Evaluating an Experimental Setup for Pipe Leak Detection

by

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Abstract

An experimental setup with 4 inch inner diameter PVC pipe modules is designed to mimic a real life piping system in which to test possible leak detection mechanisms. A model leak detection mechanism is developed which consists of a ring with threads that follow the streamlines of the flow inside the pipes, allowing for a visualization of the flow patterns. Two experiments were conducted in order to test the effect of the leak on the threads of the detection mechanism. The first experiment was successful in that the threads were clearly affected in the proximity of the leak; however, it was not realistic because of the lack of cross flow. The second experiment allowed for cross flow. On the other hand, this experiment failed in that the threads of the detection mechanism were not affected by the leak due to the small leak flow rate. A theoretical model of the second experimental setup is proposed in order to estimate how the exit hole diameter will affect the leak and outflow volumetric flow rates. From the model it is concluded that a small exit hole is needed to increase the leak flow rate; however this would reduce the cross flow rate inside the system to a value below real life conditions.

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Chapter 1

Introduction

Piping systems are used in a variety of applications to transport fluids from one point to another; from water that we use on a daily basis in our homes to oil pipes that cross entire countries to deliver this commodity to its users. However, when dealing with piping systems there is always the potential problem of a leak occurring in the system. Since these pipes run enormous lengths and tend to be placed out of sight or underground, it is usually hard to visually detect a leak in the system.

Currently, research is being conducted at the MIT Laboratory for Manufacturing and Productivity to design a mechanism that would travel inside a pipe and allow for remote detection of leaks. In one such mechanism, a leak is identified by detecting flow pattern variations in the proximity of the leak. One possible approach is a mechanism that would consist of a solid ring with threads that follow the streamlines of the flow (as shown in Figure 1-1). In the event of a leak, the flow pattern inside the tube will alter and the threads will be able to capture this alteration and thus detect the leak.

In order to design such a mechanism it is important to be able to experimentally replicate the flow patterns from a large piping system on a smaller system inside the laboratory. The objective of the work presented here is to design and evaluate one possible experimental setup for mimicking flow in a piping system. This work should serve as an initial and preliminary analysis on the design of an experimental setup in which to test potential leak detection mechanisms.
Figure 1-1: Ring and thread leak detection mechanism representation

The work is divided as follows: In Chapter 2 the experimental set up is described and testing procedures used are presented. Chapter 3 shows a theoretical model used to predict the behavior and limits of the experimental setup. Finally, conclusions and future work are presented in Chapter 4.
Chapter 2

Experimental Setup & Preliminary Experiments

The experimental setup is a system that allows one to visualize the effect of a leak on the flow patterns within the pipe; that is the piping system consists of water flowing through transparent PVC pipes. The preliminary leak detection mechanism consists of a ring with threads attached to it (as shown in Figure 2-1), and a set of six magnets (three on the inside attached to the ring by strings and three in the outside) that allows one to move the ring along the pipe to observe the behavior of the threads at different distances from the leak. A ring was chosen as the optimal shape for the mechanism since this would be the least disturbing shape for the flow within a cylindrical pipe. The threads were 1 mm in diameter for them to be easily carried by the flow within the pipe. Several mechanisms were made with rings of different diameters, but the 2 inch diameter ring was selected because not only it allowed to see what the flow looked like in most of the pipe, but it also left a gap of 1 inch with the walls of the pipe, thus making movement within it easier.

The rings were made out of steel thus making the manipulation of the mechanism harder in the proximity of the magnets. In the future, I recommend the use of aluminum for the rings due to its non-magnetic property.

The piping system was designed in separate modules for easy handling of the weight and to allow for a variety of settings in which to test the performance of the
leak detection mechanism. The pipes were transparent PVC pipes with an inner diameter of 4 inches. The rest of the materials available for the construction of the modules were a pump connector, a hose connector, male and female pipe connectors, 90 degree elbow joints, and end caps. The main module or testing module consisted of a 3 feet long PVC pipe with male and female end connectors and a leak at the center of 2 mm in diameter.

2.1 Preliminary experiment 1

As a preliminary experiment, the testing module of the system was placed vertically, the outflow port was sealed with an end cap so that all flow would go through the leak, and the inflow was driven by a hose connected to the facilities water pressure system and to the testing module through a hose connector. The reason for setting this experiment vertically was that since there was no coaxial flow, gravity was needed to keep the threads aligned with the pipe walls. The setup is shown in Figure 2-2 (a). When the detection mechanism was set far away from the leak, the threads were aligned with the pipe (also seen in Figure 2-2 (a)). When the ring mechanism was
set with the tip of the threads at the height of the leak, the threads started to deflect slowly towards the leak until some of them were suddenly pulled through it because of the high pressure inside the pipe and the high flow rate through the leak (as shown in Figure 2-2 (b)).

Figure 2-2: First preliminary experiment. (a) Overview of the experimental set up. (b) Close up showing the deflection of the threads near the leak.

This experiment was only meant to allow for a visual idea of how a future experiment with a horizontal setting should behave. The internal mechanism succeeded in changing its behavior as the flow pattern was altered; that is some of the threads deflected around the leak area. However, this experiment didn’t account for the cross-flow in a real life piping system, nor the hose had enough pressure to allow an open ended setting, thus it wasn’t representative and a new setup was made to account for these important factors.
The final setup used was the following:

A 1/2 hp pump (Marathon Electric AQL 56C34D5588B shown in Figure 2-3) with a 3/4 inch exit diameter was attached to a first module consisting of a 1 foot long PVC pipe rising at a 45 degree angle to stabilize the flow. The 1 foot PVC pipe was attached using a 90 degree elbow joint to a horizontal 3 feet long PVC section which was the main testing area. Finally the end of the 3 feet long PVC pipe is attached to a 90 degree elbow joint to make sure that the testing area is completely full of water throughout the test. Different end caps with holes varying in diameter were used in order to vary the pressure and flow rate inside the testing area. Figure 2-4 shows all three PVC sections.

Figure 2-3: Pump used in experiments
Figure 2-4: Piping Modules. (a) 1 foot 45 section used to feed the water at a 45 degree angle. (b) 3 foot horizontal testing area. (c) Upright end section to maintain testing area full. Not shown here is the elbow joint that links modules (a) and (b).
2.2 Preliminary experiment 2

For the second preliminary experiment the final horizontal setup was used except that the outflow was not restricted by an end cap. This experiment was done to see how it would actually work with a pump and a horizontal system, and to be able to get some volumetric flow rate measurements both at the leak and at the exit point in order to estimate how big the exit hole should be to get the desired results. An observation was that the water coming out the end of the pipe didn’t come out through the entire cross sectional area of the elbow module, instead it was only flowing through the bottom half. The volumetric flow rate through the pipe was measured to be in the order of 5 liters per second, while that of the leak was measured to be of the order of 0.005 liters per second. These measurements were done by timing how long it would take for the two flows to fill up a recipient of known volume.

The detection mechanism didn’t move in the proximity of the leak (as shown in Figure 2-5) thus proving that a higher pressure and higher volumetric flow rate through the leak are necessary in order for such a mechanism to be successful. The next step was to make an educated guess on how large the exit hole should be in order to get a reasonable pressure in the proximity of the leak, and a large enough volumetric flow rate through the leak. It was assumed as reasonable, that the volumetric flow rate through the leak should be of the order of one tenth the volumetric flow rate in the pipe. In order to reach this objective, a theoretical model of the system was developed in order to predict how the outflow should be restricted in order to achieve a desired leak flow rate.
Figure 2-5: Second preliminary experiment showing how the flow rate at the leak was insufficient to affect the threads.
Chapter 3

Theoretical Model

The objective of the following theoretical model is to predict the volumetric flow rate at the leak as a function of the end cap diameter. As shown in Figure 3-1 the flow is modeled as passing through three sections of different diameters. The end cap outflow is controlled by the diameter $d_3$ and can be varied to adjust the behavior of the system. As shown in Figure 3-2 the leak is located at the center of the system at a distance $L/2$ from where the flow first expands onto the main section of the system.

In order to simplify the analysis we take a two part approach to the modeling of the system. In the first part the leak is neglected for the sake of simplicity and all inflow from the pump flows out through the end cap of diameter $d_3$. Neglecting the leak
allows one to solve for the velocities and pressure inside the system. The second part of the analysis focuses on the leak and the pressure at the position of the leak, which is shown in Figure 3-2 and found in the first part of the analysis. The pressure at the location of the leak is used to calculate the volumetric flow rate at the leak. Although ignoring the leak is a simplification that is unrealistic it allows for the solving of the system in relatively simple manner and provides us with a preliminary theory through which to understand the piping system’s behavior.

3.1 Finding the internal pressure variation of the pipe as a function of end cap diameter \(d_3\)

The analysis begins by mass conservation which yields

\[
\rho A_1 v_1 = \rho A_2 v_2 = \rho A_3 v_3 \quad (3.1)
\]

which simplifies to

\[
d_1^2 v_1 = d_2^2 v_2 = d_3^2 v_3 \quad (3.2)
\]
The losses through the system are modeled as follows

\[ h_{\text{Pump}} = h_{SE} + h_{\text{Pipe}} + h_{SC} \]  \hspace{1cm} (3.3)

Where \( h_{SE} \) is the loss due to sudden expansion, \( h_{\text{Pipe}} \) is friction loss through the length of the pipe, and \( h_{SC} \) is the loss due to sudden contraction. According to White [1]:

\[ h_{SE} = \frac{K_{SE} v_1^2}{2g} \]  \hspace{1cm} (3.4)

where \( K_{SE} \) is the minor loss coefficient for sudden expansion and

\[ K_{SE} = \left( 1 - \frac{d_1^2}{d_2^2} \right)^2 \]  \hspace{1cm} (3.5)

\[ h_{SC} = \frac{K_{SC} v_3^2}{2g} \]  \hspace{1cm} (3.6)

where \( K_{SC} \) is the minor loss coefficient for sudden contraction and

\[ K_{SC} = \begin{cases} 
0.42 \left( 1 - \frac{d_3^2}{d_2^2} \right) & \text{if } \frac{d_3}{d_2} \leq 0.76 \\
\left( 1 - \frac{d_3^2}{d_2^2} \right)^2 & \text{if } \frac{d_3}{d_2} > 0.76 
\end{cases} \]  \hspace{1cm} (3.7)

Finally the friction pipe loss, \( h_{\text{Pipe}} \), is defined as

\[ h_{\text{Pipe}} = f_{\text{Pipe}} \frac{L v_3^2}{d_2^2 2g} \]  \hspace{1cm} (3.8)

where \( f_{\text{Pipe}} \) is the friction factor coefficient and

\[ f_{\text{Pipe}} = 0.316 \, Re_d^{-1/4} \]  \hspace{1cm} (3.9)
Plugging in Equations 3.4 through 3.9 into Equation 3.3 yields

\[
h_{\text{Pump}} = \left(1 - \frac{d_1^2}{d_2^2}\right)^2 \frac{v_1^2}{2g} + 0.316 \left(\frac{\rho v_2 d_2}{\mu}\right) \frac{L v_2^2}{d_2^2 2g} + 0.42 \left(1 - \frac{d_3^2}{d_2^2}\right) \frac{v_3^2}{2g}
\]  

(3.10)

A relationship is now required for the pump head, \( h_{\text{Pump}} \), as a function of the volumetric inflow. This relationship is inherent to the pump and provided by the manufacturer. Figure 3-3 shows the manufacturer’s plots for pump head versus volumetric flow rate of the pump, the pump in use in the experiments corresponds to curve G. From curve G of Figure 3-3 several points were extrapolated which were used to create a quadratic fit for pump head as a function of volumetric flow rate.

Figure 3-3: Pump performance curves. Curve G corresponds to the pump used experimentally in this work.
The extrapolated points and fit are shown in Figure 3-4. The resulting function is

$$h_{Pump} = -5.254 \times 10^5 \left( v_1 \frac{\pi d_1^2}{4} \right)^2 - 2983 \left( v_1 \frac{\pi d_1^2}{4} \right) + 21.93 \quad (3.11)$$

The reason this fit is required is that for a given piping system the pump will operate at a certain point along the performance curve shown in Figure 3-3. It is expected, for example, that a smaller end cap diameter hole will result in a higher pressure inside the tank which will in turn reduce the volumetric flow rate of the pump. In order to calculate at what point the pump is operating and what the internal conditions of the piping system are it is necessary then to equate the pump head equation, Equation 3.11, with the head losses through the system, Equation 3.10. This results in the following

$$-5.254 \times 10^5 \left( v_1 \frac{\pi d_1^2}{4} \right)^2 - 2983 \left( v_1 \frac{\pi d_1^2}{4} \right) + 21.93 = \left( 1 - \frac{d_1^2}{d_2^2} \right)^2 \frac{v_1^2}{2g} + 0.316 \left( \frac{\rho v_2 d_2}{\mu} \right) \frac{L v_2^2}{d_2 2g} + 0.42 \left( 1 - \frac{d_3^2}{d_2^2} \right) \frac{v_3^2}{2g} \quad (3.12)$$
Using the mass conservation relations, Equation 3.2, it is possible to simplify Equation 3.12 to an equation with only a single velocity, either \( v_1 \), \( v_2 \), or \( v_3 \), and the variable end cap diameter \( d_3 \). The following equation has been simplified to be solved for the velocity \( v_1 \) for any given end cap diameter

\[
0 = v_1^3 \left[ 0.316 \frac{\rho L}{2g} \frac{d_3^5}{d_2^5} \right] + v_1^2 \left[ \left( 1 - \frac{d_1^2}{d_2^2} \right)^2 \frac{1}{2g} + \frac{0.42}{2g} \left( 1 - \frac{d_3^2}{d_2^2} \right) \frac{d_1^4}{d_3^4} + 5.25 \times 10^5 \left( \frac{\pi d_1^2}{4} \right)^2 \right] + v_1 \left[ 2983 \left( \frac{\pi d_1^2}{4} \right) \right] - 21.93
\]  

(3.13)

The above equation is solved numerically using excell. For a given end cap diameter \( d_3 \) the head pump and pump volumetric flow rate are adjusted along the curve described by Equation 3.12 until the pump head is the same as the head losses of the system. Table 3.1 shows this solution for various values of \( d_3 \) Table 3.1 shows that, for example,

<table>
<thead>
<tr>
<th>( d_3 ) (in)</th>
<th>( h_{\text{pump}} ) (m)</th>
<th>( h_{\text{pipe}} ) (m)</th>
<th>( h_{\text{SE}} ) (m)</th>
<th>( h_{\text{SC}} ) (m)</th>
<th>( h_{\text{total}} ) (m)</th>
<th>( h_{\text{pump}} - h_{\text{total}} ) (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25</td>
<td>18.9</td>
<td>2.01E-4</td>
<td>0.505</td>
<td>18.4</td>
<td>18.9</td>
<td>0.0</td>
</tr>
<tr>
<td>0.5</td>
<td>11.6</td>
<td>1.11E-3</td>
<td>3.55</td>
<td>7.98</td>
<td>11.5</td>
<td>0.1</td>
</tr>
<tr>
<td>1</td>
<td>7.01</td>
<td>1.80E-3</td>
<td>6.18</td>
<td>0.828</td>
<td>7.01</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Table 3.1: Tabled values for head losses as varying with end cap diameter \( d_3 \)

for a 1 in diameter end cap hole the pump is expected to put out 7.01 meters of head. Of this head, 0.0018 meters of head are lost due to pipe friction, 6.18 meters of head are lost due to sudden expansion, and 0.828 meters of head are lost due to sudden contraction, which results in zero head at the end of the system as is required for the solution to converge. From the pump performance then the 7.01 meters of head from the pump can be translated to a volumetric flow rate of 0.00325 meters cubed per second. Knowing the volumetric flow rate of the pump means that all the velocities in the system are now known.
3.2 Determining leak volumetric flow rate from the internal pressure of the piping system

In order to estimate the volumetric flow rate at the leak, we ignore any friction losses and apply the Bernoulli equation at the leak. An assumption is made that there exists a streamline that begins inside the pipe at a velocity of \(v_2\) and pressure \(P_{leak}\) and ends right outside the leak at a velocity of \(v_{leak}\) and a pressure of \(P_{atm}\). This yields that the leak velocity can be related to the pressure and the velocity inside the system by

\[
v_{leak} = \sqrt{\frac{2(P_{leak} - P_{atm})}{\rho} + v_2^2}
\]  

(3.14)

where the leak pressure is found by calculating the head loss at half way through the pipe, that is

\[
P_{leak} = h_{leak}C + P_{atm}
\]  

(3.15)

where \(C\) is a conversion factor equal to 9792.5 Pa/m. Substituting Equation 3.15 into Equation 3.14 yields

\[
v_{leak} = \sqrt{\frac{2C}{\rho} \left( \frac{h_{pipe}}{2} + h_{SC} \right)}
\]  

(3.16)

Finally, substituting Equations 3.7 and 3.8 into Equation 3.16 yields and equation for \(v_{leak}\) which is solely dependent on \(v_1\) which as shown in the previous section can be found for any given end cap diameter \(d_3\), the equation is

\[
v_{leak} = \sqrt{\frac{2C}{\rho} \left[ 0.316 \left( \frac{\rho L}{2 \mu g} \right) \frac{d_3^6}{d_2^6} v_1^3 + 0.42 \left( \frac{d_3^3}{d_2^3} \right)^2 \frac{d_1^1}{d_2^1} v_1^2 \right] + \frac{d_1^1}{d_2^1} v_1^2}
\]  

(3.17)

Using the numerical solutions for \(v_1\) with varying \(d_3\) as found through Equation 3.13 and the iteration solution shown in Table 3.1, it is now possible to use Equation 3.17 to solve for the leak velocity with varying end cap diameter \(d_3\). Table 3.2 shows values
for the volumetric flow rate found through the use of the previously found values for
the internal velocities in the piping system. Finally, the iterative process can be used

<table>
<thead>
<tr>
<th>$d_3$(in)</th>
<th>Pump Flow Rate ($m^3/s$)</th>
<th>Leak Flow Rate ($m^3/s$)</th>
<th>Ratio of Leak to Outflow Flow Rates (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25</td>
<td>9.29E-4</td>
<td>5.97E-5</td>
<td>6.42</td>
</tr>
<tr>
<td>0.3</td>
<td>1.26E-3</td>
<td>5.63E-5</td>
<td>4.45</td>
</tr>
<tr>
<td>0.5</td>
<td>2.46E-3</td>
<td>3.93E-5</td>
<td>1.60</td>
</tr>
<tr>
<td>1</td>
<td>3.25E-3</td>
<td>1.27E-5</td>
<td>0.39</td>
</tr>
</tbody>
</table>

Table 3.2: Tabled values for flow rates in the system as varying with end cap diameter $d_3$

to create a plot of the leak volumetric flow rate as a function of the end cap diameter,
as was the original goal of the theoretical model. Figure 3-5 (a) shows how reducing
the diameter of the end cap hole increases the flow rate at the leak, as is expected.

Looking at the outflow volumetric flow rate as a function of the end cap diameter
the opposite relationship can be observed. Figure 3-5 (b) shows, as expected, how
the outflow volumetric flow rate increases with increasing end cap diameter.

Depending on the pump used and the head losses in the system the trade off
between the leak volumetric flow rate and the outflow volumetric flow rate varies. It
is this trade off that must be tailored, by careful pump selection and system design,
in order to achieve an experimental setup in which to test leak detection mechanisms.
Essentially as shown through Figures 3-5 (a) and (b), improving the leak volumetric
flow rate by reduction of the end cap hole diameter results in a reduction of the
outflow volumetric flow rate and thus a reduction of the velocity of the fluid inside
the piping system testing area.

With a more powerful pump, for example the pump corresponding to the perfor-
manence curve D in Figure 3-3, it would be possible to achieve a higher outflow
volumetric rate while maintaining a larger pressure in the system. This, according to
the model presented here, should result in a higher leak volumetric flow rate without
such a significant reduction in outflow volumetric flow rate.
Figure 3-5: (a) Leak Volumetric Flow Rate as a function of End Cap Diameter $d_3$. (b) Outflow Volumetric Flow Rate as a function of End Cap Diameter $d_3$. 
Chapter 4

Conclusions & Future Work

Two experiments were conducted in order to test the effect of the leak on the threads of the detection mechanism.

The first used a pressurized sealed pipe with a leak and a hose to drive the flow. The system was mounted vertically to allow the threads to hang parallel to the pipe walls. The experiment was successful in that the threads of the detection mechanism were clearly affected by the leak. When the tips of the threads were aligned with the leak, they started to slowly deflect towards it, until some of them suddenly got pulled through the leak (as seen in Figure 2-2 (b)). However, it was not realistic because of the lack of outflow. In order to solve this problem, a second setting was designed.

The second experiment was mounted horizontally and the end of the pipe opened to allow for cross flow. A pump was used to drive the flow. However this experiment failed in that the threads of the detection mechanism were not affected by the leak due to the small leak flow rate (as seen in Figure 2-5). The leak flow rate and outflow flow rate were measured to be of the order of 0.005 L/s, and 5 L/s respectively. In order to increase the leak flow rate, the outflow hole diameter had to be decreased.

A theoretical model of the experimental setup is proposed in order to understand how the exit hole diameter affects the leak volumetric flow rate and the outflow volumetric flow rate.

From the theory it was calculated that with the current pump and piping system design, in order to achieve a reasonable leak pressure and leak flow rate, an end cap
hole of 5 millimeters in diameter is required. Although this value would create the necessary pressure in the proximity of the leak, it would also reduce the outflow flow rate to approximately 0.6 liters per second, making this experiment invalid because of the low velocity of the flow inside the pipe (approximately 0.8 meters per second) which is not representative of a real piping system.

Therefore, the pump that is currently being used is not powerful enough to achieve the required pressure and flow rate conditions necessary to mimic a real system. It is recommended that a suitable pump be used allowing for a leak pressure of approximately 0.5 MPa while maintaining an internal velocity of approximately 1 meters per second.

It is also important to note that the above theory is a first cut analysis and thus neglects the presence of the leak at first for the sake of simplicity. Future work should include more experiments to validate and improve the above theory.
Bibliography