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| **NUCL 355 Experiment 1** |
| Manometry and Basic Hydrostatic Pressure  Professor S. T. Revankar |
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| School of Nuclear Engineering  Purdue University  Report of the Experiment By:  Weston Cundiff, Stephen Cox, Kara Luitjohan, Patrick Burk, Dominic Ghering, Michael Stryker, Austin Curtis, Matt Metzger, et. Al. |
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# Executive Summary

The main purpose for performing this experiment was that of demonstration. Several concepts were demonstrated through the use of an apparatus consisting of a network of tubing, tanks, and valves. By the configuration of the piping and valves, manometry could be shown, as well as Bernoulli’s equation and natural circulation. The section involving a pressure transducer also demonstrated how to calibrate a system for accurately measuring pressure based on the pressure generated in a water column. Values were taken and these were correlated with the voltage drop across the pressure transducer, yielding a linear relationship for correlation.

The setup was then utilized to show that no matter the volume or shape considerations, the water height of two connected tanks will equalize because gravity is the only force working on the liquid elements. A tank of much larger diameter than another was filled, and then flow was opened between the two. Despite the much smaller diameter in the second tank, the height of the water column was exactly the same. That demonstrated that the height is the only factor to be considered in manometry.

Then natural circulation was demonstrated, as well as dynamic head. When flow is allowed, the pressure in the system measured will be less than the static head before flow is allowed because of the dynamic head. This means that some of the pressure will be tied up in a term, and the value of that term will be exactly equal to the term in Bernoulli’s equation. This explains why flow between two tanks will oscillate when nearing equilibrium until finally equalizing.

This concept was further demonstrated in a simple demonstration of natural circulation. The system was set up so that there was a large diameter tank filled much higher than a small diameter nozzle, facing upwards. The static head was taken in the tank, and the height of the nozzle and the height of the water level in the large tank were measured. It was estimated that the water jet from the nozzle would reach close to the height of the water level in the tank. When flow was allowed, the water jet reached almost 15” below the water level in the tank. This was because of the dynamic head as demonstrated in the Bernoulli’s section of this experiment, but also because of non-conservative losses categorized into major (mostly friction) and minor (because of valves, tube turns, etc.). This part of the experiment did efficiently demonstrate that with pressure differences, water can be made to run upwards against gravity.

# Introduction and Theory

The theory introduced in this lab can be split up into four different sections, namely the sections of pressure measurement, manometry, Bernoulli’s equation, and then natural circulation. The section of pressure measurement involved calibration of a very accurate instrument as well as a typical pressure gauge. The manometry section utilized a simple manometer. The Bernoulli’s section as well as the natural circulation section utilized the concepts of dynamic head, and the fact that a water column can be used to generate a pressure difference and cause flow within a system.

Pressure measurement is of great importance to the field of fluid dynamics and more specifically to the field of Nuclear Engineering (in the cooling systems within reactors). Pressure is measured as the amount of force exerted over a certain area, and thus is taken in units equivalent to Newtons/meter^2. It accurately can describe many fluid systems. Two ways typical ways of measuring pressure are with gauges or transducers. The pressure gauge is made of a needle attached to a bent flattened brass tube. When pressure is forced into the tube, it tends to straighten out, pushing the needle clockwise. This can be aligned with a scale and, within the elastic region of deformation for the tube, yield accurate results over and over again. A more accurate and reproducible measurement can be taken using a transducer. The transducer includes a piezoelectric crystal. Piezoelectric systems generate current for the different amount of force placed on them. In this case, because of the circuitry, the system can start to create a different voltage drop for different amounts of pressure (utilizing an RC circuit). Using a voltmeter, a linear relationship between pressure values and voltage readings can be used to take very accurate pressure readings using this transducer.

Manometry plays on a simple principal. The principal that gravity is the most common (in fact, in all terrestrial systems, ever-present) body force is used to demonstrate a very simple property. In manometry, systems are set up so that the only body force is the force of gravity. Because of this force of gravity, only the height of the water column can be considered when modeling the system. Vertical tubes partially filled with water are utilized, and connected to other vertical tubes. Because the water height (and only gravity, the body force) is the only non-negligible consideration, the height in either tube must be equalized. This can be used to measure pressure differences. At equilibrium, if two water heights in tubes are different, the amount of pressure created in that height difference is exactly equal to the pressure difference on the surface of both tube surfaces. This concept is proven and used over and over again, often in slanted tubes. Slanted tubes allow for more precise measurement of the height difference in the water column because of the longer length and the exact nature of sine calculation.

Natural circulation and Bernoulli’s equation are interconnected. Bernoulli’s equation states that:

This implies that the only concerns in modeling a system are based in the pressure put on the system, the dynamic head of the system, and the height of the water column in the system. The height of the water column consideration has already been discussed and is the core of manometry. The term *gz* is Bernoulli’s way of calculating it in a system. The pressure term, normalized to differing densities, explains how to calculate a system that has differing pressures in the separate parts of the system. This difference in pressure must be made up by the other two terms in the Bernoulli equation, to ensure the constant value that the equation is equal to.

The dynamic head term, namely is the term that must be considered when modeling systems that involve moving fluid. This term states a fact that is not apparent by conventional reasoning: that a system of moving water will lose some component of its pressure or water column height because of the movement of that fluid. This concept is best visualized when considering differing pressures on a tube filled with water. The water will start to flow because of that differing pressure. That fact is an easy fact to visualized, but at first glance the concept does not seem that simple.

Dynamic head and manometry go hand and hand into developing natural circulation. Natural circulation is creating flow within a system upward against gravity without using pumps or pressure differences, only gravity. This is done in all towns, using water towers to ensure water pressure in all taps within the town. The difference in height between the highest water level and system and the nozzle or flow valve must be great enough to overcome the losses due to dynamic head (as discussed), as well as to major loss and minor loss. Major loss is the loss in a system due to the friction developed by flow against rough surfaces (the pipe surfaces). Minor loss has to do with turbulence in a system that is caused by the movement through U-Tubes, elbows, valve openings, nozzles, and other pipe elements.

Overall, many concepts of hydrostatic pressure as well as fluid dynamics must be understood in order to gain the full impact of the demonstrations in this experiment. The concepts include pressure measurement, manometry, Bernoulli’s equation, and natural circulation, but also go into more topics such as pipe elements, major loss, and minor loss.

# Experiment Description

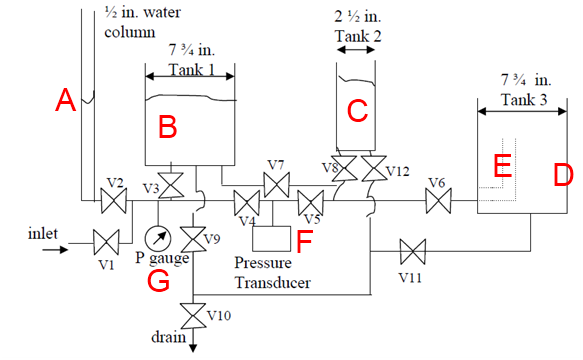
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Figure .1 Experimental Setup Adapted

The setup above shows an involved system for demonstrating simple hydrostatic pressure principals as well as manometry and Bernoulli’s equation. It is made up of four tanks. One tank (A) is a scaled water column that can be used for calibration of more accurate pressure measuring devices (F, G).

Another tank (B) is simply a large water tank that can be isolate from the entire system. This tank allows water to be filled up to a certain level and then allowed to flow through the rest of the system.

A third tank (C) is similar, but is height adjustable. This tank can be moved upward and downward to attain the required amount of head for the experiment. It can also be isolated from the entire system.

The fourth tank (D) is simply an overspill tank for a fountain (E). The fountain has a small diameter outlet, allowing for small streams of water to be projected upward at higher velocities than the rest of the system. This fountain and tank is also able to be isolated from any other component.

The pressure transducer (F) is the most technologically advanced part of the entire system. A small piezoelectric crystal is placed in a circuit and opened to the line pressure from the system. A piezo crystal will generate a different current based on the physical pressure placed on the crystal itself. When put in an R-C circuit, this creates an easy way to measure the pressure on the crystal. Using a voltmeter of some sort, the voltage across the circuit can be taken. This voltage is proportional to the pressure that is being placed on the circuit.

The pressure gauge (G) is another, less accurate way to measure pressure, although with a more visual approach. Using the concept of hose unraveling under flow, a small bent brass tube will tend to straighten, which in turn will turn a needle. This needle will read a pressure for the amount of straightening that is in the hose. It is a very common way of checking pressure in a line.

The rest of the system is made of piping components, including valves, inlet and pump, and outlet to drain. These components are configured so that each component may be filled individually and also isolated from the pressure in the entire system.

# Data Acquisition

Acquisition of data in this experiment was a straight forward matter. The experiment was set up in four different stages: the calibration stage, the manometry stage, the flow stage, and the natural circulation phase. They were implemented as follows:

The calibration stage involved using known pressure values to compare to the values given on the pressure gauge and the pressure transducer. A column of water was filled to height, and that height was recorded, as well as the corresponding reading off of the pressure gauge (given in inches of water) and the reading of voltage from the Digital Multimeter which indicated the reading of the pressure transducer. This was done for various heights along the entire range of the water column height.

The manometry stage was done to show how the geometry and components of a system do not matter if they are under the same pressure. The heights will equalize because the pressure is only overcoming gravity in any system. One large tank (tank 1) was filled to height, and that height recorded from the table. Flow was then allowed between that tank and another tank (tank 2) of different geometry. The heights of the water level in each tank were taken again. The physical height of the second tank was changed, and the water level was measured again after time was given for the tanks to come to equilibrium.

The flow stage was a good demonstration of the progression of equalizing that two tanks go through due to dynamic head and Bernoulli’s equation considerations. Two tanks were filled, with one tank then physically moved so that its head was much higher than the other tank. The pressure transducer readings were taken for the static head in each tank. Flow was then opened, and the pressure transducer reading was taken every five seconds for an appropriate amount of time.

The natural circulation stage showed the robbing effects of dynamic head. A tank was filled and held above a fountain. When flow was allowed, the height of the water level in the tank was recorded as well as the height of the fountain.

# Analysis and Discussion of Data

## Instrumentation Calibration and Static Pressure Measurement

### Instrument Calibration (versus rough pressure gauge)

The graph shown below shows the correlation between the values (in inches of water) measured on the rough pressure gauge and the voltage measured by the pressure transducers. The linear fit shows a good correlation, meaning the pressure transducer can be used to more accurately measure the pressure in the system, using the equation of the trendline, shown on the graph.

Figure .1 Pressure Gauge vs. Pressure Transducer

### Static Pressure converted to Pascals and comparison to measured values

The pressure gauge has inherent error, but is often used because of the visual nature of the measurement. Using the sample calculation 9.3.1 and the pressures measured off of the pressure gauge, this inherent error can be found. The table below shows the differences in pressure from the pressure gauge (converted from inches of water to Pa) and the pressure caused by the water column (calculated using 9.3.1). It is clear that the pressure measured by the gauge is slightly lower than the actual pressure created by the water column.

|  |  |
| --- | --- |
| Pressure (from Height, Pa) | Pressure (from Gauge, Pa) |
| 17738.0741 | 16688.9563 |
| 16289.750 | 15642.7829 |
| 14857.000 | 13948.9784 |
| 13673.423 | 12828.0784 |
| 12427.553 | 11482.9983 |
| 11493.151 | 10710.8227 |
| 10184.987 | 9440.4693 |
| 8970 | 8419.2048 |
| 7739.9674 | 7223.5781 |
| 6509.671 | 6102.6781 |
| 5233 | 4981.7780 |
| 4017.931 | 3736.3335 |

Table .1 Pressure (Water Column, Pressure Gauge) [Pa]

### Calibration Curve Correction

Because of the inherent error in the pressure gauge (as shown above), the correct calibration for the pressure transducer must be done using the values calculated from the water column. The chart below shows the pressure created from the water column versus the voltage from the pressure transducer, showing a linear correlation again, and showing the trendline and equation that can be used to calculate pressure from the transducer voltage.

Figure .2 Pressure (Water Column) vs. Pressure Transducer Voltage

## Manometer Principal

### Measured Pressure Values

Sections of the system in the manometry section of this experiment were partitioned and the pressures were taken through these sections. The pressures that were measured are considered the “static” head, and they can then be used to compare the two sections in manometry. After a long enough period of time with flow allowed, the static head (if measured again) will be equal between the two components.

### Equilibrium Water Levels

In the two tanks, despite the shape considerations, and even differing cross-sectional areas of the tanks, when two tanks were connected, the water level always returned to equilibrium at the exact same height in both tanks. This means that, no matter how large one tank is and small the other tank is, the water levels will return to the exact same elevation in both tanks. This can be shown between Tank 1 and Tank 2, when they returned to the height of 25.75” above the table, despite Tank 1 having a diameter of 7.75” and Tank 2 having a diameter of 2.5”. This can be explained by the concept of manometry. The equation shows that the only contribution to pressure is the contribution of gravity. Because pressure between the two tanks is likely to move towards equilibrium, the only term that can be changed is *h* the height of the water column, thus showing why the levels equalize and there is no dependence on shape or cross-sectional area.

### Manometry in a PWR

Because of the incredibly high pressures in a PWR, manometry as a way of measurement is practically impossible, and will never be used. In sample calculation 9.3.2, a water column height is calculated to equal a pressure differential of 1500 psi, which is a typical pressure within a PWR pressure vessel. This calculation shows that to measure that high of a pressure; the water column would be more than a kilometer in height (1.05 km). This type of structure, as well as the equipment required to read it, would be extremely expensive and fragile, making manometry a very unfavorable way to measure pressures in a PWR.

## Bernoulli’s Equation

### Dynamic Head

In the Bernoulli’s Equation experiment, pressures were taken throughout a time interval while flow was allowed between two different tanks. The initial pressure was taken and calculated to be approximately 13 kPa, but when flow started, the pressure dropped all the way to 5.9 kPa. This can be explained by the Bernoulli Equation, which states that. The atmospheric pressure is the same in all parts of the system, meaning the term can be neglected. This shows that from initial to final condition, the heights of the water columns will tend to move towards a *z* that is equal. This principal was shown in the manometry section of the experiment. But the equation also shows that while flow is occurring (*V* is nonzero) there is a certain amount of this pressure that cannot be read because it is “tied up” in the velocity of the fluid component. This dynamic head explains why there would be such a large pressure drop as soon as flow was allowed to begin.

## Natural Circulation

### Fountains

Because of the concepts of manometry found in earlier sections of this experiment, it is possible for water to move upward against gravity. If a setup is created where the water level in one tank has enough difference between a nozzle in the other component of the setup, the pressure generated by the high water level will be enough to push the water through the nozzle and upward into a fountain. This fountain will not reach as high as the higher water level because of the losses due to friction, minor losses, and also dynamic head, but it is possible for the water to become a fountain. In the experiment done, the higher water level was measured at 42.75” above the table surface, whereas the fountain height only reached to 26.75” above table surface. This demonstrates not only the ability for water to move upward against gravity, but the non-negligible losses to friction and dynamic head.

### BWR Fountain Concepts

In a BWR, the water coolant is forced upward through the core. This can cause problems because if a pump were to break, the water would not be able to be forced upward through the core. It would be a good idea to connect the coolant system to a very high water tower. In this case, the difference in height when flow was opened would create such a pressure difference, that a fountain of coolant water would be shot upwards into the core and void above the core. The water tower would have to be tall enough to overcome the losses due to friction, minor losses, as well as the dynamic head. This water tower would end up being very tall, but could help avoid a design-based accident if there was a mechanical malfunction in the pumps of the coolant system.

# Unusual and Unexpected Findings

Because of the simplicity of the theory behind this experiment, there is nothing that was observed that can be considered unusual or unexpected. It was unexpected that the height of the fountain in the natural circulation stage was so much lower than the pressure head, but this can be completely accounted for in friction losses as well as dynamic head.

# Conclusions, Recommendations and Comments

This experiment successfully demonstrated several concepts of simple hydrostatic pressure as well as manometry and natural circulation. The transducer was successfully linearly correlated with actual pressure measurements, which were taken using the pressure gauge. This linear correlation can now be used to convert voltage measurements to accurate pressure readings of static head within the system. The equation found in part 1 of the experiment is:

*Pressure = 5539 [Pa/V] (Voltage [V]) - 7158.4 [Pa]*

This was used to accurately generate static head within the rest of the system during parts 2, 3 and 4 of the experiment.

The demonstration of manometry was very successful. It was shown that between two tubes, one of much larger diameter than the other (7.75” vs. 2.5”) and one with a differently shaped tubing element connected to the bottom that the water level would equalize because of the dependence only on the water column height. Two different times, the water level equalized (to 24.5” and 25.375”) between the two tanks. This successfully showed that manometry works.

Bernoulli’s dynamic head was also successfully demonstrated. In a system with differing water heights, static head was taken in both systems. When flow was allowed between these two systems, the pressure dropped dramatically and did not equal the equilibrium pressure (dropped to a voltage reading of 2.358 V immediately, versus 2.440 V). This showed that some of that pressure was tied up in the dynamic head of the system and could not be read by the transducer (as it was only reading static head).

This concept was also successfully proven along with natural circulation. A nozzle at a height much below the water level was allowed to have flow through it. The fountain that came out proved that not only can water be made to flow above gravity, but that considerations for dynamic head and major and minor losses must be made. The height of the fountain was nearly 15” below that of the higher water level (42.75” to 26.75”).

Overall, I would make a decently large change to the experimental setup. The use of one large system to connect all of these principals and apparatuses together was clever, and generally got the point across. But I believe that singular systems for each separate experiment would be better served. This would generate a much more visual understanding of the systems and concepts. Because of how important the concepts are to all of fluid dynamics, I believe that the concession should be made to separate it into separate experimental systems.

# Works Cited

Fox, R. W., McDonald, A. T., & Prichard, P. J. (2004). *Introduction to Fluid Mechanics* (6th ed.). New York: Wiley.

Revankar, S. T. (2011). *Lab 1: Basic Hydrostatic Pressure and Manometer Experiments.* West Lafayette, IN: Purdue University School of Nuclear Engineering.

# Appendices

## Original Data

|  |  |  |  |
| --- | --- | --- | --- |
| Trial | Gauge Reading (" W) | Height (' and " W) | Transducer Reading (V) |
| 1 | 67 | 5'11.1875" | 4.45 |
| 2 | 62.8 | 5'5.375" | 4.24 |
| 3 | 56 | 4'11.625" | 3.99 |
| 4 | 51.5 | 4'6.875" | 3.77 |
| 5 | 46.1 | 4'1.875" | 3.546 |
| 6 | 43 | 3'10.125" | 3.376 |
| 7 | 37.9 | 3'4.875" | 3.143 |
| 8 | 33.8 | 3' | 2.922 |
| 9 | 29 | 2'7.0625" | 2.691 |
| 10 | 24.5 | 2'2.125" | 2.464 |
| 11 | 20 | 1'9" | 2.230 |
| 12 | 15 | 1'4.125" | 2.000 |

Table .1 Calibration Data (Original)

|  |  |  |
| --- | --- | --- |
|  | Tank 1 Height (" W) | Tank 2 Height (" W) |
| Fill | 25.375 | -- |
| Equilibrium 1 | 24.5 | 24.5 |
| Tank 2 Lifted | 24.5 | 44.75 |
| Static Head | **2.337 V** | **3.079 V** |
| Equilibrium 2 | 25.375 | 25.375 |

Table .2 Manometry Data (Original)

|  |  |
| --- | --- |
| Time (s) | Transducer Reading (V) |
| Initial Tank 1 | 2.440 |
| Initial Tank 2 | 3.818 |
| 5 | 2.358 |
| 10 | 2.540 |
| 15 | 2.545 |
| 20 | 2.548 |
| 25 | 2.550 |
| 30 | 2.552 |
| 35 | 2.554 |
| 40 | 2.555 |
| 45 | 2.557 |
| 50 | 2.559 |
| 55 | 2.560 |
| 60 | 2.563 |
| 65 | -- |
| 70 | 2.565 |
| 75 | 2.566 |
| 80 | 2.567 |
| 85 | 2.567 |
| 90 | 2.568 |
| 95 | 2.569 |
| 100 | 2.570 |
| 105 | 2.572 |
| 110 | 2.573 |

Table .3 Bernoulli's Equation Data (Original)

|  |  |  |
| --- | --- | --- |
|  | Tank 2 | Fountain |
| Height (" W) | 42.75 | 26.75 |

Table .4 Natural Circulation Data (Original)

## Reduced Data

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Trial | Gauge Reading (" W) | Height ('," W) | Height (" W) | Pressure (from Height, Pa) | Pressure (from Gauge, Pa) | Transducer Reading (V) |
| 1 | 67 | 5'11.1875" | 71.1875 | 17738.0741 | 16688.9563 | 4.45 |
| 2 | 62.8 | 5'5.375" | 65.375 | 16289.750 | 15642.7829 | 4.24 |
| 3 | 56 | 4'11.625" | 59.625 | 14857.000 | 13948.9784 | 3.99 |
| 4 | 51.5 | 4'6.875" | 54.875 | 13673.423 | 12828.0784 | 3.77 |
| 5 | 46.1 | 4'1.875" | 49.875 | 12427.553 | 11482.9983 | 3.546 |
| 6 | 43 | 3'10.125" | 46.125 | 11493.151 | 10710.8227 | 3.376 |
| 7 | 37.9 | 3'4.875" | 40.875 | 10184.987 | 9440.4693 | 3.143 |
| 8 | 33.8 | 3' | 36 | 8970 | 8419.2048 | 2.922 |
| 9 | 29 | 2'7.0625" | 31.0625 | 7739.9674 | 7223.5781 | 2.691 |
| 10 | 24.5 | 2'2.125" | 26.125 | 6509.671 | 6102.6781 | 2.464 |
| 11 | 20 | 1'9" | 21 | 5233 | 4981.7780 | 2.230 |
| 12 | 15 | 1'4.125" | 16.125 | 4017.931 | 3736.3335 | 2.000 |

Table . Calibration Data (Reduced)

## Sample Calculations

### Converting Water Column Heights to Pressures

### PWR Water Column Height

## Error Analysis

Error analysis in this experiment is simply a reflection on the precision of the instruments used. Because this was a lab based only in demonstration, and findings were not particularly concluded, the error analysis is trivial.