the third and also has two elbows in it. The runs are in ascending order from the main solenoid valve because the runs are transparent and the manifold is not. From intuition gained from the isentropic compression of a gas and the relation that length is proportional to volume, we gain some feeling for the steady state water air interface's location. The water-air interface's final location should be within the run and not within the manifold. Because the manifold has length and thus volume the run with the smallest volume, indicated by it's diameter, needs to have the smallest amount of manifold length.

Run Construction

The key requirement of this project was demonstrating the air-water interface under the surge flow condition. To accomplish this the runs were fabricated out of clear PVC pipe. The manifold was constructed using brass ball valves with stainless steel balls, and treaded copper pipe. To keep the brass fittings looking consistent throughout the system red brass was used for all fittings. Red brass has a lower quantity of alloying elements in it than yellow brass. Meaning that there is more copper in red brass than in the yellow brass. This was purely an aesthetic touch. Figure four gives a complete view of the runs including the supply and drain manifolds.

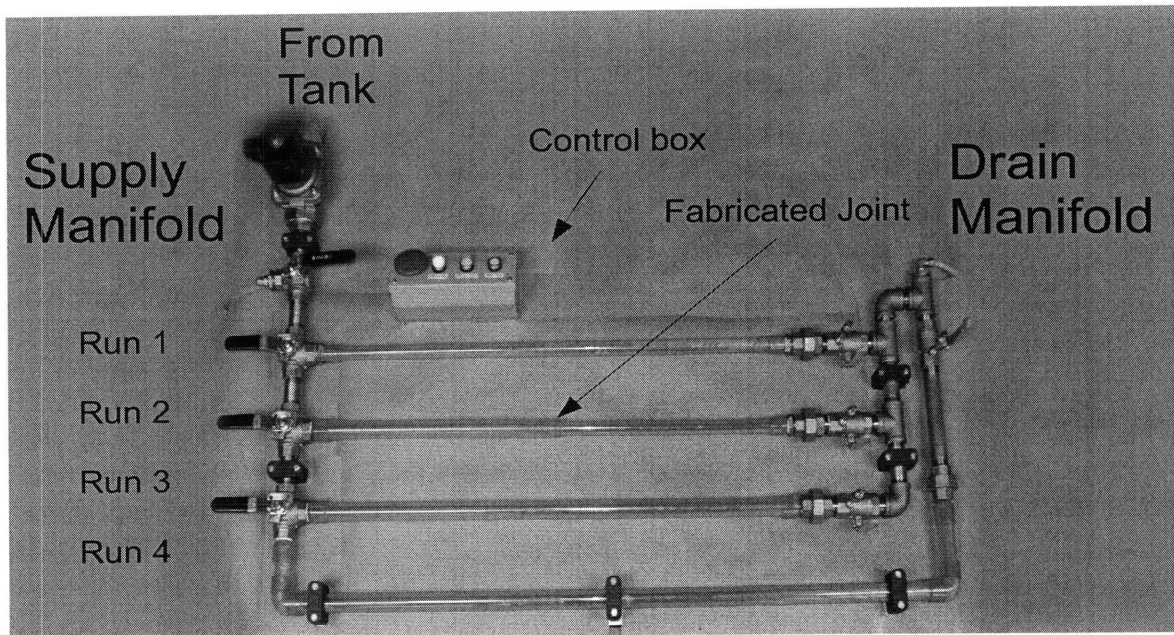


Figure #4: This shows the entire system. Labeled are the supply and drain manifold. As well as the control box and the runs. The fabricated joint it also indicated.

Each run terminates in a ball valve that has a pressure transducer connection port. The specific application for the eighth inch NPT connection on the terminating ball valves was as a drain. For this system they will be used as pressure ports. The pressure ports have quick connections on them so that only one pressure transducer needs to be used to collect data from the system. The terminating ball valves lead to the drain manifold. The drain manifold construction will be discussed in a subsequent section.

To facilitate disassembly the runs are threaded into the inlet manifold and connect to the drain manifold with one inch union connections. The union connections have a one inch inside diameter. The seam between the run and the union connection should be negligible. Because one of the goals in constructing this model is to have it behave ideally the union connections were put on the drain side of the run. On the drain side of the run the union will be in contact with air during a test cycle of the system. The loss associated with air flowing over the seam in the union is much less than if water was flowing over the seam. This is because the viscosity of air is much less than that of water. The second reason for installing the union on the drain side of the runs was to allow the clear section of PVC to start closer to the main solenoid valve so that the air-water interface can be observed for lower pressures.

The runs were constructed out of food grade clear schedule 40 PVC pipe. Food grade PVC was chosen so that algae and mineral deposits in

Cambridge water did not form films on the inside of the runs. Schedule 40 PVC indicates the wall thickness of the pipe. The pipe the runs were constructed out of is pressure rated to 220psi for the one inch pipe and 240psi for the $\frac{3}{4}$ inch pipe. This should be more than enough to ensure that the runs will not rupture. Further discussion of the maximum pressure that the tank should be run at will follow in the mathematical model section.

The ends of the pipe interfaced with the brass and copper manifolds via socket weld to male NPT adapters. The recommended adhesive was used to join PVC parts together as per *The Piping Handbook's* installation instructions. One joint needed to be fabricated because the appropriate fitting could not be located.

The run that starts as a one inch pipe and shrinks to a $\frac{3}{4}$ inch pipe has a machined joint. A clear PVC reducing coupling could not be found. The one inch pipe was bored out so that it accepted the $\frac{3}{4}$ inch pipe. The end of the $\frac{3}{4}$ inch pipe was turned so that there would be as smooth a transition between sections as possible. The joint ended up lapping over 1.25" which is more than most fittings. The failure mode of this joint, should it happen, will be at the base of the bore where the $\frac{3}{4}$ inch pipe ends. There should be enough adhesive in this joint so that this interface will meet the pressure requirements of the system.

High Pressure Delivery Side

From the main solenoid valve back to and including the pressure tank is considered the high pressure delivery side of the system. The pressure tank is mounted under the table to allow for more space on the table for runs and workspace. The main two inch solenoid valve connects to the pressure tank with a two inch flexible, wire and mesh reinforced tube. The tube connects the valve and tank with barb fittings and is held on with two hose clamps on each fitting. The tube is rated for 250psi. This ensures a factor of safety of two. The tank was mounted horizontally under the table. A special fitting needed to be fabricated so that water could be drawn off the bottom of the tank through the end. Figure four shows a schematic of the high pressure side.

Tank Schematic

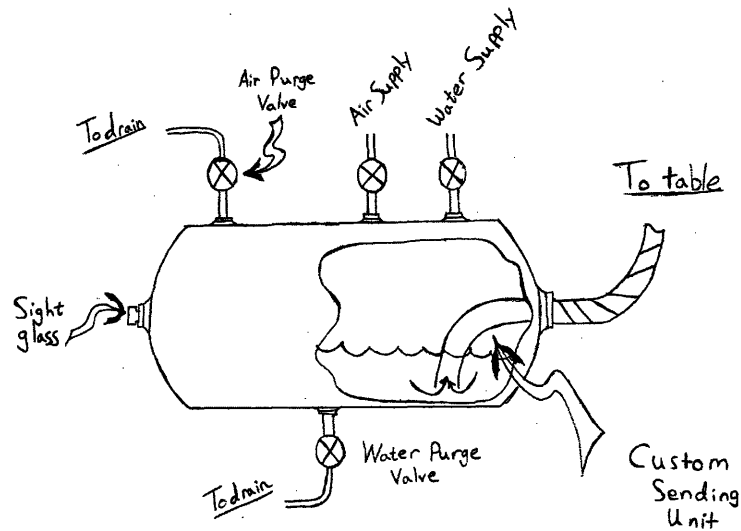


Figure #5: Schematic of the high pressure side. Showing;
1.) Tank 2.)Water supply valve 3.)Water purge valve 4.)Air supply 5.)Air purge valve
6.) Water outlet to table

The largest orifice on the tank was at the end. This was a 1.5 inch female NPT orifice. It was concluded that in order to minimize losses through the delivery side of the system this orifice would need to be utilized. It was suggested that the tank be filled more so that the end orifice would be submerged such that water would flow up the hose when the tank was under pressure. This idea, while an easy solution, would have limited the potential energy that could be stored in the compressed air in the tank. To remedy this issue a section of 1.5 inch tubing was bent to 90degrees at a six inch radius. one end of this tube was then welded into a 1.5 inch double male nipple. The nipple was then installed so that the bend was down and water could be drawn from the bottom of the tank. This seemed like the safest solution to this problem. Even if the welds fail there is no pressure differential across them. There may be air on the tank side but it will be at the same pressure as the water on the hose side. Other tank orifices have other valves on them.

There is a valve for purging air out of the tank as well as one for purging water. Another solenoid valve fills the tank. The operation of these valves will be discussed in the actuation section and in appendix one.

Drain Manifold

The drain manifold is where the runs terminate. It consists of ball valves at the end of each run that link the runs to the common drain in the table. The common drain for the table is a 3/8" plastic tube that connects drain elements on the table to the drain at the wall. The drain manifold connects to the common drain as well as the tank air purge and water purge. The tank air purge is connected to the common drain in case the fluid level in the tank gets too high and causes water to come out of the air purge valve. Figure six shows the drain manifold.

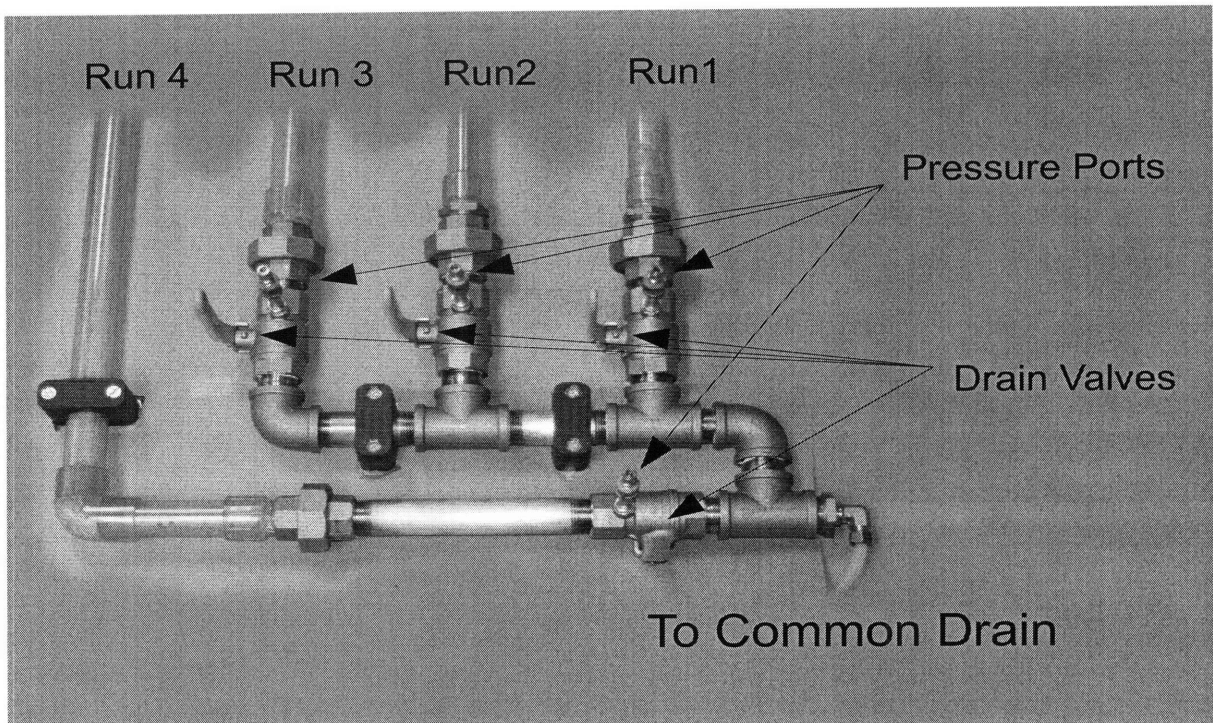


Figure #6: The drain manifold. The pressure transducer quick connects are indicated. As well as each runs termination valve and the common drain.

The ball valves that terminate the runs have one-eighth inch NPT drain screws up stream of the ball. This drain screw was replaced with a quick connect coupling where the pressure transducer will connect. This allows one pressure transducer to be used, reducing cost and complexity.

The drain manifold is also the low point of the system. All the runs pitch toward the drain end. This facilitates draining the runs after they have been "fired". The overall pitch is about .8%. This is within the range that most sewer and drainage systems are specified to. The intake manifold is also higher to allow for clearance around the main solenoid valve.

Better results should be attained when the system has been completely purged of water because there will be a consistent amount of air

in the run. When the run has water standing in it there is less air. This means that the pressure rise will not be as high as predicted.

Solenoid Valves

The four solenoid valves are identical in construction. The main solenoid valve is a two inch valve while the other three valves, that control the tank are three quarter inch valves. Selection of the solenoid valves was critical to the project.

The first parameter to be addressed was the minimum pressure difference needed to close. As addressed above the solenoid valves chosen don't need any pressure differential across them to close. This is important for the water fill valve and the main solenoid valve. Because the first valve purchased, the main solenoid valve, performed so well the same style valves were used throughout the system.

All the solenoid valves run off of 120VAC. This allowed them to be wired straight from the wall with no intermediate transformer to convert to direct current system or a lower AC voltage. The power comes in from the wall and comes up through the table into the switch box. There it powers both the illuminated switches and the valves. The valves are normally closed. Meaning they open when energized.

The solenoid valves control the tank, so users don't need to venture under the table, and the initiation of the experiment. The main solenoid valve's consistency should translate into more consistent data gathered from trial to trial. The valve will be opened the same way in every trial. This removes human variation in opening the valve.

The valves control the experiment. The air pressure coming from the wall should be controlled at the wall. This reduces the complexity of having multiple pressure regulators.

Actuation

The switch box is a NEMA 4 grade indoor/outdoor weather tight enclosure. It is grounded to the table ensuring that any shorts will short back to the wall. The hole where the wires come into the switch box is sealed against the enclosure with silicone sealant. Figure seven shows the control box.

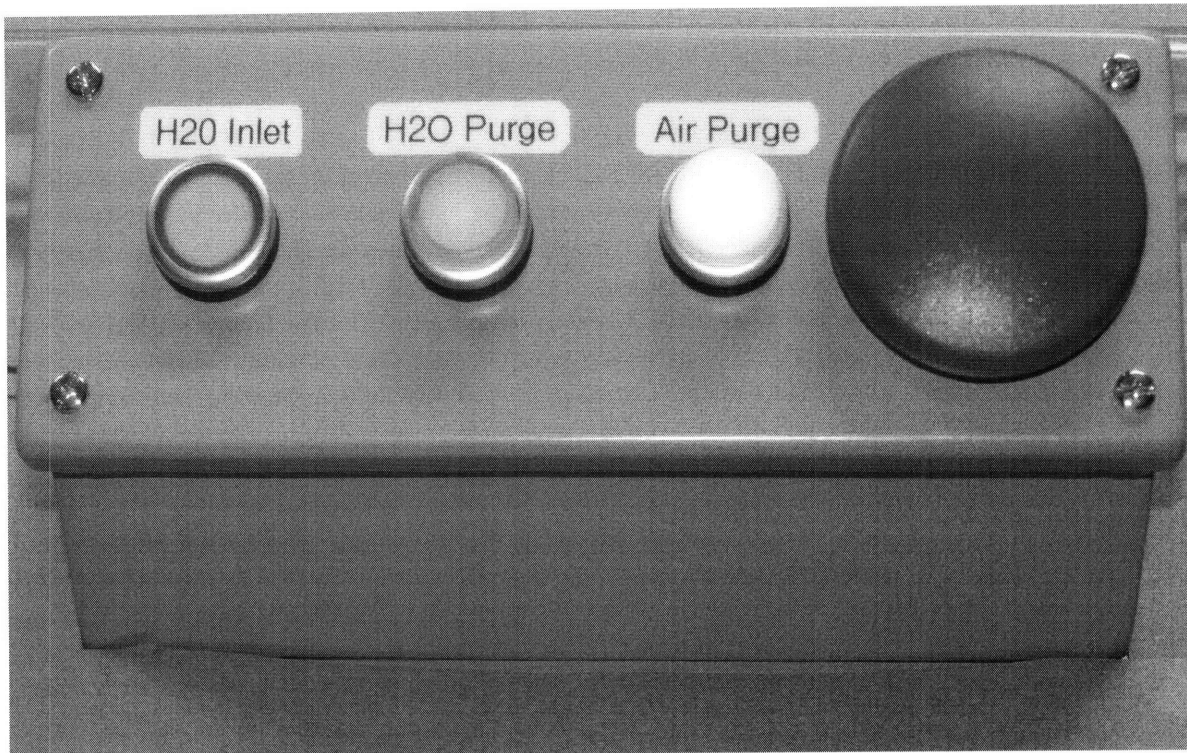


Figure #7: The buttons that control the operation of the valves on the high pressure side of the main solenoid valve. The big red button is clearly the fire button for the main solenoid valve.

The switches installed in the enclosure are momentary switches. This means that they will only power the valves while they are depressed. This ensures that they are not left in the “on” position to over fill the tank or run. They are illuminated to enhance their appeal.

The buttons on the control panel, other than the large red one that actuates the main solenoid valve, control the tank conditions. The green recessed button corresponds to filling the tank with water. Air pressure will be controlled on the wall with the wall mounted valve and regulator. The yellow button corresponds to the valve that purges water from the tank directly to the drain. The white button purges air from the tank to lower the pressure in the tank for filling or lowering the pressure to the system. The buttons are also labeled with their function on the switch box.

Pressure Measurement

The pressure transducer chosen was an Omega sensor px181b-500G5V. To interface the sensor to the computer several options were investigated. Though no product performed as ideally as hoped the sensor, when coupled with its power supply, puts out a one to five volt signal that is easy to read with most data acquisition products. There was some noise in the data that was being collected so a one hundred picofarad bypass capacitor was installed. This reduced the signal noise considerably.

Mathematical Model

Goals

To validate the assumptions made in constructing the physical system a mathematical model was developed. The goals of the mathematical model are to; develop a program that will represent the transient response of the flow based on loss factors, length, and diameter, and to determine the actual loss factors in each run.

Mathematical Assumptions

There are several assumptions that need to be made to simplify the system to a state where an analytic solution can be implemented. The first assumption is that the time it takes to open the valve is small compared to the time scale of the transient response. The valve takes approximately one tenth of a second to open. In the smallest pipe, before the flow will start to be slowed by the building pressure of the air in the pipe, the water will have traveled approximately four tenths of a meter. This is for a pressure of approximately 50kPa. The water would need to be traveling at near four meters per second for the timescale of the experiment to compare to the timescale of the valve. Due to the high loss coefficients in the system four meters per second seems high. Though the timescale for the valve may be small the subsequent loss through it varies with pressure as discussed below.

The second assumption that needed to be able to idealize the system was that there was no mixing between the water and air during the transient phase of the experiment. While this is not exactly the case, from observation the water-air interface has the same length scale as the diameter of the pipe, which is much less than the length scale of the run. This means that there will not be enough sufficient mixing to cause a change in volume sufficient to lead to a noticeable change in the pressure response. That is to say that there won't be enough air mixing with the water to change the overall volume of air in the pipe enough to matter. If the length of the air-water mixing zone was two diameters and the shortest run was taken into consideration the loss of volume would be on the order of 4%. This should over predict the result.

The third assumption is that the compression process is isentropic. This allows us to use the isentropic index of the gas to relate the pressure in the air to the pressure felt at the water-air boundary. The air will not be moving fast enough to consider viscous effects. We can show that heat loss will also be negligible by the convective heat transfer equation and the ideal gas law. If the air compressed to five times its original pressure it will experience a 30% rise in temperature. From the convective heat transfer equation this would translate into a heat loss rate of one Watt. This is assuming a convective heat transfer coefficient of $100 \text{ W/m}^2\text{-K}$ at a temperature of 278K and a pipe length of .8m. The potential energy added to the system by the compression is on the order of about four joules. The time scale for heat

transfer to happen is on the order of one hundred milliseconds. This would only allow for a energy loss of around two percent. The timescale is derived from the empirical evidence. The isentropic compression assumption will also lead to an over estimation of the solution. The isentropic index for dry air is 1.4 while for saturated air is ~1.2. This difference may not seem significant but it directly relates to how "stiff" the air spring is.

Governing Equations

The governing equation for this system is the unsteady Bernoulli equation.

$$\int \frac{dx}{dt} + \frac{V_2^2 - V_1^2}{2} + \frac{P_2 - P_1}{\rho} + gz = losses$$

In the standard form of this equation the RHS is equal to zero. Because we have considerable flow losses we need to include loss terms from friction against the pipe walls and fitting joints. These are called minor and major losses respectively. The loss term can be written as:

$$losses = \frac{friction\ factor * V^2}{2} + \frac{K\ factor * V^2}{2}$$

The K factor is the sum of the K factors of each fitting from a table of loss coefficients. The friction factor is derived empirically for turbulent flow for a calculated Reynolds number. The Reynolds number and friction factor follow.

$$\Re = \frac{\rho V d_{pipe}}{\mu}$$

$$friction\ factor = \frac{1}{\sqrt{-1.8 \log \left(\frac{6.9}{\Re} + \frac{\frac{\epsilon}{d_{pipe}}}{3.7} \right)^{1.11}}}$$

One end of the Bernoulli streamline lies at the top of the water in tank and the other moves along the with the water air interface. The top of the water in the tank should have negligible displacement and be kept at a constant pressure. These assumptions leave the unknowns being the pressure at the water air interface and the velocity of the water air interface. The pressure can be solved for using the isentropic compression equation. This will also give rise to the displacement which can be used in a finite difference scheme to solve for the velocity of the water air interface.

Iterative Scheme

To solve the system a backward first order finite difference scheme was utilized. A first order scheme was used because other simplifications in the model lead to errors that made the first order approximations valid. The scheme used was as follows:

- 1.The Reynolds number is calculated from previous iterations velocity
- 2.The friction factor is calculated based on the Reynolds number
- 3.The losses term is calculated from the previous velocity using the friction factor and the sum of "k" factors.
- 4.The pressure at the water air interface is calculated from the PV^{gamma} equation
- 5.The Bernoulli equation is solved for the new time step.

Data

To characterize the system four data points were collected for each run. They ranged from 15psi to 45psi. The system is rated for 200psi but to ensure that the maximum pressure would not get that high low pressures were used until the mathematical model was validated. The model was fit to the data at each pressure at each run by varying the tank pressure and loss factor. These two parameters adjusted the steady state pressure and overshoot respectively. The frequency response is slightly different between the model and the data due to simplifications in the mathematical model discussed below.

Figures eight through eleven show the results of fitting the model to the data for runs one through four respectively. The title of each graph reflects the tank pressure and the loss factor used to fit the model to the data.

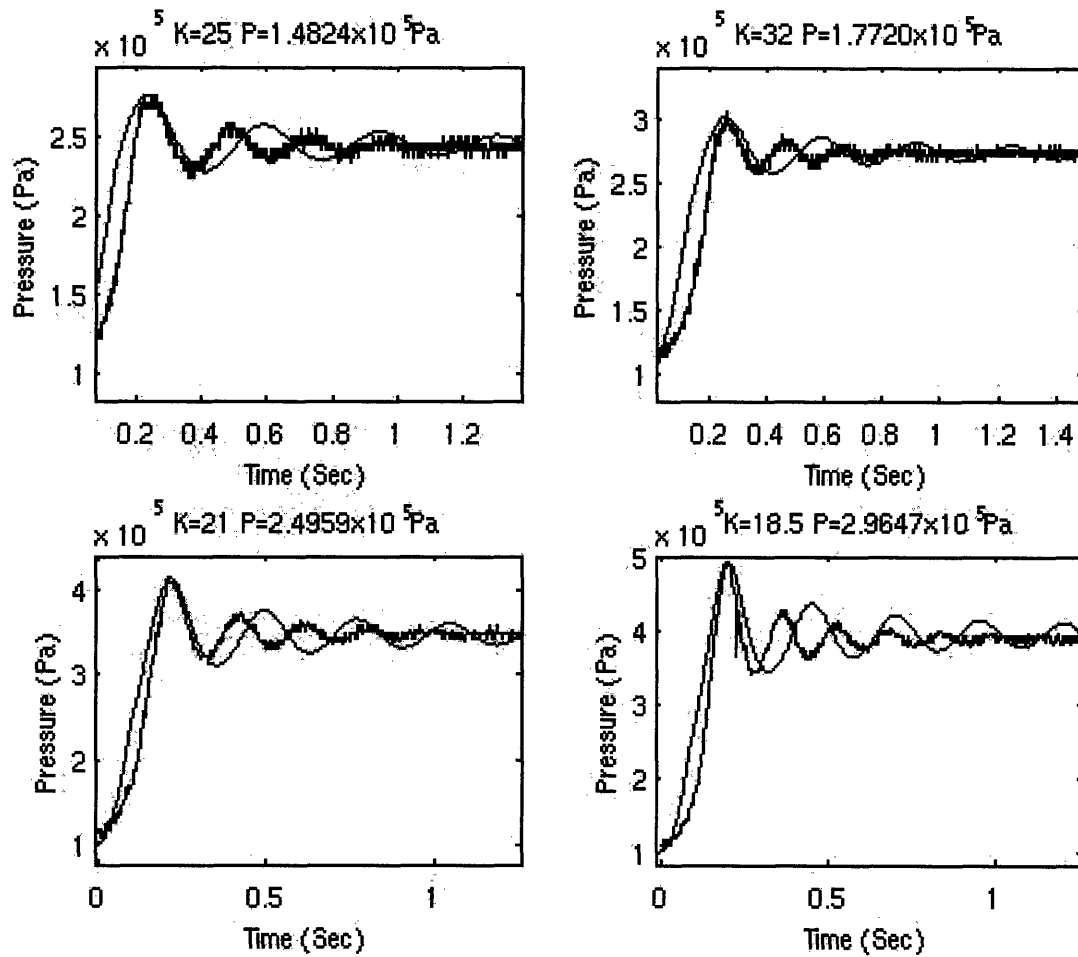
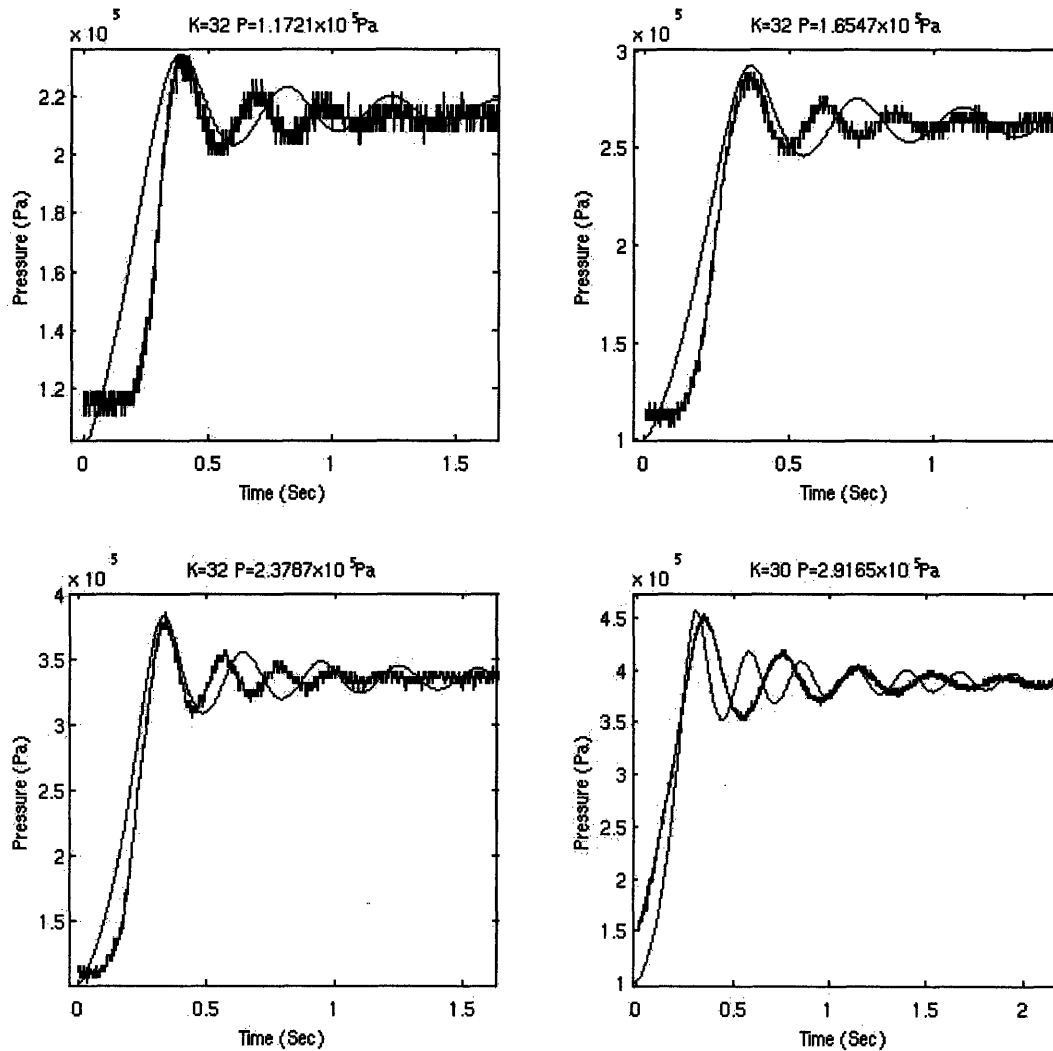


Figure #8: The results for the first run. The rougher line is the collected data. The roughness arises from noise in the system. The model rises less dramatically than the collected data and oscillates at a lower frequency.



Figure#9: The results from the second run. This run consists of a restriction from a one inch pipe to a $\frac{3}{4}$ " pipe that causes the initial rise to appear exponential. This causes increased difficulty in modeling this run. While other runs have diameter variations the water is not oscillating around that area. As above the smooth line represents the model while the rougher line represents the collected data.

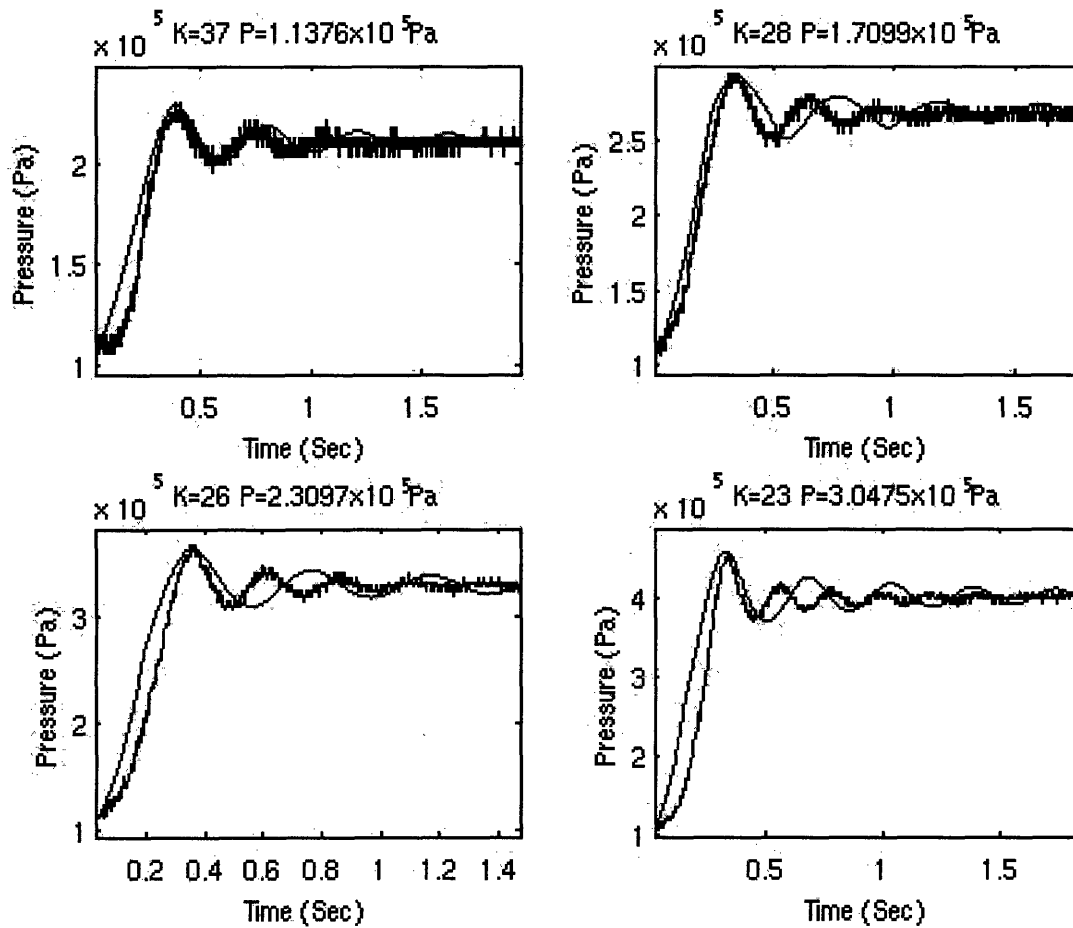


Figure #10: The results from the third run. This run also exhibits the exponential initial pressure rise. The lowest pressure trial seems to have had more noise in it than the other runs.

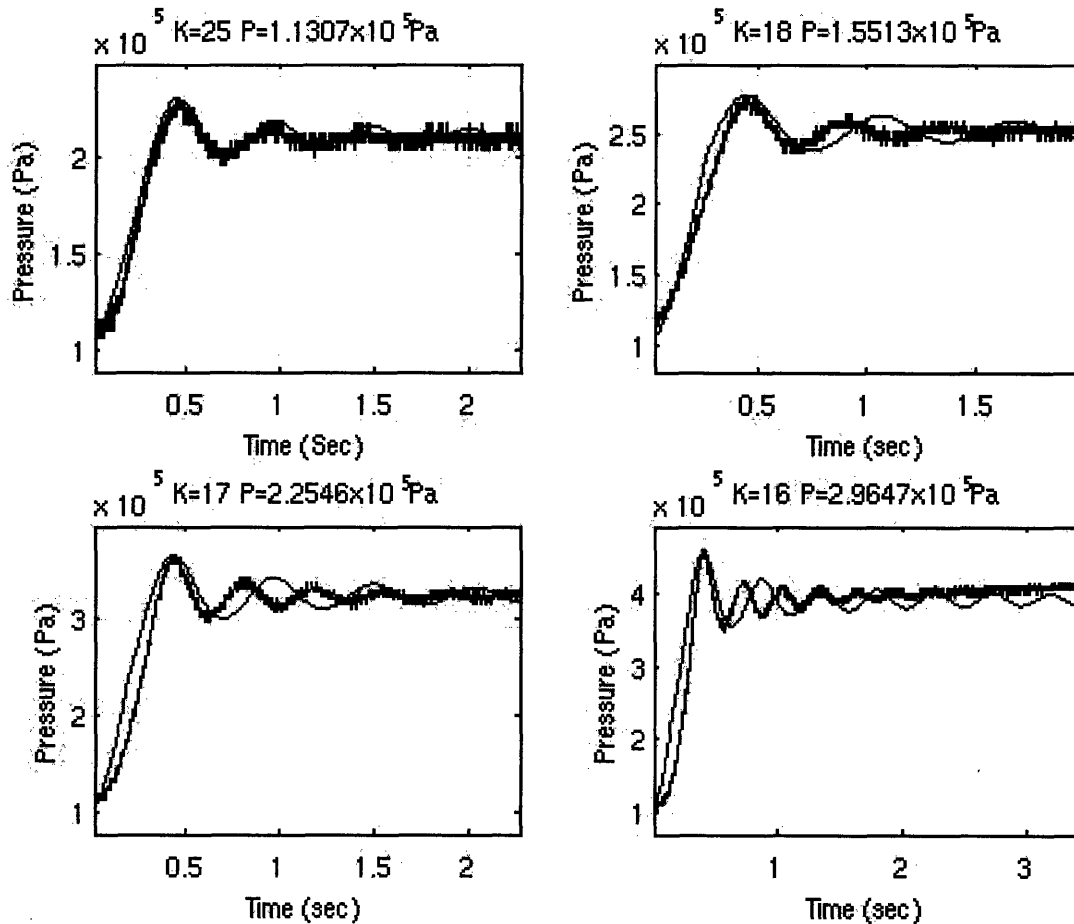


Figure #11: The results from the fourth run. The low pressure trial of this run has the best agreement between the data and the model of any run. This run is also the longest by far. The other trials exhibit the same characteristics found throughout the experiment. Namely that the model has a lower frequency than the data and the model rises more linearly than the data. The high pressure trial exhibits some unusual behavior. The pressure in the tank seems to rise with time. This may indicate that the assumption that the tank is at constant pressure is false.

What can be concluded from these graphs is that lower pressures have higher agreement between the model and the data. It can also be seen that the loss coefficients decrease with increased tank pressure. The exception to this trend is the 25Psi trial of the first run. The loss coefficient for this trial is higher than the loss coefficient for the lower pressure trial on the same run. The higher loss coefficient could be a result of the water oscillating around the area where the pipe diameter decreases.

Sources of Error

The major source of error in the mathematical model is the linearization of the loss coefficients. The major loss “k” factors were summed for all the fittings in the run. This lead to the frequency being slightly off. A more appropriate scheme would use a piecewise function to make the loss factors dependent on the position of the water air interface.

Similar to the linearization of the loss factors it was assumed that the main solenoid valve had the same loss factor of the operating pressure range. In actuality the main solenoid valves loss factor is reduced as the driving pressure increases. This is intuitive because the more pressure that is put on the valve the faster the plunger will actuate. The valves speed is not controlled by the solenoid. If the valve were opened at a constant rate the data would not reflect changing loss factors over different pressure ranges.

On par with the error associated with linearizing the loss factors is the error in the regulated pressure. The regulated pressure from the wall may be off as much as three PSI. This is a significant source of error. To deal with this the model was parameterized for the tank pressure and was then fit to the data. To fit the model to the data the steady state pressures were matched by varying the tank pressure for the model. This lead to excellent agreement between the model and the collected data.

Another source of error is assuming that the air's viscous effects are negligible. This error is very small compared to the linearization of the loss factors but it is the other simplification that would cause the frequency of the response to differ from the collected data.

Further Mathematical Modeling Considerations

Though the mathematical model is not perfect, a priori determination of how the system performs is nontrivial. A good table of loss coefficients and accurate tank pressure measurements are very important to arriving at a model that resembles the data. The actual loss coefficient is much higher than the one summed from the tables which leads to a model that predicts a much higher over pressure than the pressure actually seen.

Operating instructions

- Software
 - Put CD in drive
 - From the left hand menu select “Install Drivers”
 - Install drivers
 - From the left hand menu select “Install Additional Software”
 - Install quickDAQ
 - Exit installer without starting quickDAQ
 - Plug in USB cable from DAQ
 - Install the drivers as recommended by the wizard
 - Run quickDAQ
 - Set sample rate at 2000S/s
 - Select analog channel 5 to sample from
 - The options should all be fine in their default setting.
 - Click the green arrow to start recording
 - When done recording save the data as a tab separated value file. (.tsv)
 - The file will be very similar to the output of chart recorder.
 - The beginning errata can be deleted and just the column of valves can remain to be imported into MatLab or another software package.
- Layout
 - buttons (what each one does)
 - green – Press and hold to increase water level in tank. The air pressure may need to be reduced so that water will flow into the tank. This can be accomplished by closing the air off at the wall and then purging the air from the tank. See below.
 - Orange – Press and hold to release water from the tank to the drain. This button will lower the water level in the tank provided there is some pressure in the tank to help force the water up into the drain.
 - White – Press and hold to purge air from the tank. This is to help drain the tank of air when reducing the pressure in the tank for filling or taking a different data point. The amount of air pressure in the tank should be controlled at the wall with the regulator and shutoff valve there.
 - Big Red Button – This is the Fire button. It will actuate the main solenoid valve and start the experiment. It should be pressed and held for the duration of data collection.
 - Supply manifold
 - Main solenoid valve – This is described above.
 - Run selector valves – There are three run selector valves for four runs. If the run selector valve handle is perpendicular to

the intake manifold than the water from the main solenoid valve will pass through that selector valve. If the valve handle parallel to the intake manifold the run that is connected to that valve will be the active run as long as no other run is selected that is closer to the main solenoid valve. This ensures that only one run will be active at a time.

- Air water selector valve – The first valve after the main solenoid valve is the air-water selector valve. After data has been collected, open the drain valve on the end of the run(discussed below). Next turn the air-water selector valve from “water” to “air”. This will take air from the wall, at whatever pressure is marked on the regulator, and push it into the just filled run. The air will run until the air-water selector valve is turned back to “water”. It is fairly important to get as much water out of the run as possible.
- Pressure sensor calibration -The air-water selector valve is also used to calibrate the pressure sensor. To calibrate the pressure sensor select a run with a run selector valve. Ensure that the drain is closed on that run and that the pressure sensor is reading pressure on that run. Position the air-water selector valve in the “air” position. Change the pressure on the wall mounted regulator and record the data from the pressure sensor. This will allow correlation between voltage and pressure.
- Drain Manifold
 - Pressure sensor locations – There are ports to connect the pressure sensor at the end of each run. They are the ¼ inch copper pipes that come out of the drain valves. There are quick connects to attach the pressure sensor to the pressure port.
 - Drain valves – When the drain valve handles are perpendicular to the run, i.e. vertical, they terminate the run.
- Running the experiment
 - Filling the tank
 - De-pressurize high pressure side – Do this by shutting of the air supply and purging the air from the tank using the white button.
 - Fill to desired level – by holding the green button until the water reaches the desired level.
 - Re-pressurize the system – Here the air supply is turned back on and the regulator set to the desired pressure.
 - Purging the high pressure side – Because the main solenoid valve stops the air in the braided tube from escaping that air needs to be purged. To do this select a run, open the drain on

that run and press and hold the main solenoid actuator button. Continue depressing the button until there is no more air in the braided hose. The run now needs to be purged of water using the air-water selector valve. The system is now ready to be used.

- Selecting the run
 - Turn run selector valve parallel to intake manifold on the run to be tested. Ensure that the other run selector valves are perpendicular to the intake manifold.
 - Ensure the drains are closed – If more than one drain is open when the water is purged from the run it can backup into other runs.
 - Attach pressure sensor to appropriate pressure port.
- Running the test
 - Start recorder
 - Press and hold big red button until the transient response has damped to an acceptable level.
 - Stop recording
- Purging the result
 - Without changing the run selector!!!!
 - Open drain on run
 - Select air with air-water selector valve
 - For optimum results move the air/water selector valve between the air and water positions a few times to get rid of any excess water in the pipe between the large solenoid valve and the air/water selector
 - Select water with the air-water selector valve
 - close drain
 - repeat run if desired or select other run or change air pressure or water level.