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Performance Testing of Small Water Pumps: A Versatile and Economical Laboratory Exercise for Engineering Technology Students

Prof. T. Sean Tavares Ph.D., University of New Hampshire

The author is an Assistant Professor in the Mechanical Engineering Technology Program located at the Manchester campus of the University of New Hampshire. He has held this position since the fall of 2014 following more than 20 years of industry experience. His industry experience has included performance testing of compressors and gas turbine engines; vibration and pulsation testing and troubleshooting of rotating machinery, piping, and structures; Computational Fluid Dynamics (CFD); fluid dynamic design and analysis of turbomachinery (compressors, turbines, fans and pumps); root cause failure analysis; development of engineering software; and engineering design audits. While in industry he taught a number of professional short courses and seminars to both specialist and non-specialist audiences, and provided personalized technical and software training to industrial clients. He holds Bachelor's, Master's, and Doctoral Degrees from the M.I.T. Department of Aeronautics & Astronautics.

Performance Testing of Small Water Pumps: A Versatile and Economical Laboratory Exercise for Engineering Technology Students

T. Sean Tavares, Ph.D.

University of New Hampshire at Manchester

Applied Engineering and Sciences Department, Engineering Technology Program

Abstract

A laboratory exercise based on the performance testing of small consumer-grade water pumps provides a versatile and economical platform for teaching engineering technology students the basics of industrial experimental testing practices. This exercise also provides a practical means for students to learn firsthand about the basic operating characteristics of centrifugal pumps and closely related devices such as centrifugal compressors and fans. This experimental platform provides ample opportunities for students to gain experience with pre-test planning and uncertainty estimation, with unanticipated situations that may arise during tests that may introduce measurement error, and with post-test statistical analysis of the derived pump performance parameters. As an example, in this experiment flow rate is determined by measuring the time it takes for a pump to discharge a measured volume of water at a fixed pumping height. The flow rate is thus derived from measurement of two variables, volume and time, each prone to sources of experimental error that are easily visualized by the students. Such tangible examples of experimental uncertainty go a long way in helping students to understand techniques such as the Kline-McClintock method of uncertainty estimation, since the Kline-McClintock method involves mathematics (partial derivatives) to which many engineering technology students have had little or no exposure. The equipment used consists of consumer-grade submersible pumps sold in home improvement stores that are intended for use in small fountains. With maximum head rises of about four feet and maximum flow rates of a few gallons per minute, quantities of water involved are small meaning that the testing can be carried out in minimally equipped lab spaces, in classrooms, and even outdoors. Other equipment consists of readily available measuring vessels, stopwatches, and hardware grade buckets and tubing. The pumps are nearly silent in operation, creating no noise issues on campus. Because of the low cost of purchase and operation of the pumps, each laboratory group can have its own test setup. It has been found beneficial to have lab groups swap pumps after a first round of tests. Comparisons of performance results obtained by different groups with a common pump allows for reflection on discrepancies that may have resulted from differences in experimental techniques, care taken with measurements, and differences in compensation for various sources of loss (such as hydraulic friction in the pump discharge tubing) which are not necessarily directly attributable to the capabilities of the basic pump.

Introduction

An ability to plan, execute, and interpret experimental tests is an important part of the skill set for engineering technology graduates. In the industrial settings in which our graduates are likely to find themselves it is important to be able to plan and execute a quality test while working within constraints which may be in place. Limitations on such factors as available instrumentation, constraints on operating conditions, and availability of test time all need to be considered when planning and executing a test. Failure to do so may squander resources and waste the sometimes limited opportunity to make tests on machinery being used operationally in an industrial environment.

Student Outcomes for Engineering Technology programs (ABET, 2017) include educating engineering technologists with respect to experimental methods. In this document for both associate’s and bachelor’s degree programs 3.A.c. and 3.B.c both state:

“c. an ability to conduct standard tests and measurements; to conduct, analyze, and interpret experiments; and to apply experimental results to improve processes; “

It is the authors’ view that an important part of helping students to achieve this outcome is providing opportunities for hands-on experimentation that allows them ample opportunities to explore best practices for performing experimental tests. These best practices fall in the areas of test planning, choosing instrumentation and test procedures that will help ensure measurements with the desired level of accuracy, and taking enough repeated data to be able to perform post-test statistical analysis.

It is therefore desirable to have some lab experiments that are economical enough to allow students to take repeated data sets and also to allow the sources of experimental uncertainty to be tangible enough to be easily understood. This is particularly important as it is common in engineering practice.

This paper describes a laboratory exercise in which students measure the performance characteristics of small water pumps. The principal measurements are the variation of head rise (as manifested in the pumping height of water) and the corresponding volume flow rate while operating at a fixed rotating speed. Experiments based on this apparatus can be employed in a variety of courses and with students at various levels. The author developed this experiment while teaching a graduate level course on experimental methods in the Mechanical Engineering Department at The University of Texas San Antonio. Presently, it is being employed in a bachelor’s level course in the Mechanical Engineering Technology program at the University of New Hampshire at Manchester.

Key aspects of experimental testing that can be studied using this experiment include:

1. Pre-test assessment of experimental uncertainty and planning of test to meet uncertainty goals.
2. Practice in executing tests and developing an appreciation for unanticipated circumstances that can compromise the quality of the results.
3. Post-test analysis to see if the quality of the data is consistent with that was anticipated in the pre-test phase.

These are the principal aspects of the test that will be discussed in this paper. Other areas that can be explored are elements of a study of variations of performance of a batch of pumps in the spirit of a consumer product test, and examining ways that variations in the details of the test setups used by the students might affect performance.

Apparatus and Test Procedure

Pumps Employed and their Characteristics

The pumps used for this laboratory measurement are small capacity rotary pumps fitted with centrifugal impellers. They are commonly used in small fountains and water sculptures and are readily available in home improvement and department stores. They are available in a wide range of pumping height capabilities and flow capacities. However in the laboratory classes taught by the author, it has been found convenient to work with pumps that have a maximum flow capacity of about 10 liters per minute, and a maximum head rise of up to about 1.5 meters. These flow rates and head rises are easily measured with simple apparatus. Further the amount of water needed is small enough that tests can be performed in a minimally equipped laboratory or classroom. The water needed can be easily drawn, transported and disposed of, and if a spill occurs, the amount of water is easily contained and cleaned up. The purchase price is typically $20-30 US per pump; therefore multiple units can be acquired for a class at modest cost.

A typical pump suitable for the experiment is shown in Figure 1. The photo on the left of the figure shows an assembled pump with a length of discharge tubing attached. Water enters the pump through the gills in the area labelled with “Inlet” and is discharged from the pump through the tubing. The pump is shown fitted with clear flexible polymer discharge tubing. There are some advantages to using clear polymer tubing that allows observation of the water. However, if the tubing chosen is relatively soft care must be taken to avoid kinks that will restrict the flow. The pump is shown partially disassembled in the right hand photo. The inlet grating and the cover on the inlet side of the pump impeller have been removed. The white star-shaped piece is a six-bladed rotating impeller.

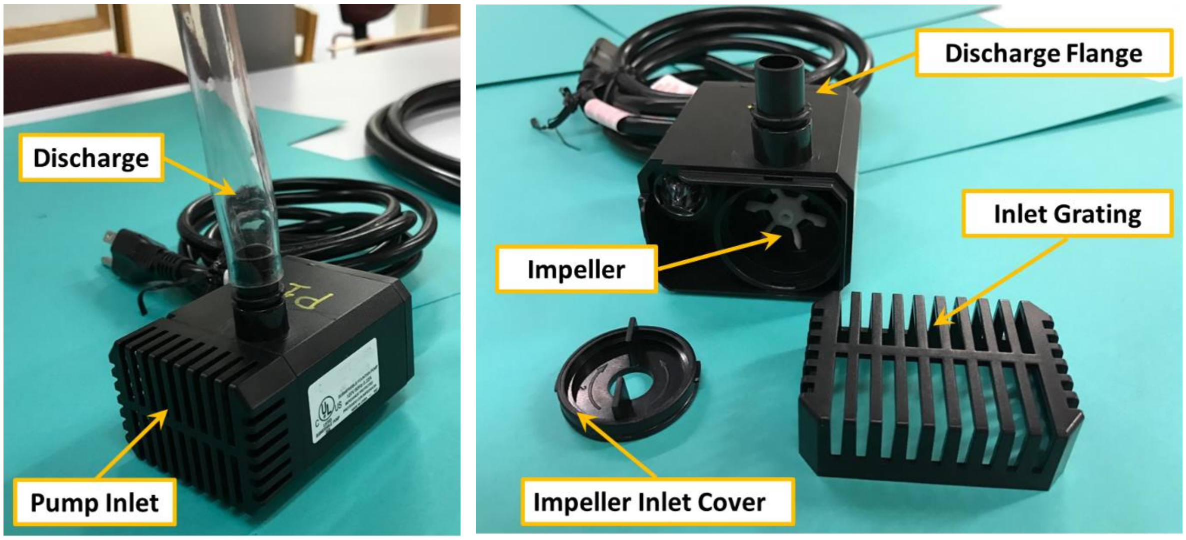


Figure 1 Typical submersible water pump suitable for performance measurement laboratory. Left: Pump with discharge tubing attached. Right: Partially disassembled pump showing magnetic-drive impeller.

The pumps employ a magnetic-drive mechanism that allows the electric motor drive to be isolated from the portion of the pump in contact with the water. Figure 2 shows the impeller removed from the pump. The attached magnet (greyish cylinder) serves as the pump shaft. Torque is transmitted to the shaft by a rotating drive magnet located inside the sealed unit containing the electrical components. This arrangement eliminates the need for a mechanical shaft seal that would be needed by a direct mechanical coupling, which helps to reduce chances of contact between the electrical equipment and the water.

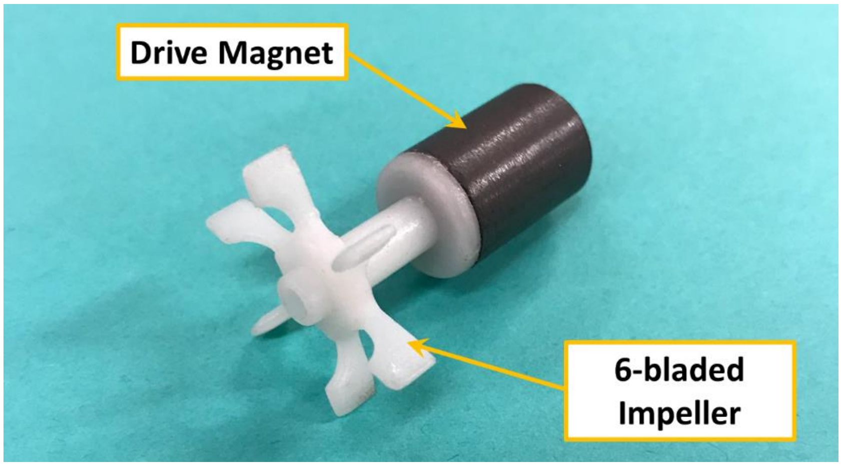


Figure 2 Pump impeller with attached magnet.

As mentioned above, one of the principal performance parameters measured is the volume flow rate (i.e., gallons per hour) that is attained when the pump delivers the water at different heights above the surface of the water reservoir. When the pump is not running, the water level in the discharge hose will be the same as that on the surface of the reservoir from which the water is pumped. Therefore, the pumping height is measured from this level as drawn in Figure 3.

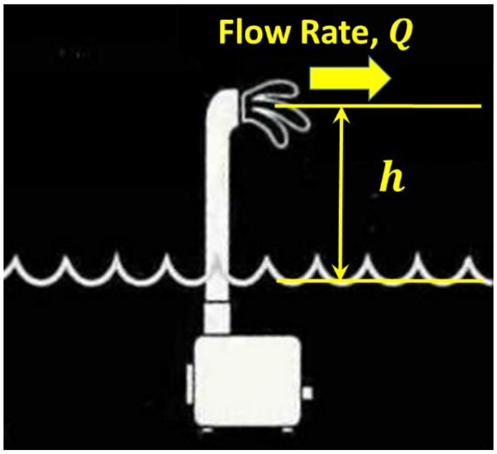
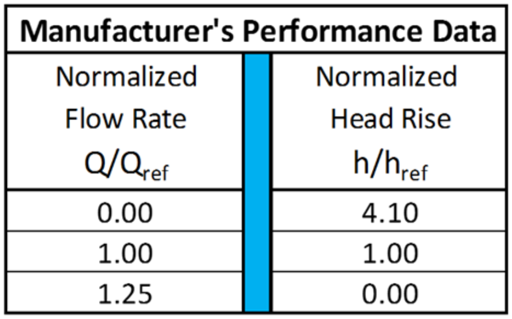


Figure 3 Pump nomenclature and illustrative manufacturer supplied performance data.

Manufacturers of small water pumps typically provide the user with a table of head rise and flow rate values at a few key operating points as an aid in choosing the correct pump for a specific application. Table 1 is an example of such manufacturer data. However, for purposes of the paper the values have been normalized in order to not identify a specific make or model of pump. The table provided by the manufacturer will contain the data in straightforward dimensional terms (i.e. gallons per hour of water pumped at the corresponding inches or feet of head rise).

Table 1 Typical data table showing variation of head rise with flow as provided by pump manufacturers. Data is presented in normalized form for purposes of the paper.



Manufacturer's Performance Data	
Normalized Flow Rate Q/Q_{ref}	Normalized Head Rise h/h_{ref}
0.00	4.10
1.00	1.00
1.25	0.00

Figure 4 shows a head vs. flow performance curve that results from plotting a curve using the performance data in the table. As is typical practice when working with turbomachinery the plot is drawn with the flow rate on the horizontal axis, and the head rise (pumping height) shown on the vertical axis.

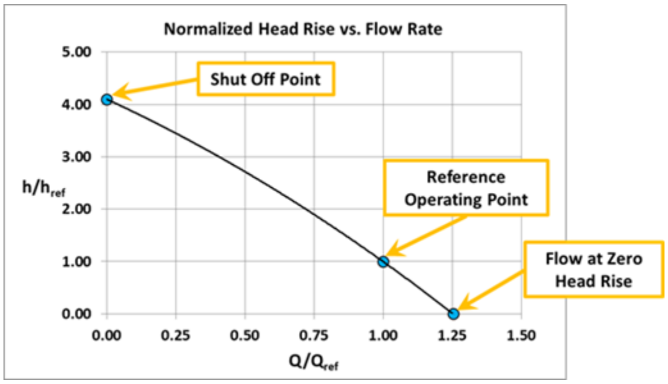


Figure 4 Typical head vs. flow curve for a centrifugal pump with flow points of interest labelled.

As is generally true for an inexpensive pump sold to consumers, there is no indication given by the manufacturer about how much an individual pump's performance might vary from that on the curve. It is not untypical for a manufacturer to state that the performance given is that of an "average" pump of this make and model.

The general shape of the curve in Figure 4 is typical of the behavior of a well-designed centrifugal pump in that the head rise gets smaller as the volume flow rate is increased. This feature tends to help the pump maintain a stable flow rate. This characteristic is also typical of compressors and fans used in applications involving air and other gases. Three particular operating points of interest on the operating curve are shown with the blue circular symbols in the figure. The first of these, located at a normalized flow rate of $Q/Q_{ref} = 1$ and a normalized head rise $h/h_{ref} = 1$ is the so-called "Reference Operating Point". Often this point corresponds to the nominal design operating head and flow of the pump. To the right of this point is the point labelled "Flow at Zero Head Rise", which is the operating point of the pump when the discharge height of the water is at the same level as the surface of the reservoir from which the pump is drawing the water. The third point is the point at which the pump delivers no net flow. This point is the so-called "Shutoff Point". At the shutoff condition, the pump will maintain a column of water at a certain height above the surface, known as the "Shutoff Head" of the pump. These points are of interest when carrying out a laboratory exercise with students, as a goal can be to try to resolve the performance at these three operating points. Operation at the shutoff point can easily be produced by raising the discharge tubing to a height beyond which the pump can raise the water. Depending on the test setup used, it may be possible to lower the discharge hose to the level of the supply reservoir and directly measure the flow at zero head rise. Alternatively, the curve constructed by measuring head and flow at a number of operating points can be extrapolated to the zero head rise point.

Head Rise and Flow Measurement

In an effort to have students come to terms with the uncertainties and inaccuracies inherent in all experimental measurements, the measuring apparatus and configuration of the test setup are intentionally somewhat rudimentary. Engineering technology graduates are quite apt to find themselves working in industrial environments and in other situations where operational conditions cannot be as precisely controlled as in a scientific laboratory. See for example discussions of uncertainties involved in field testing of large scale operational fluid machinery in Brun & Kurz (2001) and Tavares, Gatewood & Sivadas (2013).

The method used to determine volume flow rate involves measurement of the time necessary to collect a sample of water in a container. Dividing the volume of the sample collected by the time interval in which the sample is collected yields the average flow rate (volume per unit time) produced by the pump. Provided the operating conditions are held constant, this average flow rate will also be the instantaneous flow rate. Measurement by such a timed collection technique is an example of a Positive-Displacement flow measurement technique (Holman, 2012). This method can produce high accuracy, and is often employed as a method to calibrate other types of devices that are more convenient for measuring flow without having to capture a sample in a vessel. The accuracy of the timed-fill method can also be easily increased by taking larger volume samples over longer collection times.

A few examples of the types of measurement devices used for this lab are shown in Figure 5. They include common household volume measuring devices such as drink pitchers, paint buckets, and kitchen measuring cups. While adequate for their intended purposes, these are obviously not laboratory grade measuring devices. They generally have relatively coarsely spaced volume measurement increments, and the accuracy of the volume markings may be found to be off by several percent.

Figure 5 Examples of common household measuring devices used for pump flow measurement.

However, inaccuracies in the liquid volume measurement indications from these devices can be overcome by calibration against a more accurate measuring device such as a graduated cylinder. This provides an opportunity to teach basic principles of instrument calibration.

Test Setup and Practices

Figure 6 is a schematic drawing showing the setup for the pump performance test. Photos of tests in progress are shown in Figure 7. The pump is submerged in a bucket that serves as the reservoir. Since the head rise required from the pump is the difference in the height between the exit of the pump discharge tube and the surface of the feed reservoir, it is important to keep this height difference constant. This is accomplished by having one member of the test team replenish the water in the feed bucket. It is convenient to maintain the water level at the top rim of the feed bucket. Placing the feed bucket in a large plastic tub contains any water that may overflow in the course of replenishment, and prevents spillage on the laboratory or classroom floor. If the tub is sufficiently sturdy, it can also serve as a support for mounting the tape measure or ruler used to measure the head rise.

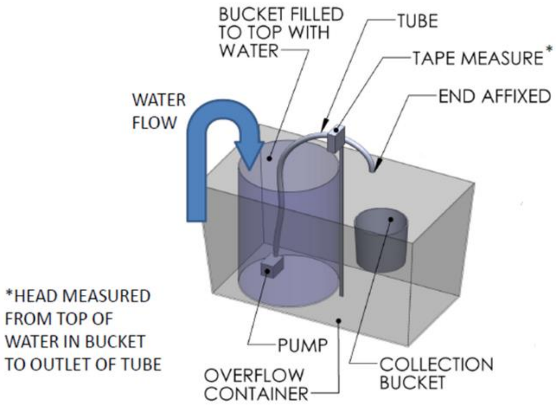


Figure 6 Schematic drawing of test setup for water pump performance measurement.

The photo at the left of Figure 7 shows how the measurement typically involves enough tasks to require three students to perform the test. In classes where a fourth student is available, this extra team member can be employed in recording data, taking photos that may be useful for documenting the tests, and in observing any anomalies in the test setup or procedure. It is felt that having a test that requires coordination of students in a team is realistic practice for many test situations encountered in industry.

Figure 7 Annotated photos showing water pump test setup and testing in progress and roles of test team.

Uncertainty Analysis

An ability to appreciate the factors that may affect the accuracy of a test, and to quantify the effect of uncertainties in individual measured quantities on the test results, is a vital part of performing high quality experimental measurements. Knowledge of the effects of uncertainties assists the experimenter in choosing the correct instrumentation and other test equipment, and also in formulating appropriate test procedures and practices in a given situation. Often a test performed in an industrial environment is subject to a number of constraints that makes this planning especially important. Testing must sometimes be carried out on equipment that is being used in production, where opportunities to run the equipment at special operating conditions can be both limited and expensive.

Documents of best practices and industry standards for performance testing are available for most types of equipment. Examples that are pertinent to fluid machinery include society standards such as ASME PTC-10 (1997) and Brun & Nored (2006). A good society standard for uncertainty analysis that is applicable to a wide range of testing is ASME 19.1 (1990). This ASME standard includes discussion of the uncertainty estimate method developed by Kline & McClintock (1953). These methods are also well explained in a number of textbooks, an example being the one by Holman (2012). The sections below discuss a few aspects of quantifying experimental uncertainty that can be explored within the pump performance laboratory described in this paper.

Use of Uncertainty Ellipses in a Two Variable Measurement

Producing an experimental pump performance curve involves the measurement of two quantities, head rise and volume flow rate, at a series of operating points. Figure 8 is an illustration of such a measurement point overlaid with a reference performance curve. Such a reference curve might be a manufacturer's performance claim or the result of a design calculation. At first glance, an observer might be tempted to conclude that the experimental measurement indicates that the pump head rise is definitely higher than the reference curve indicates at the corresponding flow rate. However, the head rise and flow measurements are subject to experimental uncertainty, and these uncertainties need to be quantified before drawing a reliable conclusion.

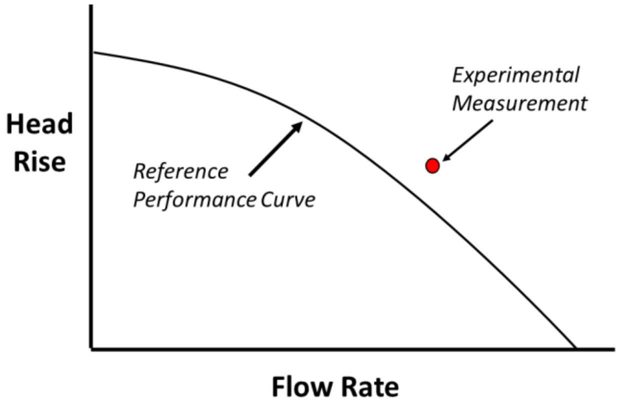


Figure 8 Illustrative comparison of an experimental measurement at one operating point to a reference operating curve.

The concept of the uncertainty ellipse as described by Brun & Kurz (2001) is helpful in showing the how effects of uncertainty on a two variable measurement can be illustrated effectively. Figure 9 illustrates the development of this concept. In the plot on the left, the experimental data point is shown with error bars added to show the estimated uncertainty in the head rise and flow rate. A dotted line rectangle has been added that encloses the error bars. Given these levels of uncertainty, the actual head and flow quantities corresponding to this measurement can conceivably lie anywhere inside the rectangle, with the corners of the rectangle representing instances where the errors in both quantities would be at the limits of their estimated uncertainty.

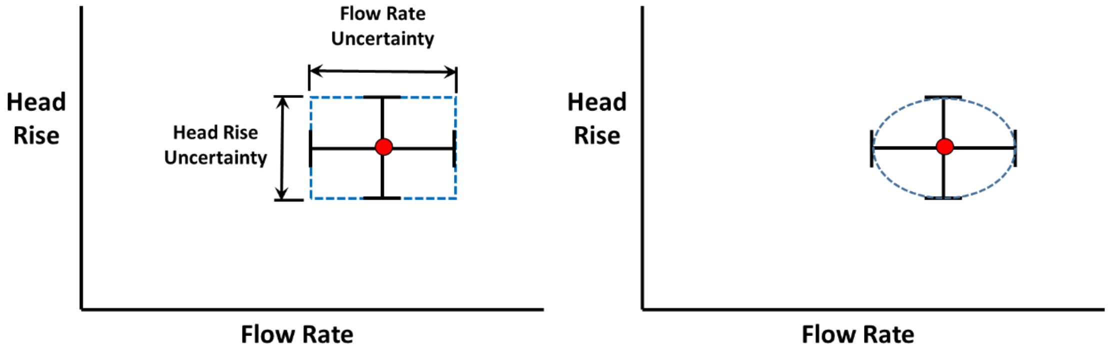


Figure 9 Illustration of the concept of the uncertainty ellipse for a two variable measurement.

From a statistical standpoint however, it is unlikely when taking a particular data point that the maximum levels of uncertainty will occur simultaneously in the measurements of both head rise and flow rate. It is instead more probable for the uncertainty to lie within an ellipse having axes of the length of the two uncertainty levels. This is the underlying concept of representing uncertainty with an ellipse, as illustrated in the right hand plot on the figure.

The value of the uncertainty ellipse in drawing a conclusion from an experimental measurement is shown in Figure 10. In the plot on the left, the experimental uncertainty is rather large, in the respect that the uncertainty ellipse overlaps the reference performance curve. This means that statistically, the actual value of the measurement cannot be conclusively determined to be different from the reference performance curve. As drawn in this example, there is enough uncertainty in the measurement of head rise and flow rate that a significant overlap is present. However, if the quality of the measurements can be improved sufficiently, the size of the uncertainty ellipse will be small enough that there is no overlap with the reference curve, and the measurement can be interpreted as demonstrating a distinct performance difference.

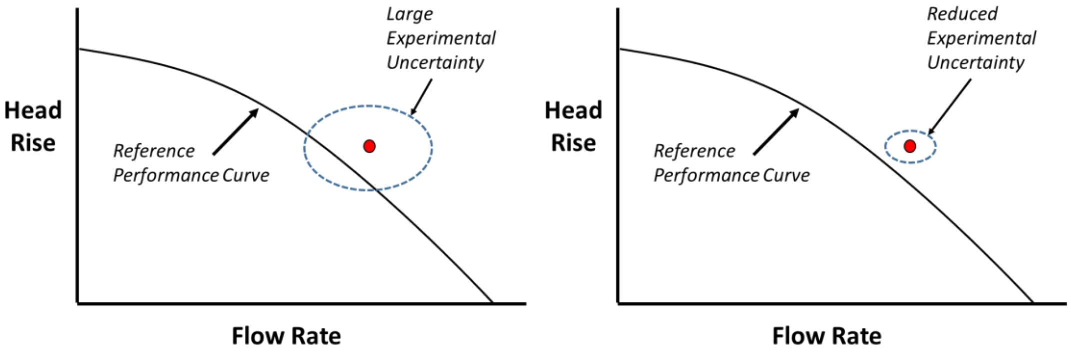


Figure 10 Illustration of the effect of uncertainties of different magnitudes represented by ellipses on evaluating experimental results.

Pre-Test Uncertainty Analysis

An important part of obtaining high quality experimental results involves making pre-test estimates of uncertainties in the measurements to be taken, and selecting instrumentation and test techniques accordingly. Making uncertainty estimates and quantifying the propagation of uncertainties in two or more measured quantities into a final experimental value can be a somewhat complex subject for students. A standard technique for uncertainty analysis and propagation of uncertainty is that of Kline and McClintock (1953). In particular, the standard treatment of the Kline and McClintock technique involves the use of partial differentiation to obtain the sensitivities of a quantity to each measured variable. This level of mathematics is often not yet familiar to engineering technology students. However, a simplified treatment, which at least incorporates the propagation of the effects of two uncertainties can usefully introduce the concept. The book by Holman (2012) refers to this simplified treatment as "Error Analysis on a Commonsense Basis".

As an example, the flow rate in the experiment described here is obtained by dividing a measured amount of fluid collected in a container by the time required to collect it. The measured volume, V_{meas}, can be represented as the sum of the volume which was actually collected, V_{actual}, and any measurement error, ΔV. Therefore, $V_{meas} = V_{actual} + \Delta V$. Similarly, the time interval measured consists of the sum of the actual time interval and any time measurement error: $t_{meas} = t_{actual} + \Delta t$. The measured volume flow rate that results from these two measurements, Q_{meas} , can then be expressed as:

$$Q_{meas} = \frac{V_{meas}}{t_{meas}} = \frac{V_{actual} + \Delta V}{t_{actual} + \Delta t}$$

From this result, one can see that both the volume and time measurement errors will have a cumulative effect on the flow rate derived from these measurements. Depending on the signs of the errors in the two quantities (which are equally likely to be positive or negative in the case of random measurement error), the measured errors can either compound or compensate each other in some manner. In the case where the measurement errors ΔV and Δt are taken to be small relative to their respective actual values, a good approximation to the difference between the measured and actual flow rate, Q_{actual}, is:

$$Q_{meas} - Q_{actual} \cong Q_{meas}\left[\frac{\Delta V}{V_{actual}} - \frac{\Delta t}{t_{actual}}\right]$$

For the same statistical reasons discussed in connection with the uncertainty ellipses, it is unlikely that one will encounter the maximum uncertainties in both the volume measurement and the time measurement simultaneously. This means that the equation above is somewhat conservative in its calculation of the total uncertainty. The more sophisticated analysis used in the Kline and McClintock method calculates the combined error using the square-root of the sum of the squares of the individual uncertainty values.

However, the simplified analysis given above gets across the basic ideas of sensitivities to individual measurement errors and how these errors propagate into quantities calculated from them. With these concepts introduced, the extension to use of the full Kline and McClintock method is relatively straightforward. One can, if desired, continue to use finite difference representations of the sensitivities to uncertainties rather than ones based on partial derivatives.

Post-Test Data Reduction, Uncertainty Analysis, and Reflection

Following collection of data, the flow rates can be calculated from the timed volume measurements. Standard techniques can be used to obtain averages and to assess scatter in the data, and to reject data points that are clearly outliers. If multiple points have been taken at a fixed operating condition, outliers can be formally identified using Chauvenet's criterion (Holman, 2012). Data reduction and plotting of the resulting performance parameters can easily be done using a spreadsheet. Figure 11 shows a representative comparison of student test data to the manufacturer's performance curve. The plot shows that in the test performed in the classroom, the head rise at a given flow is noticeably lower than that shown in the curve supplied by the manufacturer. For the three test points where the flow rate is non-zero, ellipses representing the estimated uncertainty in head and flow are included. The ellipses do not overlap the manufacturer's curve for any of the data points shown. This indicates that, provided the uncertainty estimates are reasonably correct, the lab test demonstrates that the pump tested underperforms relative to the manufacturer's supplied data. Since there is no net flow at the shutoff point, there is no uncertainty in the flow rate. Therefore the only uncertainty in performance at this point is in the head rise, which is shown as a solid blue bar with circular symbols.

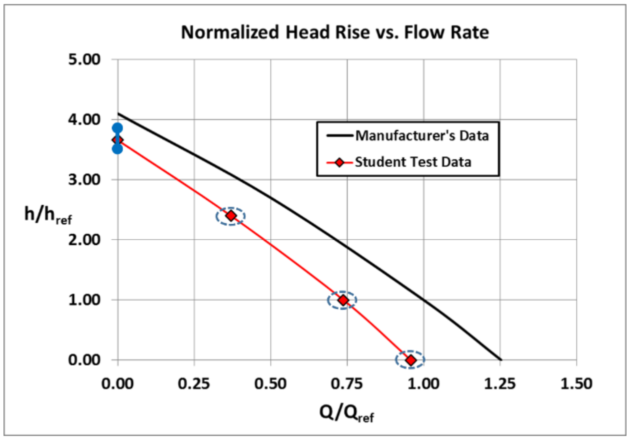


Figure 11 Representative comparison of observed pump performance data to manufacturer supplied performance curve.

Because the tests are easily repeated, there are ample opportunities for students to make multiple measurements at a single operating point and to perform some post-test analysis of the consistency of the data.

Figure 12 shows an example of a post-test examination of observed flow rate measurements, represented by red X symbols, at a fixed amount of head rise. The observed flow rates had a range of 345-379 liters/hr. with a mean of 363 liters/hr., which is shown as a solid red line. The pre-test uncertainty measurement was approximately +/- 7.5 liters/hr. The observed range of 345-379 is approximately twice as large as the pre-test uncertainty level, which suggests that the students may wish to go back and revisit the assumptions used in making the flow rate error estimate.

Students can easily repeat experiments using longer or shorter measurement times and observe the effect on uncertainty. Other aspects of post-test reflection may include calculations or experiments to quantify losses due to the tubing used and how variations in test technique could affect the results.

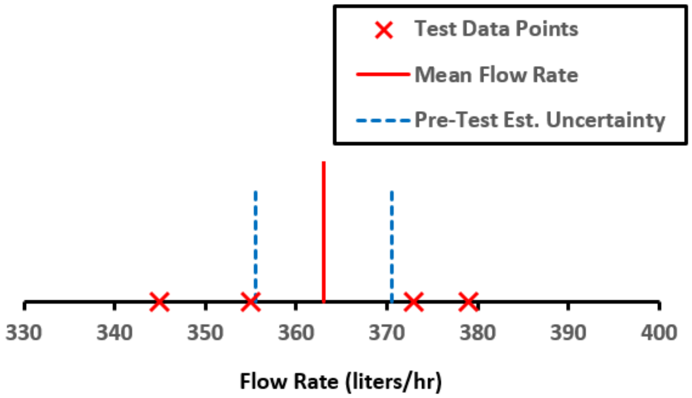


Figure 12 Example showing results of 4 flow rate measurements at a fixed operating condition.

Conclusions

Experiences with incorporating the testing of small water pumps in an engineering technology curriculum have shown that it is a versatile and economical tool for learning valuable techniques in experimental testing. The tasks involved in carrying out this laboratory are relatively simple, but at the same time are very effective in illustrating the effects of uncertainty on the quality of the results obtained. A pre-test uncertainty analysis is valuable in demonstrating how the effects of errors in individual measurements can compound themselves when used in calculating performance parameter values. An appreciation of the effects of errors can help the students learn how to choose appropriate instrumentation and test procedures. Since the testing is inexpensive and proceeds relatively quickly, it is also practical for students to take enough repeat measurements to allow post-test statistical analysis to be performed. This post-test analysis can be compared to the pre-test uncertainty analysis, and provide a basis for reflection on factors that may not have been anticipated, and thereby guide changes to the test technique that will yield higher quality measurements.

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Author

The author is an Assistant Professor in the Engineering Technology program at the University of New Hampshire at Manchester. His areas of expertise include turbomachinery, gas turbine engines, and thermal-fluid analysis. He holds Bachelor's, Master's, and Doctoral Degrees from the M.I.T. Department of Aeronautics & Astronautics.

Disclaimer

The information presented in this paper is intended to illustrate the methods and typical quantities measured in an educational exercise. None of the data presented should be interpreted as representative of any particular make or model of pump. No conclusions about quality of any product or correspondence of performance measured in the classroom with the actual capability of the pumps should be drawn. The photos and performance data are drawn from a mixture of pump makes and models.