Laboratory Experiment: PUMPING POWER LAW FLUIDS

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"I'm approaching my junior year in my Chem E degree … and that's the year which is considered the most difficult. … Any tips would be much appreciated" an anonymous student posted on Reddit.com. The first response posted: "It was hell." As educators, this is probably not the way we want aspiring chemical engineers to view their educational experience. View it as challenging—yes. But does it need to be hell? Experiential learning is one way faculty can help the students succeed and thrive. It is well established that it increases the percentage of students who understand concepts and improves long-term retention of the material.[1,2] It also has been linked to enjoying courses more.[3] Further, hands-on learning experiences support integration and synthesis of knowledge, which will help students throughout their careers.[4] Listening to student comments about dreading junior-year courses and their fear of failing led to the development of the laboratory experiment described in this paper.

One of the challenging courses in the third year is a course in fluid mechanics/dynamics or transport phenomena. Calculating friction losses, sizing pumps, and learning how different pumps operate are important themes of the course. The students often take a chemical engineering laboratory course at the same time, where they may create a characteristic curve for a pump or calculate friction losses. Many laboratory experiments study water flowing through a centrifugal pump, which is logical, since that is how industrial pumps are characterized. These hands-on experiences are helpful, but perhaps more can be done to help students understand the complex material.

WHAT PUMP TO USE? A REVIEW OF THE LITERATURE FOR STUDENTS

A review of the literature shows few papers studying the effect of viscosity on specific pumps. In 1945, Arthur Ippen studied the flow of viscous oils through centrifugal pumps, and established rules for the influence of viscosity on the head, discharge, and input power characteristics of a pump.[5] Journal articles such as this are intimidating for third-year chemical engineering students. Textbooks provide basic information on pumps, but as a first source of information the students find the drawings and mixture of theory and empirical equations complicated. *The Encyclopedia of Chemical Engineering Equipment* contains basic information on pumps, which is helpful.[6] However, pump manufacturers often provide appropriate initial literature on their websites. While the intended audience may be less technically literate than students, the students are able to read and understand the literature, appreciate the colorful schematics, and use the information as the basis for building further knowledge: scaffolding their learning.

PumpSchool.com is a useful place for students to begin learning about pumps. The pdf "When to use a positive displacement pump vs. centrifugal" provides useful diagrams. In plain language, many other concepts are explained, including net positive suction head (NPSH), pump selection scenarios, and pumping shear sensitive fluids. In addition, a section on "Typical Liquids" provides insight to pumping fluids from acetone to zinc oxide. While the site provides

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basic introductory information, it contains little information on centrifugal pumps.

Thus links to other industrial resources are useful, such as the *Pump Selection Handbook*,[7] which covers the basics of both centrifugal and diaphragm pumps, and the Alfa Laval *Pump Handbook*,[8] which thoroughly covers terminology, theory, and pump selection and description. These resources are all available online, so students can refer to them as they complete homework problems and analyze their experimental results. Familiarity with the language used in these resources and vendors' websites is also helpful when students have an internship or co-op experience. A recent article confirmed the need students have for practical knowledge about pumps.[9] This article will now be required reading for our students. Links to these and other resources (some of which contain information about pumping viscous liquids) are provided to the students on the classroom management system.[10-14] Homework questions are also assigned online to ensure the students read the literature.

Few undergraduate experiments using non-Newtonian fluids have been published. One experiment has students find the effective shear rate for non-Newtonian fluids near an impeller of a mixing tank.[15] Another experiment introduces students to the differences in flow of Newtonian and non-Newtonian fluids by comparing the drag force on a sphere whose velocity can be controlled.[16]

The experiment described in this paper uses solutions of xanthan gum dissolved in water as the non-Newtonian liquid. Xanthan gum is a high-molecular-weight extracellular polysaccharide produced by bacteria and is widely used in the food and personal care product industries. At the experimental concentrations used it behaves as a shear thinning power law fluid, and the degree of shear thinning behavior increases with concentration.[17] Eq. (1) shows the relationship of apparent viscosity to shear rate for a power law fluid, where η_{app} represents the apparent viscosity [Pa s], γ is the shear rate [s^{-1}], K is the flow consistency index [Pa s^n], and n is the flow behavior index.

$$\eta_{app} = K(\dot{\gamma})^{n-1} \tag{1}$$

In the assigned readings, students learn that the shear they measure with a viscometer is much lower than the shear experienced in a pump or pipeline, as diagrammed in Figure 1 (modeled after the Alfa Laval *Pump Handbook*[8]), which they verify in the experiment. The shear rate at the wall for a Newtonian fluid is calculated by

$$\dot{\gamma}_w = \frac{4\nu}{R} = \frac{4Q}{\pi R^3} \tag{2}$$

where γ_w is the shear rate at the wall (s^{-1}), v is the average velocity (m/s), R is the radius of the tube (m), and Q is the volumetric flow rate (m^3/s). For a power law fluid, the wall shear rate, γ_w, can be expressed in terms of the apparent wall shear rate, γ_{app}, according to Eq. (3):

$$\dot{\gamma}_w = \frac{(3n+1)}{4n}\dot{\gamma}_{app} \tag{3}$$

where $\dot{\gamma}_{app} = \frac{4Q}{\pi R^3}$ and n is the flow behavior index of the fluid.[18]

The experiment described in this paper was developed as an interesting way to allow students to directly observe the differences when pumping water as well as viscous Newtonian and non-Newtonian fluids

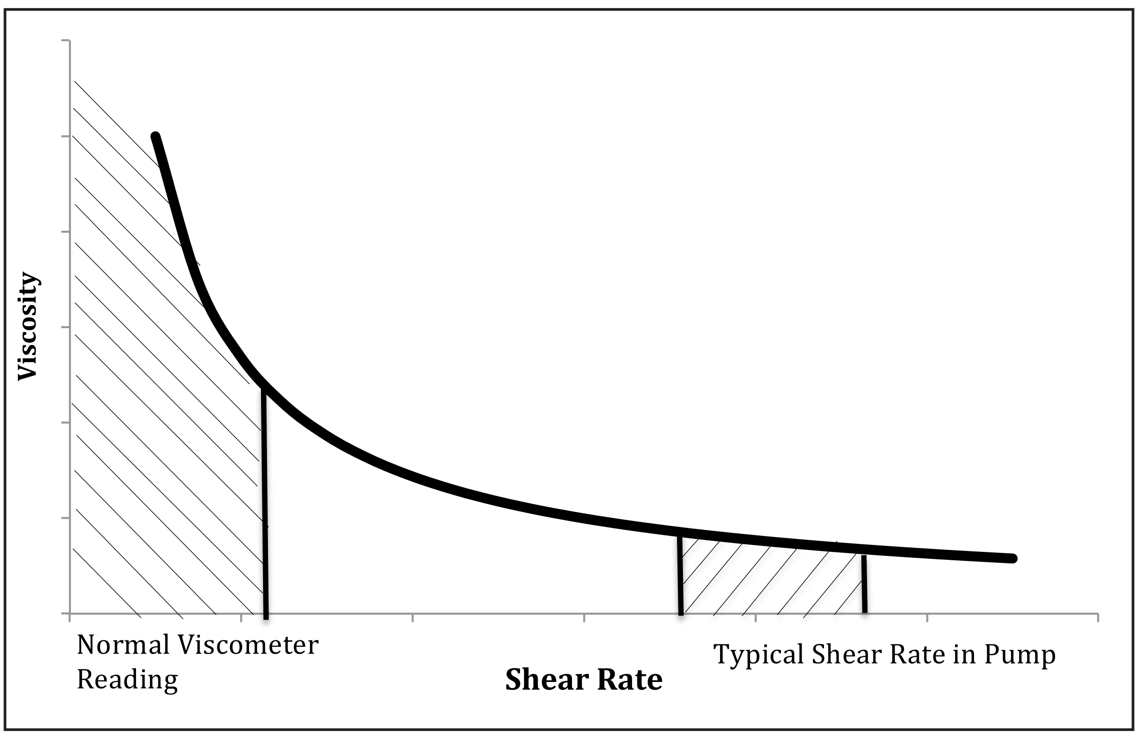

Figure 1. *Viscosity as a function of shear rate for a power law fluid. Modeled after Reference 8.*

TABLE 1
Learning objectives for the experiment

Learning Objectives: At the end of the experiment, the students will be able to • Calculate the flow behavior and flow characterization indices from power law fluid data • Explain why different pump types are used for viscous and non-Newtonian fluids • Collect data and create a pump characteristic curve (Head vs. flow, Flow vs. power) • Explain the difference in the curves for Newtonian and non-Newtonian fluids

TABLE 2
Supplies for the experiment. C indicates equipment for the centrifugal pump experiment, PD indicates equipment for the positive displacement pump experiment.

	Part	Description	Cost
C	Fittings	12 couplings, tube mounting clips	$42
C	Fittings	2 elbows	$16
C	Tubing	3/8” OD, 72” long,	$4
C	80/20	72” for one support stand, available from 8020.net	$34
C	Centrifugal Pumps	PacificHydrostar mini submersible pumps, models 68389, 68396 and 68395, available from HarborFreight.com	$41
PD	Positive Displacement Pump	SEAFLO 12v Water Pressure Diaphragm Pump 4.3 L/min 1.2 GPM 35 PSI – Model PDP1-012-035-21, available from Amazon.com	$30
C	PD Xanthan Gum	Anthony’s Xanthan Gum, 1 lb package, available from Amazon.com	$13
	Total		$180

using centrifugal and positive displacement pumps. The learning objectives are listed in Table 1.

Currently the experiments can be constructed for less than $200. The data is consistent with theory and addresses major concepts within fluid-flow operations. To fully explain the results requires a deep understanding of how both pump types operate and non-Newtonian flow phenomena.

LABORATORY DESCRIPTION

Table 2 lists the equipment necessary for the experiments. The 80/20 aluminum used for each centrifugal pump support frame is one of the more expensive items, but is lightweight, sturdy, easy to work with, and professional looking. The base of the frame is H-shaped with the long sides constructed from 30 cm lengths of 30mm × 30mm T-slotted Profile Aluminum and the crossbar constructed from a 25 cm length of 30mm × 60mm T-slotted Profile Aluminum. The length of the vertical tubing support depends on the maximum pump head, and ranged from 90 to 120 cm. It was constructed from lengths of 30mm × 30mm T-slotted Profile Aluminum. Tube mounting clips fit in the aluminum slots on the vertical support and can slide up and down to hold the tubing firmly to the frame. End caps are available at 8020.net and ensure the frame looks professional. The material is easy to work with and thorough assembly instructions are provided on the website. One frame per group is needed. Figure 2 is a photo of the frame and a centrifugal pump. Clear tubing is cut to various lengths (from 3 – 9 cm) so students can construct heads of different heights using the couplings. One elbow connects the tubing to the pump and the other is used to direct the exiting fluid. In an early version of the experiment, flexible tubing was used instead, and the students lifted it to different heights on the support stand to vary the head. This was sometimes messy and inaccurate, but it is less expensive if multiple setups are needed.

Students or the instructor prepared the fluid samples by slowly adding xanthan gum to water while stirring to make solutions of 1000, 2000, 4000, and 8000 parts per million by mass (ppm). Patience is necessary in order to avoid “fish eyes,” or lumps of undissolved xanthan gum. The students used each solution in the following experiments.

Figure 2. *The frame used for the centrifugal pump experiments. One submersible centrifugal pump is on the left. It was placed in a container of the fluid during the experiments.*

First, the students poured about 400 ml of each solution into a 600 ml beaker, let it sit until bubbles dissipated, and measured the viscosity from 20 to 200 rpm using a Brookfield viscometer. The students had used the viscometer in the previous semester, and were familiar with its operation, so if time was short the instructor provided the data instead. However, since they had not found the flow characteristic index and flow behavior index for a power law fluid, they were expected to do the calculations.

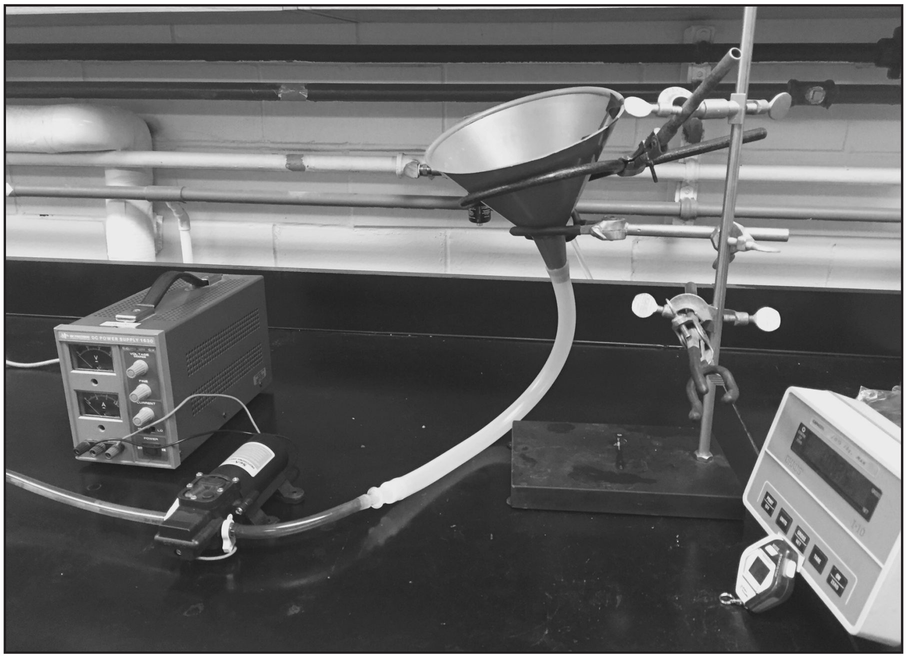

__Figure 3.__ The diaphragm pump and the DC power supply. The funnel held the solution to be pumped.

For the pump experiments, students were divided into four groups: one group for each of the three centrifugal pumps and one group for the positive displacement pump. All data were shared. Three groups collected data for a Head vs. Flow characteristic curve for water and the four xanthan gum solutions using the centrifugal pumps with the apparatus. Three pump sizes (maximum heads of 70, 110, and 140 cm) were available, and each group measured the flow of the five solutions through one pump. Pieces of tubing were connected in sequence (*i.e.*, first one 3 cm piece, then two 3 cm pieces, then one 3 cm and one 5 cm piece, and so on until the maximum head was reached). Quick connect fittings made it easy to adjust the height. The flow rate at each height was measured using a stopwatch and a graduated cylinder.

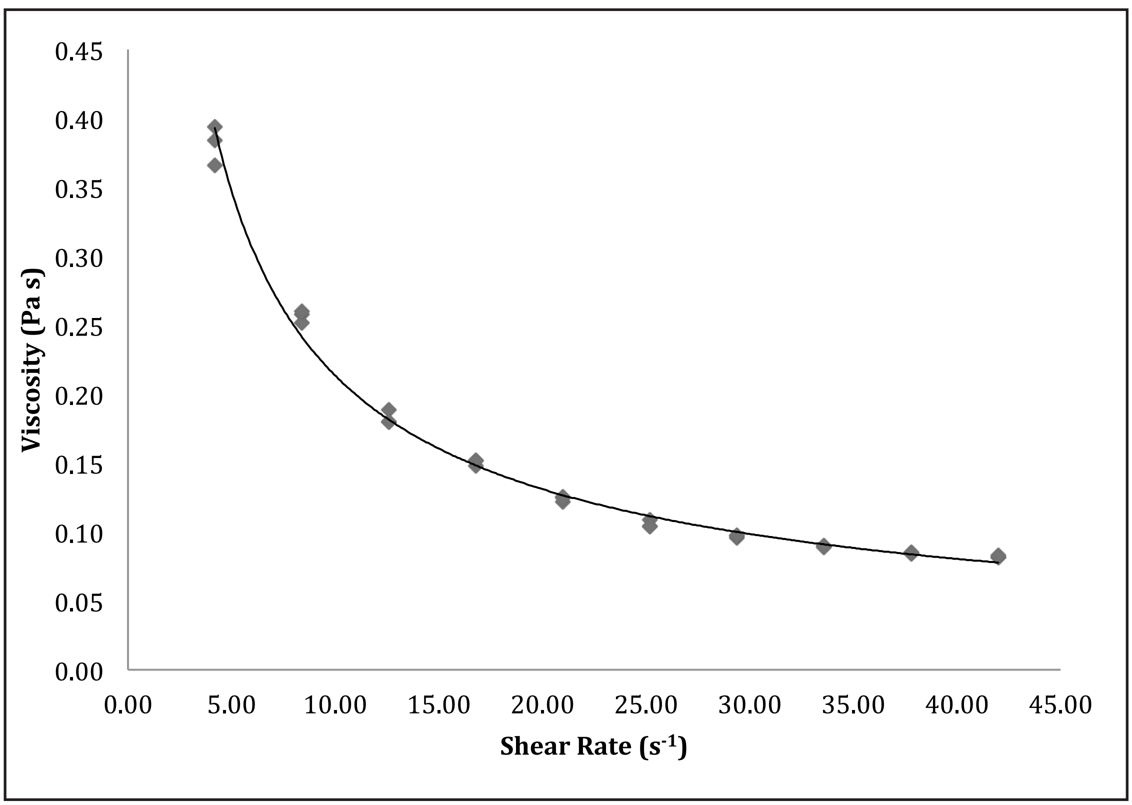

__Figure 4.__ Viscosity data for 4000 ppm xanthan gum. Three replicates were collected for each shear rate.

The last group of students used the diaphragm pump to measure the volumetric flow vs. power for water and the xanthan gum solutions with power inputs from 2 – 12 W. The apparatus is shown in Figure 3. The students used the DC power supply to set the voltage, and then measured the flow rate at different power inputs. This apparatus also has pressure sensors across two elbows, so friction losses could also be measured for the non-Newtonian fluid.

DATA ANALYSIS

First, the students linearized the equation for a power law solution in order to find the parameters that characterize the viscosity of the xanthan gum solutions. A typical graph is shown in Figure 4. Students obtain flow behavior and consistency indices for the solutions using the Brookfield viscometer. As the concentration of xanthan gum increases from 1000 to 8000 ppm both indices increase – the solutions become more viscous and less Newtonian (the flow behavior index, n, varies from 0.6 to 0.3 over the range studied).

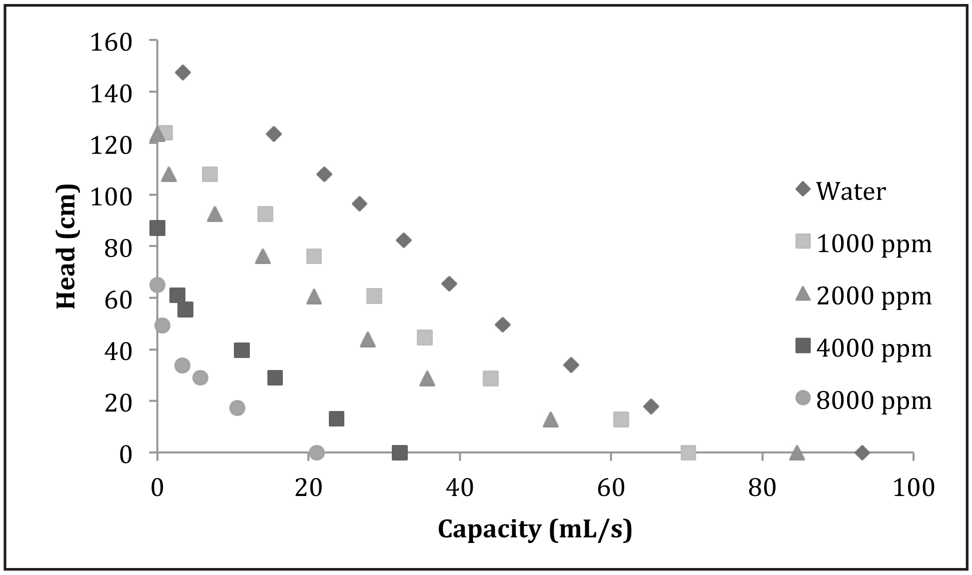

Figure 5. Data from the centrifugal pump (Rating: max head = 140 cm). Each data point is the average of three replicates.

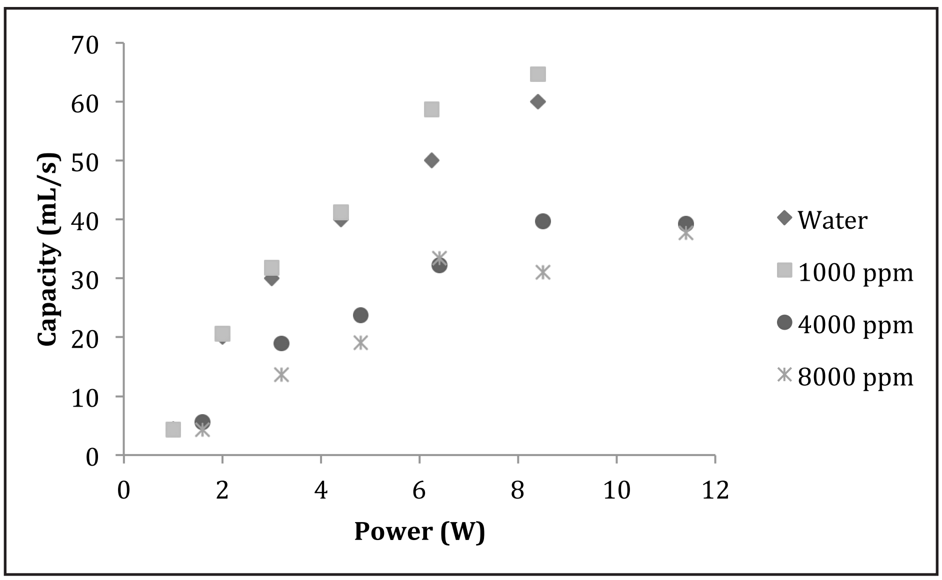

Figure 6. Data from the diaphragm pump.

The Brookfield viscometer provides rotational rates of 20 – 200 rpm (corresponding to shear rates of 4.2 to 42 s^{-1}).[19] One of the learning objectives is for students to compare the shear in a viscometer with the shear that the fluid experiences as it flows in the tubing. Students calculate the wall shear rate for the experiment, and note a difference between assuming Newtonian [Eq. (2)] and non-Newtonian [Eq. (3)] fluids (errors of 5 – 40% between the two depending on the flow behavior index, n). However, what students notice the most is the shear rates are far larger than what they tested in the Brookfield viscometer—3000 s^{-1} for a flow rate of 15 mL/s! So—what are the implications for pumping a non-Newtonian fluid? Using the shear rate of 3000 s^{-1}, they can use Eq. (1) to estimate the apparent viscosity in the tubes—about 0.0030 Pa s, about two orders of magnitude lower than found with the viscometer. As pointed out in the Alfa Laval *Pump Handbook*, the shear rates apparent during pumping are often much higher than those measured in the lab.[8] At these shear rates, the fluid may behave as a Newtonian fluid.

The characteristic curve for the centrifugal pump comparing the head for water and the xanthan gum solutions is shown in Figure 5. As the solutions become more viscous—and less Newtonian—the maximum head and the capacity both decrease. This is consistent with what the students read in the various references. Centrifugal pumps have difficulty with viscous solutions.

The students measured the capacity at different power using a diaphragm pump (see Figure 6). This graph was more difficult to interpret. A diaphragm pump moves the same volume of fluid with each cycle, and therefore, viscosity should not affect the capacity. In fact, for a positive displacement pump, as the viscosity increases the flow rate may as well, because the higher viscosity liquids more fully fill the pump clearance, causing higher volumetric flow. The data for the 1000 ppm solution agrees with this. For the higher concentration solutions, however, capacity diminishes. An extensive literature search has not led to a general explanation of this observation. The most likely explanation is the non-Newtonian behavior of the fluid—it takes a while to get the fluid moving, but once it starts, it becomes less viscous. The pump cycle begins again—and since the fluid is slow to move at the beginning, the capacity is lessened.

SUMMARY OF EXPERIENCES

After using the pumps for a few years as a project in an applied fluid dynamics course outside class time, several best practices have been developed. Initially, the students pumped ketchup and noted the drop in head and capacity compared to pumping water.[20] While the students learned the concepts from the experiment, the ketchup stained the tubing and was expensive to purchase in large quantities. Using xanthan gum is an improvement. It is best if the instructor, teaching assistant, or laboratory technician prepares the xanthan gum solutions. It can be difficult to prepare them without creating high-concentration, gel-like particles, and they need to sit for 24 hours before they can be used. They are then good for three days. Since students have tight schedules, it works best for them to be told the solutions will be available for these three days, and to plan accordingly.

The experiments described used short lengths of tubing with quick-release fittings. The initial version of the experiment used one long length of flexible tubing, and sliders on the frame to raise it to different heights. While this method was less expensive and allowed students to choose more different heights, and skin friction losses were constant, it resulted in more spills.

The centrifugal pumps can be taken apart easily and the impeller diameter measured. Then further analysis on pump affinity laws could be completed.

Students enjoyed the laboratory. Since each group only collected data for one-size centrifugal pump or the diaphragm pump, they shared the data through a spreadsheet on Google docs. If a group did not collect data from enough pump heads (by not varying the tubing length combinations), peer pressure forced them back into the lab—not the instructor! Some groups improved the data collection method by videoing the fluid collecting in the graduated cylinder, and analyzing the video.

ASSESSMENT

Table 3 contains the results from assessing the student reports and exam questions. The reports were read carefully and points were assigned for calculating the flow characteristic and behavior indices for xanthan gum solutions (Student Learning Objective (SLO) 1); creating the centrifugal pump curve for the different xanthan gum solutions and the plot showing capacity at different power supplied for the diaphragm pump for the solutions (SLO 3). The accompanying report text was assessed for SLO 4. SLO 2 was assessed through an exam question asking students to suggest the best type of pump for a list of different fluids. Additional assessment data for the learning that may have occurred due to the experiment came from two exam questions, one asking students to find the flow characteristic and behavior indices for a fluid given experimental data, and one asking them to interpret a pump curve for different fluids.

The student reports clearly showed that the students were able to characterize non-Newtonian fluid behavior and choose the appropriate pumps. Most reports also included correct pump curves for the two pumps; however, one group switched the axes on the characteristic curve (*i.e.*, they plotted the capacity as the head varied). As the scores for exam questions on the topics show, the students learned from their report, and created the correct plot on the exam. However, on the exam a few students forgot how to linearize the power law equations and were unable to determine the flow characterization indices.

CONCLUSIONS

First, the instructor learned a lot about pumps and non-Newtonian fluids while developing the experiment and helping the students explain and understand the results. At the end of the experience, the students had a far deeper understanding of both the different types of pumps and non-Newtonian fluid flow. Overall, the instructor hopes that as more of these experiences are developed and implemented in courses throughout the curriculum, students will no longer fear the junior year. It is beginning—several months after the anonymous student posted

TABLE 3
Results from the assessment of student learning

Assessment Question Topic	Assessment Mechanism	Average Score	Range
Calculate the characteristic parameters for a power law fluid	Report Exam	94.5 85.4	90-100 50-100
Choose a pump for Newtonian and non-Newtonian fluids	Exam	100	100
Create a pump curve for a centrifugal pump using four fluids and explain the different curves	Report Exam	91.3 96.9	67-100 80-100
Create a graph of capacity versus power for a diaphragm pump and explain the effect of viscosity	Report	91.1	85-100

his fears about the beginning of his junior year, he posted a thank you to the chemical engineering learning community. He survived the third year.

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