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Design, Construction, and Analysis of a Chemical Engineering Unit Operations Laboratory Pumping Experiment

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Jacob Strayer

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Abstract

Pumping is ubiquitous in the chemical processing industry, and many Chemical Engineering Unit Operations Laboratories include pumping among the experiments operated by undergraduate engineering students. The design, sizing, and specification of experimental laboratory apparatus is time-consuming, so sharing experiences with designing and constructing new laboratory equipment is useful as a time-saving strategy for chemical engineering lab instructors.

A new Unit Operations Laboratory pumping experiment was designed and constructed at The Ohio State University in Summer of 2022. The apparatus consists of a feed tank, pressure sensor, throttle valve, electromagnetic flow meter, two pumps, two variable frequency drives, two differential pressure sensors, four pipe sections of varying diameter, and an automatic data acquisition system for logging flow rate, head pressure, pressure drop, and motor power input. Flow rates in the system reach approximately 75 gallons per minute for the centrifugal pump and 30 gallons per minute for the gear pump. The total cost of the system was approximately $16,700 not including the support structure or tank. A number of potential cost-saving measures are described which could reduce the cost of a similar system to approximately $7,200.

This paper provides a detailed list of all parts of the pumping apparatus, including pipes, fittings, instruments, and equipment, along with the part number, vendor, and cost of each component. A detailed construction / assembly drawing is also provided so that other Unit Operations Laboratories can easily adopt this experiment.

This paper also discusses the learning objectives of the experiment and how they are achieved in the lab. After completing the pumping lab, students should be able to:

1. Safely operate centrifugal and positive displacement pumps
2. Predict pressure drop through a horizontal pipe section
3. Construct and interpret pump performance curves
4. Perform statistical tests to analyze the effects of the independent variables in the experiment on the dependent variables

The experimental design carried out by students is also presented, along with a sample of the data generated and the calculations and statistical analysis performed in order to achieve the learning objectives in the experiment.

1 Introduction

Chemical Engineering Unit Operations (Unit Ops) Laboratories are courses in which students get hands-on experience operating equipment commonly used in industrial processes. Nearly every chemical engineering program in the United States incorporates a Unit Ops Lab or similar laboratory experience[1].

Providing opportunities for students to get hands-on experience with authentic industrial equipment brings a number of challenges to chemical engineering programs. Common problems encountered by Unit Ops Lab managers include:

- Staff members responsible for repair and maintenance of equipment may not be chemical engineers, so they may not be familiar with chemical engineering design calculations.
- In some programs, there may be no chemical engineering faculty member assigned full-time to the Unit Ops course. In others, assigned faculty members may not be provided with the time or resources needed to design and construct new equipment.
- Turn-key instructional equipment offered by third parties may be prohibitively expensive, may not target the intended learning objectives, or may not be suited to the available facilities.

For these reasons, it is the goal of the authors to share design, sizing, and specification of laboratory equipment as a time-saving tool for Unit Ops Lab instructors and managers.

The pumping of liquids is ubiquitous in industry, so pumping experiments are common in Unit Ops Labs worldwide. A wide variety of different types of pumps are used in industry, but these fall under two primary categories: centrifugal pumps and positive displacement pumps.

While previous authors have published designs for engineering laboratory pumping experiments[2], no pilot-scale design with a detailed parts list and assembly drawing was found in literature. At Ohio State, a new pumping experiment was designed and constructed in 2022. The system includes a centrifugal pump and a positive displacement gear pump, each with variable frequency drives (VFDs), along with the instrumentation needed to collect the necessary data for analysis by students.

2 Design of Pumping System

2.1 Design Criteria

The primary goals identified for the design of the pumping experiment were for students to be able to operate pumps like those used in industry and to observe the differences in their operating characteristics. A secondary goal was for students to measure pressure drop through a pipe section and compare the pressure drop to a predicted value.

To achieve these goals, several design criteria were identified:

- The pumping apparatus should include a centrifugal pump and a positive displacement pump

- The pump speed and pumping head should be easily adjustable
- Pipes of varying diameters should be available for pressure drop measurements
- The data generated and trends observed in the experiment should be representative of industrial pumping systems, and students should be able to measure statistically significant effects of the independent variables on the dependent variables.
- The pumps should be commercially available, off-the-shelf models to ensure authenticity.
- The system should incorporate automatic data acquisition for collection of pressure and flow rate measurements.

Existing utilities in the Unit Ops Lab at Ohio State included city water, 120 VAC electrical receptacles, and one 208 VAC electrical receptacle. These utilities were available on an overhead service carrier.

2.2 System Design

Figure 1 is a process flow diagram showing the preliminary design of the pumping experiment. In this design, water is pumped from a storage tank by one of two pumps. Downstream from the pump, a throttle valve is used to adjust flow resistance / head pressure at the pump outlet. A pressure sensor is located near the pump outlet to allow measurement of the head pressure. Downstream from the throttle valve, a flow meter allows measurement of flow rate. As the water returns to the feed tank, it is routed through one of several pipes of varying sizes using hand-operated valves. The pressure drop across the pipe section can be measured using a differential pressure sensor.

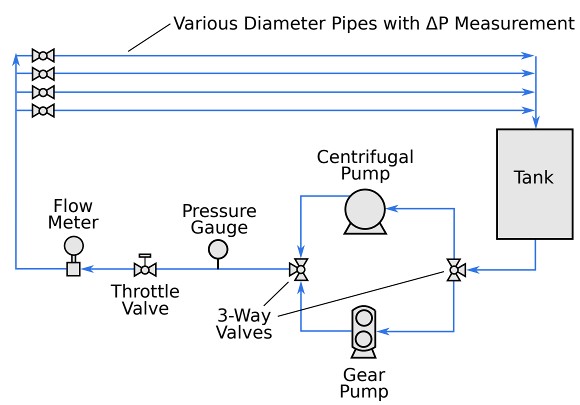

Figure 1: Initial Process Flow Diagram of Pumping System

2.3 System Specification and Assembly

With a basic design for the system completed, parts were then sized and specified. When possible, parts were sourced from common industrial suppliers to ensure availability of the components.

Table 1 shows a list of the primary flow components specified for the pumping experiment, along with their vendors, part numbers, and prices. Detailed drawings showing the location of each part are shown in Figures 2, 3, and 4. Controls / instrumentation and the aluminum support structure are detailed in separate tables (Table 2 and Appendix Table 3).

Table 1: Components of Pumping System

Label	Description	Qty	Price/ea	Cost	Model #	Vendor
-	Thick-Wall Dark Gray PVC Pipe for Water, Unthreaded, 1 Pipe Size, 10 Feet Long	1	$25.45	$25.45	48855k13	McMaster-Carr
-	Thick-Wall Dark Gray PVC Pipe for Water, Unthreaded, 1-1/2 Pipe Size, 10 Feet Long	1	$43.60	$43.60	48855k15	McMaster-Carr
-	Thick-Wall Dark Gray PVC Pipe for Water, Unthreaded, 2 Pipe Size, 10 Feet Long	5	$61.40	$307	48855k16	McMaster-Carr
-	Thick-Wall Dark Gray PVC Pipe for Water, Unthreaded, 2-1/2 Pipe Size, 10 Feet Long	1	$100.08	$100.08	48855k54	McMaster-Carr
A	Centrifugal Pump: 1 1/2 hp, 208-230/460V AC, 110 ft Max Head, 1 1/2 in , 1 1/4 in Intake and Disch	1	$1,002.40	$1,002.40	2ZXL2	Grainger
B	Gear Pump Motor: Baldor Reliance 1HP 208-230V 1765RPM	1	$759.31	$759.31	6136K93	McMaster-Carr
C	Flexible Shaft Coupling Iron Hub with Set Screw, 2-1/2" Overall Length, Keyed Shaft, for shaft dia. 1"	2	$29.99	$59.98	6408K15	McMaster-Carr
C	9000 rpm Buna-N Rubber Spider for 2-7/64" OD Flexible Shaft Coupling Iron Hub	1	$14.29	$14.29	6408K75	McMaster-Carr
D	Oberdorfer- Gear Pump, Bronze, 1-1/2"NPT Ports, Acrylic-Graphite Packed Seal	1	$2,208.80	$2,208.80	OBN13HDP	Industrial Pumps, Inc.
E	ASAHI Diaphragm Valve: 2 in Pipe Size, 43 Coefficient of Volume, 2-Way, Socket IPS, PVDF	1	$681.47	$681.47	49FA32	Grainger
F	FLOMEC Electromagnetic Flowmeter: 2 in For Pipe Size, 2 in Connection Size, MNPT, 32° to 210°F	1	$1,290.37	$1,290.37	465C60	Grainger
G	GF PIPING SYSTEMS Ball Valve: 2 in Pipe Size, Full L, 150 psi CWP Max. Pressure, 32° to 140°F	2	$330.61	$661.22	6FXG9	Grainger
H	Thick-Wall PVC Plastic Pipe Fitting for Water, Union Connector, 2 Pipe Size Socket-Connect Female	18	$31.27	$562.86	4881K66	McMaster-Carr
I	Thick-Wall PVC Plastic Pipe Fitting for Water, Short 90	16	$7.78	$124.48	4881K26	McMaster-Carr

	Degree Elbow Connector, 2 Socket Connect Female					
J	Tee: 2 in x 2 in x 2 in Fitting Pipe Size, Schedule 80, 400 psi @ 73° F, Gray	9	$27.72	$249.48	6NF85	Grainger
K	OEM Style, Compact Pressure Transmitters with Mini DIN	1	$127.08	$127.08	PX119-030GI	Omega
L	GRAINGER APPROVED Nipple: PVC, 2 in Nominal Pipe Size, 4 in Overall Lg, Threaded on Both Ends, Gray	2	$6.04	$12.08	6MW35	Grainger
M	2 Threaded 150 # 316 Full Coupling	2	$22.09	$44.18	CP2.00TH150#316	stainlessandalloy.com
N	Reducing Coupling: 2 in x 1 1/2 in Fitting Pipe Size, Schedule 80, Female Socket x Female Socket	5	$17.73	$88.65	2PMF8	Grainger
O	GRAINGER APPROVED Nipple: PVC, 1 1/2 in Nominal Pipe Size, 4 in Overall Lg, Threaded on One End	3	$6.14	$18.42	3HFT6	Grainger
P	Reducing Bushing: 2 in x 3/4 in Fitting Pipe Size, Schedule 80, Male Spigot x Female NPT, Gray	1	$11.73	$11.73	2PMH6	Grainger
Q	GRAINGER APPROVED Nipple: PVC, 3/4 in Nominal Pipe Size, 4 in Overall Lg, Threaded on Both Ends	1	$2.09	$2.09	6MV99	Grainger
R	GRAINGER APPROVED Ball Valve: 3/4 in Pipe Size, Full, 1,000 psi CWP Max. Pressure, -25° to 450°F	1	$65.77	$65.77	1WMY3	Grainger
S	Hex Head Plug: 2 in Fitting Pipe Size, Schedule 80, Spigot, 400 psi 73°F, Gray	1	$9.23	$9.23	22JY89	Grainger
T	ASAHI Ball Valve: 2 in Pipe Size, 2 in Tube Size, Full, 150 psi CWP Max. Pressure, 30° to 120°F, PVC	4	$68.99	$275.96	49EZ64	Grainger
U	2 x 1 in. Slip Reducing Schedule 80 PVC Coupling	2	$5.06	$10.12	218905	Ferguson
V	1 in. Socket Weld Schedule 80 PVC Tee	2	$2.42	$4.84	45781	Ferguson
W	1 x 1/2 in. Spigot x FPT Reducing Schedule 80 PVC Bushing	2	$1.09	$2.18	72911	Ferguson
X	Hex Reducing Bushing: 316 Stainless Steel, 1/2 in x 1/4 in Fitting Pipe Size, Male NPT x Female NPT	8	$3.55	$28.40	1LUN2	Grainger
Y	Male Connector: 316 Stainless Steel, Compression x MNPT, For 1/4 in. Tube OD, 1/4 in Pipe Size	16	$7.65	$122.40	1PZC9	Grainger
Z	2 x 1-1/2 in Slip Reducing Schedule 80 PVC Coupling	3	$5.06	$15.18	117732	Ferguson
AA	1-1/2 x 1-1/2 x 1 in. Socket Reducing Schedule 80 PVC Tee	2	$4.43	$8.86	94152	Ferguson
AB	2 x 2 x 1 in. Socket Reducing Schedule 80 PVC Tee	2	$5.61	$11.22	84919	Ferguson

AC	2-1/2 in. Socket Weld Schedule 80 PVC Tee	2	$9.02	$18.04	33129	Ferguson
AD	Reducing Coupling: 2-1/2 x 2 in. Fitting Pipe Size, Schedule 80, Female Socket x Female Socket	2	$13.77	$27.54	3TNT4	Grainger
AE	2-1/2 x 1-1/2 in Spigot x Socket Reducing Schedule 80 PVC Bushing	2	$5.77	$11.54	64414	Ferguson
AF	Hex Bushing: 304 Stainless Steel, 1-1/2 x 1/2 in Fitting Pipe Size, Male NPT x Female NPT	2	$11.25	$22.50	1LTF9	Grainger
AG	High-Accuracy Differential Pressure Transmitter, 4-20mA Output, 0-10 PSI	1	$990.71	$990.71	9917K54	McMaster-Carr
AH	High-Accuracy Differential Pressure Transmitter, 4-20mA Output, 0-1 PSI	1	$990.71	$990.71	9917K11	McMaster-Carr
AI	PARKER Mini Ball Valve: 1/4 in Pipe Size, 1/4 in Tube Size, Std, 2,500 psi CWP Max. Pressure, Nylon	4	$237.37	$949.48	1RCK1	Grainger
AJ	GRAINGER APPROVED Nipple: PVC, 1 1/4 in Nominal Pipe Size, 4 in Overall Lg, Threaded on One End	1	$5.11	$5.11	6MW08	Grainger
AK	2 in x 1-1/4 in. Spigot x Socket Weld 80 Extra Heavy Plastic Eccentric Bushing	1	$13.02	$13.02	22448	Ferguson
	Total			$11,977.83		

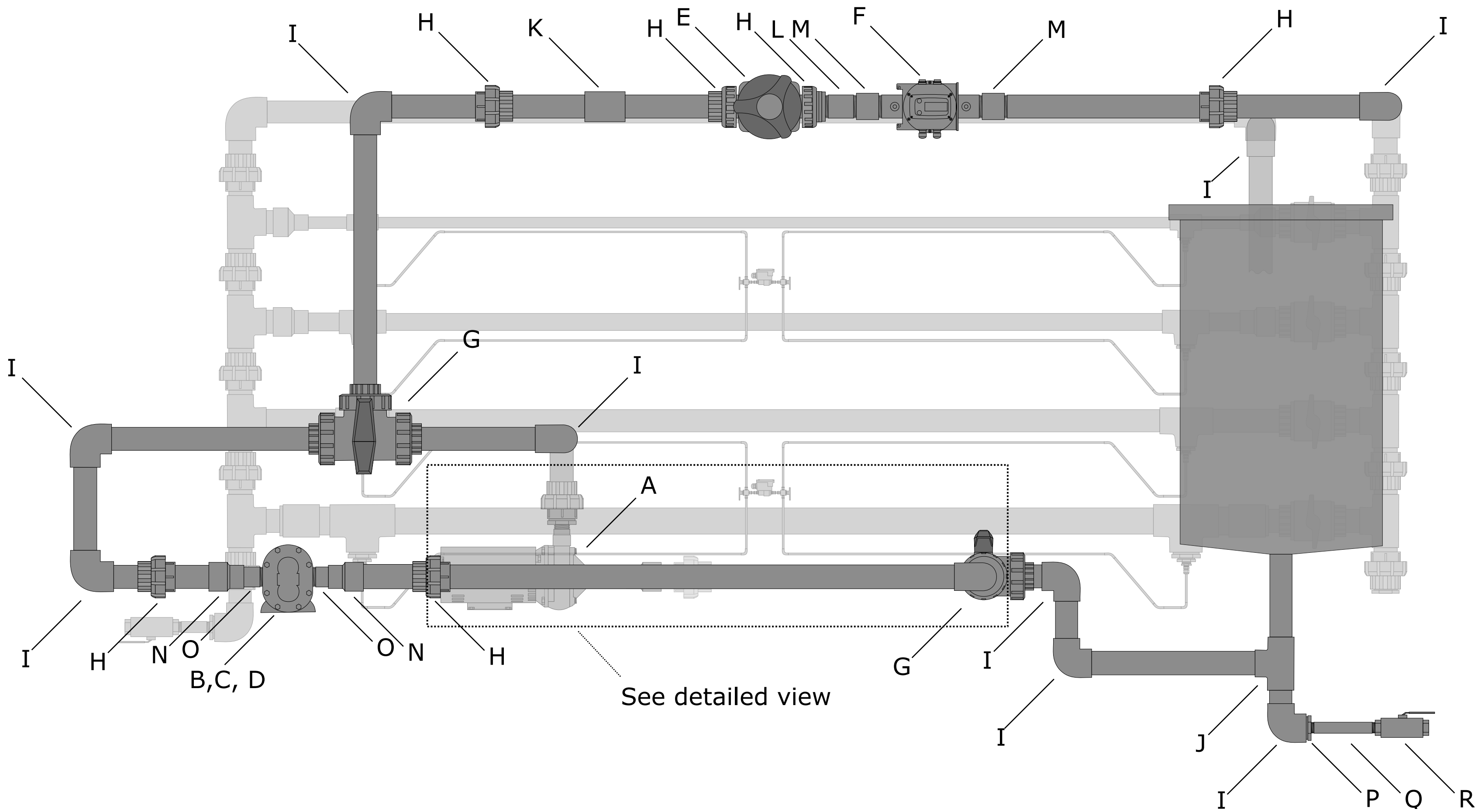

Figure 2: Detail of PHX assembly (front view). Labels reference Table 1.

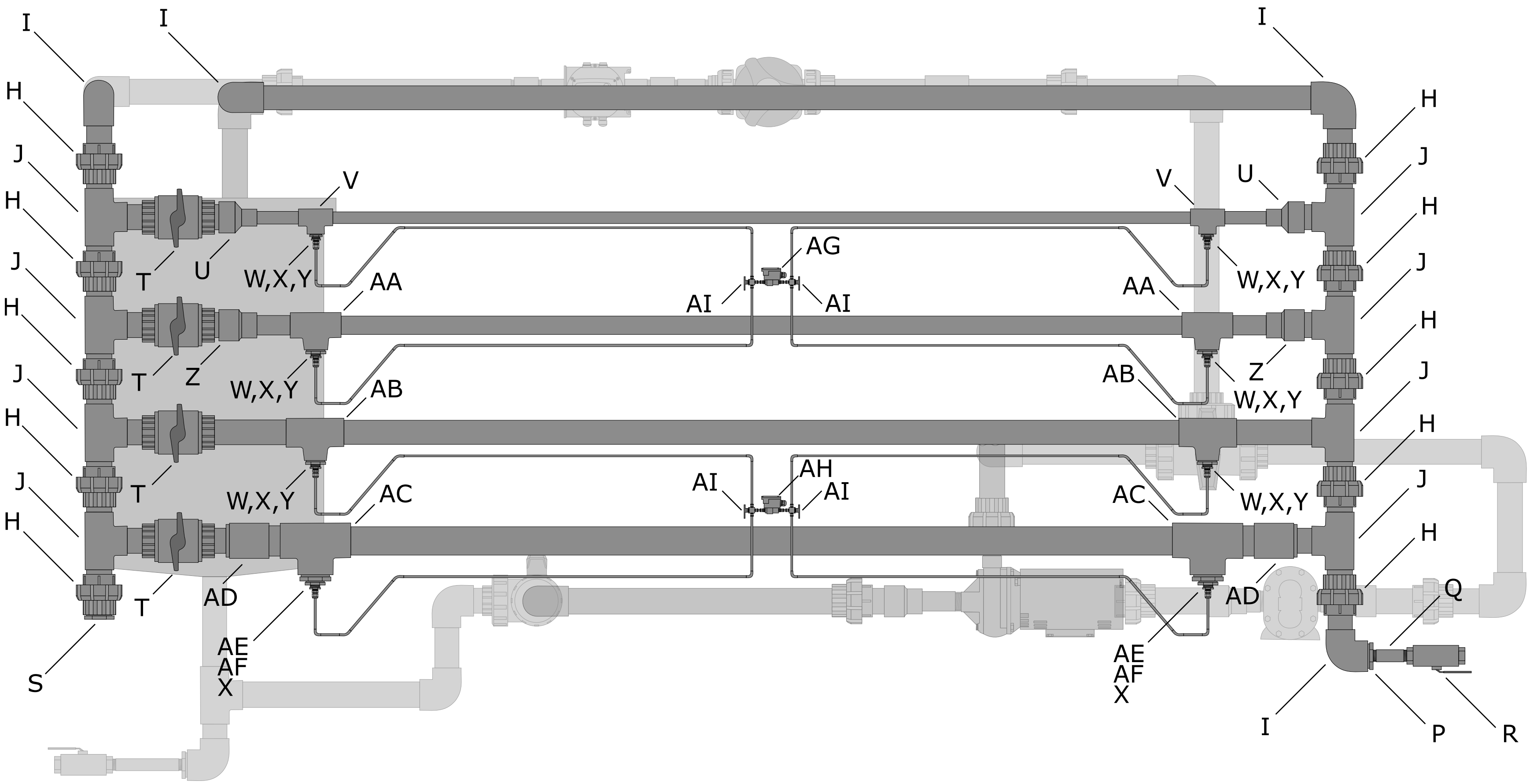

Figure 3: Detail of PHX assembly (rear view). Labels reference Table 1.

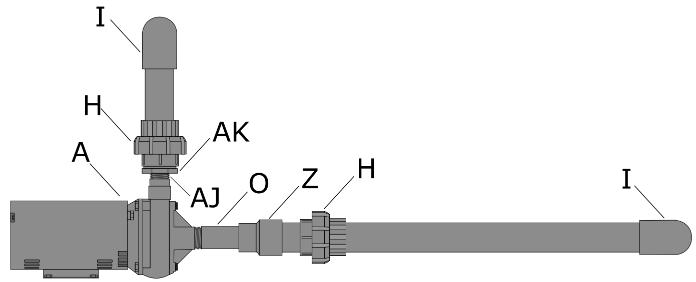

Figure 4: Detail of centrifugal pump assembly. Labels reference Table 1.

Table 2: Electronics and Instrumentation

Description	Qty	Price/ea	Cost	Model #	Vendor
DAYTON Variable Frequency Drive: 240V AC, 2 hp Max Output Power, 6.7 A Max Output Current, NEMA 4X	2	$700.89	$1401.78	13E646	Grainger
USB Data Acquisition	1	$695.00	$695.00	DI-4718B-U	DATAQ Instruments
DI-8B Series Amplifiers 4-20mA	1	$133	$133	DI-8B32-01	DATAQ Instruments
DI-8B Series Amplifiers 4-20mA (w/excitation)	3	$162	$486	DI-8B42-01	DATAQ Instruments
Differential Pressure Transmitter	1	$755.13	$755.13	PX2300-10DI	Omega
Differential Pressure Transmitter	1	$755.13	$755.13	PX2300-1DI	Omega
Total			$4701.17		

2.4 Cost Reduction Strategies

If desired, cost of the system could be reduced considerably by making the following changes:

1. Use only a centrifugal pump. This would eliminate the cost of the gear pump and motor (nearly $3,000), the need for three-way valves ($661), and one variable frequency drive ($700)
2. Use a rotameter or other flow meter in place of the electromagnetic flow meter ($1,300).
3. Use mechanical pressure gauges in place of the electronic pressure and differential pressure sensors ($1,510).
4. Use only 1” and 1.5” pipe sections. Pressure drop in 2” and 2.5” pipe sections is very small, and the observed trends are not very meaningful (see Figure 7). This would eliminate the need for the related pipe and fittings (approximately $580), as well as eliminating the need for the three-way valves used in the connections to the differential pressure sensors ($950).

These changes would also eliminate the need for automatic data acquisition ($1,000) and would reduce the cost of the system to approximately $7,200.

3 Testing: Data Collection Procedure

Experimental design for any pumping experiment is complicated by the fact that flow rate and head pressure cannot be specified independently of one another or independently of pump speed. For centrifugal pumps in particular, at a given pump speed only the head pressure OR the flow rate (not both) can be specified, and the available range of each variable depends on the other. E.g. the highest flow rates are obtained at the lowest head pressures, and vice versa. Operationally, it is easiest to specify the head pressure, because – with the components used in this system – the pressure measurement is instantaneous while the flow rate measurement has a delay of several seconds.

3.1 Centrifugal pump

The first step is to choose a pump speed. The pump speed is selected using the variable frequency drive and can be set from 0-60 Hz. Next, the throttle valve is closed completely and the head pressure is noted. This pressure corresponds to the maximum head pressure attainable at the selected pump speed.

The maximum head pressure can then be subdivided into the desired number of levels. For the sample data, the maximum pressure was divided into six increments. The throttle valve is then adjusted until the desired head pressure is reached, and the flow rate is recorded. This is repeated for the remaining levels of pressure at the selected pump speed, then the VFD is set to the next desired pump speed.

Note: the centrifugal pump is only operated at pump speeds up to 50 Hz. At higher speeds, the over-current protection on the VFD is activated and the pump is stopped.

3.2 Gear pump

Since it is necessary to avoid deadheading the gear pump, the throttle valve cannot be completely closed as in the procedure for the centrifugal pump. Instead, the maximum pressure is taken to be 16 psi. This pressure is subdivided into six levels (1, 4, 7, 10, 13, and 16 psi), and the throttle valve is used to establish the desired head pressure for each pump speed. Pump speed is limited to 20 Hz for the gear pump to minimize the noise level in the lab.

3.3 Pressure drop experiment

Pressure drop in a horizontal tube section does not depend on the type of pump used, so the pressure drop experiment is only conducted with one of the two pumps. To minimize noise in the lab, the centrifugal pump is used. First, one of the four available pipe sections is selected. The throttle valve is fully opened, and the maximum flow rate is recorded. This flow rate is then subdivided into the desired number of levels (four increments for the sample data). The throttle valve is then adjusted to obtain each of the desired flow rates for that pipe section.

3.4 Safety Considerations

The primary safety concern in this experiment is the mechanical hazard presented by the rotating shafts connecting the gear pump head to the motor, in which clothing, hair, jewelry, etc. could become entangled causing serious injury or death. To protect against this hazard, a guard was fabricated from acrylic to cover the rotating shafts (see Figure 10 in Appendix). Students are also warned of the hazard and instructed to exercise caution when they are near the gear pump.

A secondary hazard is presented by the risk of deadheading the gear pump. This could cause pipes to burst, or it could damage the pump, motor, or variable frequency drive. To address this risk, Schedule 80 PVC pipes and fittings were used in the pumping system. These have a maximum pressure rating of 400 psi, which is higher than the maximum pressure of the gear pump. In addition, students are warned of the hazard and instructed to ensure that the valves in the system are correctly configured to avoid dead-heading the pump.

3.5 Results: Pump performance curves

As described in Section 2.1, the design for the pumping system included the following criteria: data generated in the experiment should exhibit expected trends, and students would be able to observe statistically significant effects of the independent variables (factors) on the dependent (response) variables. To validate the newly constructed experiment, sample data were collected and analyzed.

Pump performance curves show how flow rate changes with pumping head and are traditionally shown differently for centrifugal pumps and gear pumps. For centrifugal pumps, the flow rate is typically plotted on the x-axis, and head pressure is plotted on the y-axis, while for gear pumps it is usually the opposite.

Sample results from the centrifugal pump are shown in Figure 5 and match the expected trends; flow rate drops off dramatically (eventually reaching zero flow) with increasing head pressure for the centrifugal pump. Also, flow rate and head pressure both increase with increasing pump speed.

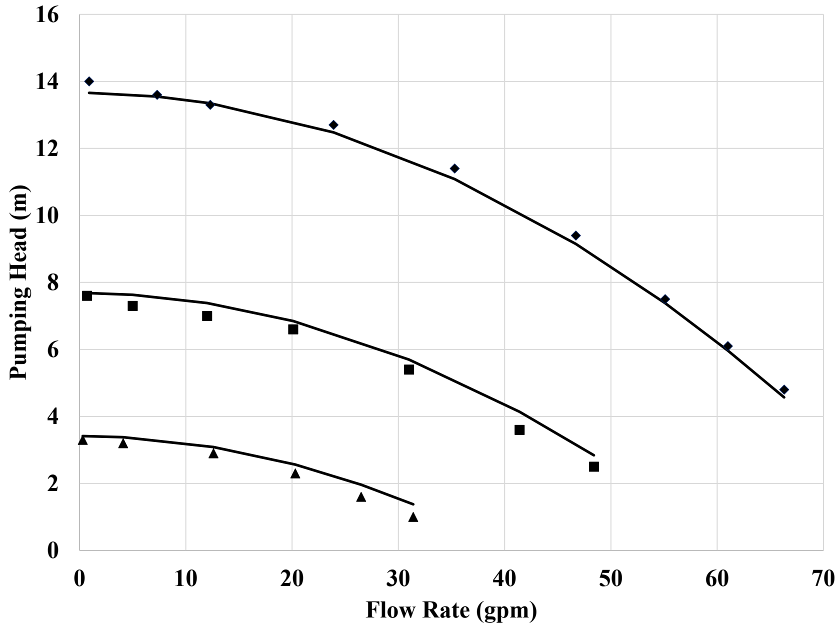

Figure 5: Flow rate and pumping head for centrifugal pump with pump speeds of 20hz (△), 30hz (□), and 40hz (◇).

Fitted curves in Figure 5 are based on affinity laws predicting that head pressure is related to the square of flow rate and pump speed[3]. In particular, the model used was:

$$H = \beta_1 Q^2 + \beta_2 n^2 \tag{1}$$

where H is pumping head in meters, Q is flow rate in gallons per minute, n is pump speed in Hz, and β_1 and β_2 are fit coefficients. This model was tested using the statistical analysis software JMP, and the effects of both Q^2 and n^2 on H were found to be significant with p-values <0.0001.

Sample results from the gear pump are shown in Figure 6. These also match expected trends; flow rate decreases slightly with increasing head pressure, flow rate increases with increasing pump speed.

Fitted lines in Figure 6 are based on expectations that flow rate will increase linearly with pump speed and decrease linearly with pressure due to slip. In particular, the model used was:

$$Q = \beta_1 H + \beta_2 n \tag{2}$$

where Q is flow rate in gallons per minute, H is pumping head in meters, n is pump speed in Hz, and β_1 and β_2 are fit coefficients. This model was tested using the statistical analysis software

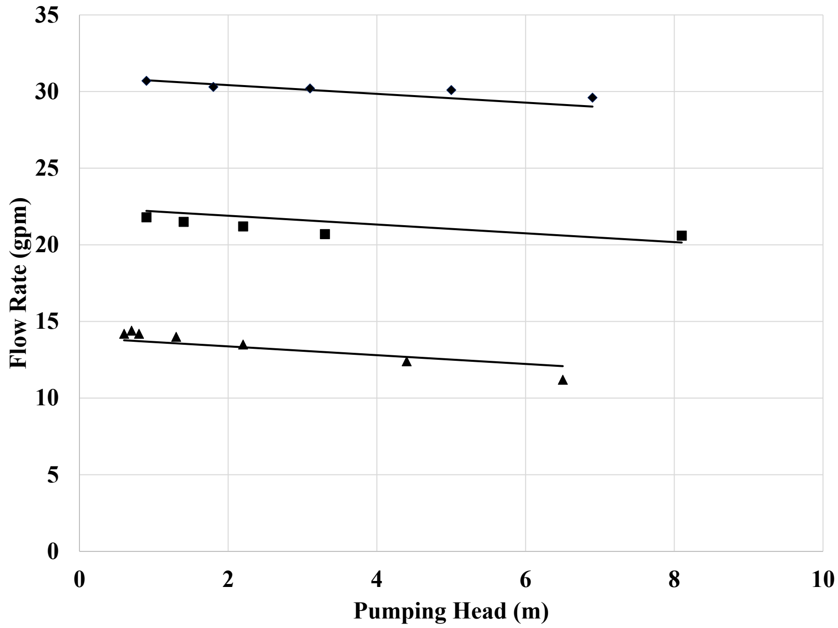

Figure 6: Flow rate and pumping head for gear pump with pump speeds of 10hz (△), 15hz (□), and 20hz (◇).

JMP, and the effects of both H and n on Q were found to be significant with p-values of 0.0003 and <0.0001, respectively. The intercept was also found to be significant with a p-value <0.0001.

3.6 Results: Pressure Drop in Pipe

Sample data were collected for pressure drop in the four pipe sections of varying diameters. The Blasius correlation was used as an approximation for pressure drop. The Blasius correlation is:

$$f = 0.3164Re^{\frac{1}{4}} \tag{3}$$

Pipe pressure drop data are shown in Figure 7 along with predictions from the Blasius equation.

A statistical analysis was performed in JMP, and $\frac{1}{Re^{0.25}}$ was found to have a significant effect on pressure drop for all four pipe diameters with p-values <0.0001.

For the larger pipe diameters (2” and 2.5”), the pressure drops are very small. For these values, measurement error makes up a large fraction of the differential pressure measurement. The authors recommend eliminating these pressure drop sections altogether in order to save cost (see related cost savings in Section 2.4).

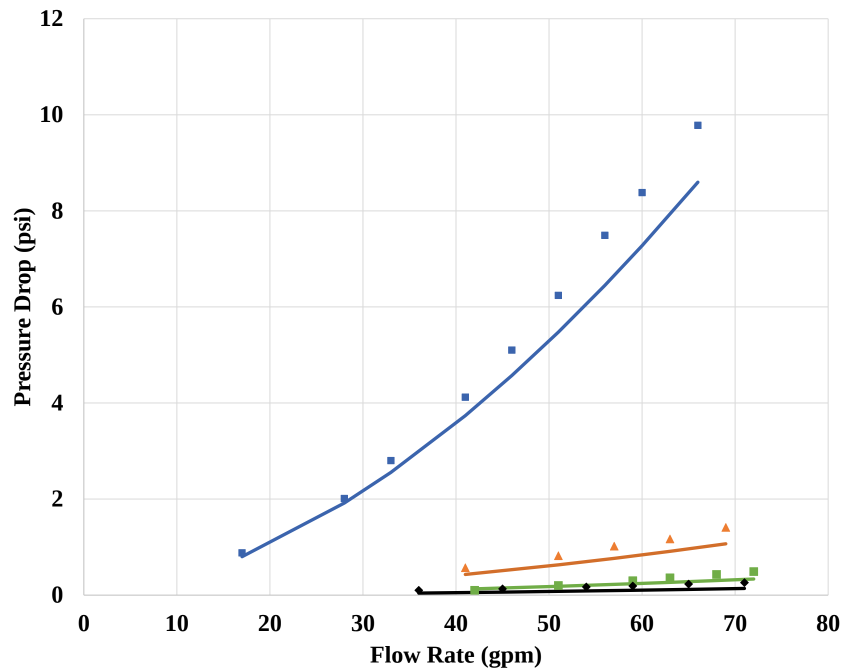

Figure 7: Pipe pressure drop results (symbols) with predictions from the Blasius equation (curves) for pipe sizes of 1” (□), 1.5” (△), 2” (□), and 2.5” (⋄).

4 Learning Objectives

The learning objectives identified for the design of the pumping apparatus included the following:

4.1 Safely operate centrifugal and positive displacement pumps

To achieve this learning objective, a centrifugal pump and a gear pump were both included in the design. Each type of pump brings its own operational and safety considerations. In particular, it is desired for students to recognize the greater risk of deadheading a positive displacement pump, so the inclusion of the gear pump requires administrative safeguards to prevent deadheading.

In addition, the direct coupling of the gear pump (in contrast to the close-coupled centrifugal pump) introduces a mechanical hazard. Although a guard was added to mitigate the danger of entanglement (see Appendix Figure 10), the presence of this hazard provides an opportunity for students to learn about the different types of risks in chemical processes.

4.2 Predict pressure drop through a horizontal pipe section

The design of the experimental apparatus includes horizontal pipe sections of four different diameters along with the instrumentation needed to measure pressure drop. Since students are always asked to compare their experimental results with expected results, this requires students to consider and predict the expected pressure drop. In doing so, they encounter Moody Charts, friction factor, wall shear stress, and other concepts used in the prediction of pressure drop in pumping systems.

4.3 Construct and interpret pump performance curves

The experimental design of the experiment performed by students includes measurement of head pressure at a range of flow rates. When students plot these data they are constructing pump performance curves. The "expected results," in this case would be the pump performance advertised by the manufacturer, so in order to compare with expected results, students must find and interpret the performance curves published by the manufacturer. In doing so, they achieve this learning objective.

4.4 Perform statistical tests to analyze the effects of the independent variables in the experiment on the dependent variables

In every experiment in Unit Operations at Ohio State, students are asked to "Use JMP or another statistical analysis software tool to determine whether it can be concluded that the independent variables had statistically significant effects on the response variables." For the pumping experiment, students typically choose pump speed and head pressure as the independent variables and flow rate as the dependent variable. Since no analytically-derived expression is available to predict the performance of a particular pump, students must employ statistical model building strategies to identify a statistical model which includes only significant effects and which describes a large portion of the variability observed in the system.

5 Conclusions

In Summer of 2022, a new pumping experiment was constructed in the Unit Ops Lab at Ohio State. The equipment has been operated for approximately 100 hours by nearly 100 students, and no operational or safety concerns have been encountered. The cost of the apparatus was approximately $16,700, not including the cost of the support structure and feed tank, but this cost could be reduced to approximately $7,200 by using only one pump and eliminating electronic data acquisition. The system was designed to achieve several important learning objectives for undergraduate chemical engineering students. A detailed description of the components and construction of the apparatus is included in this paper, including part numbers, prices, and vendors so that other Unit Ops Labs can easily adopt this experiment.

Acknowledgement

The authors would like to acknowledge high school students Owen Galvin, Muna Mohamed, and Maxi Ortiz who assisted in the construction of the pumping apparatus.

References

[1] Margot A. Vigeant, David L. Silverstein P.E., Kevin D. Dahm, Laura P. Ford, Jennifer Cole, and Lucas James Landherr. How we teach: Unit operations laboratory. In *2018 ASEE Annual Conference & Exposition*. ASEE Conferences, June 2018. https://peer.asee.org/30587.

[2] Nicholas Vanderslice, Richard Oberto, and Thomas R Marrero. Centrifugal pump experiment for chemical engineering undergraduates. *Chemical Engineering Education*, 46(1):50–57, 2012.

[3] Paul Cooper, George Tchobanoglous, Richard O. Garbus, Robert J. Hart, Carl W. Reh, Lowell G. Sloan, and Earle C. Smith. Chapter 10 - performance of centrifugal pumps. In Garr M. Jones, Robert L. Sanks, George Tchobanoglous, and Bayard E. Bosserman, editors, *Pumping Station Design (Third Edition)*, pages 10.1–10.44. Butterworth-Heinemann, Burlington, third edition edition, 2008.

Appendix A: Images

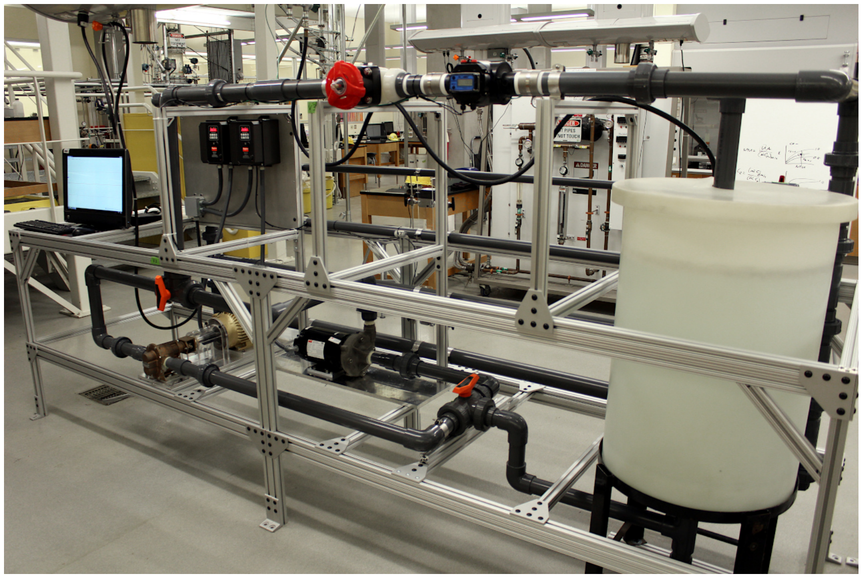

Figure 8: Front view of pumping system

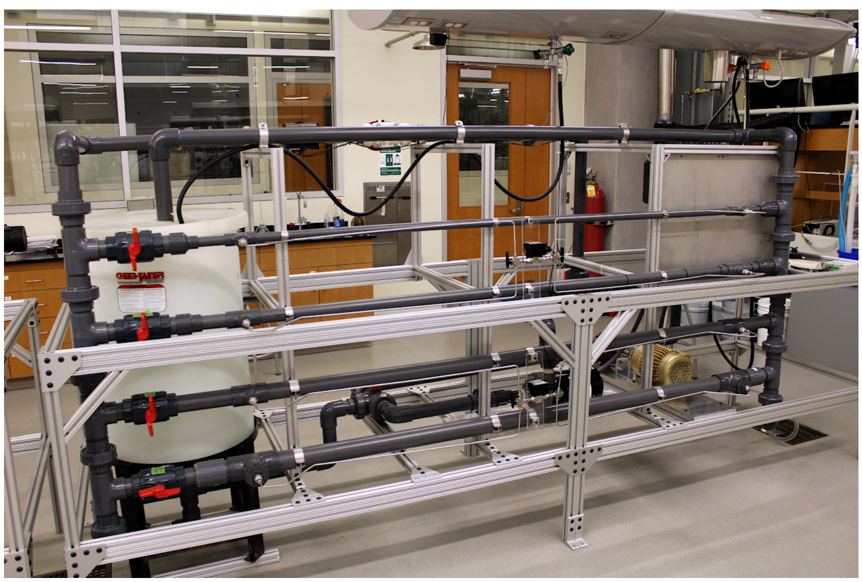

Figure 9: Rear view of pumping system

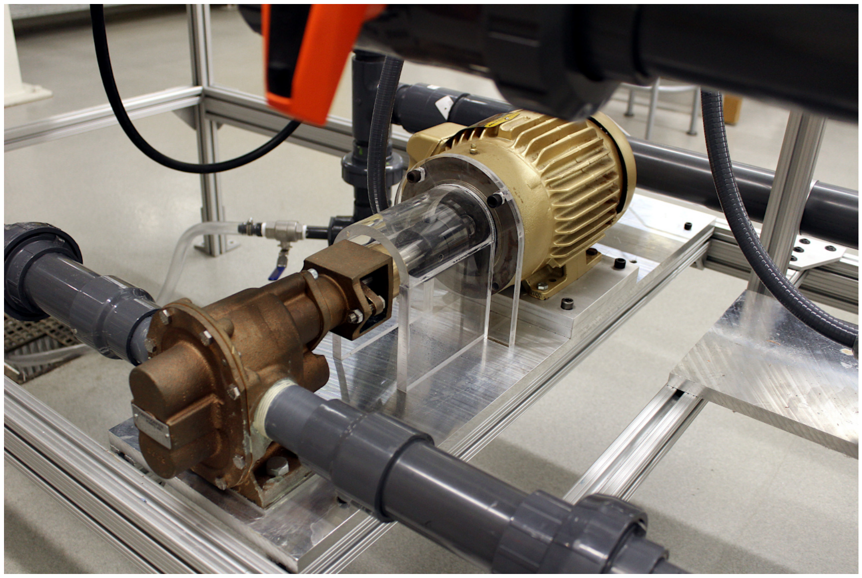

Figure 10: Gear pump, motor, and acrylic guard

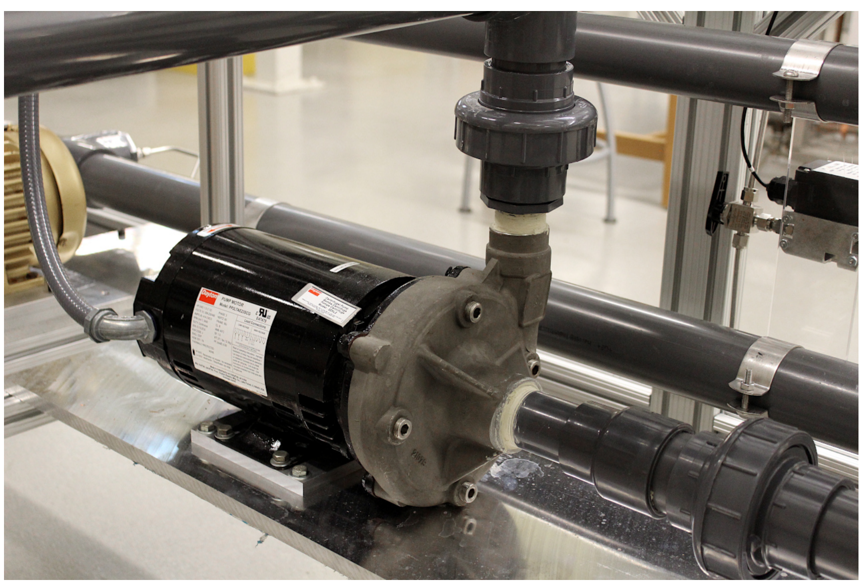

Figure 11: Centrifugal pump

Appendix B: Structural Components

Table 3: Structural Components (80/20 Framing)

Description	Qty	Price/ea	Cost	Model #	Vendor
T-slotted framing; double rail 6 slot; 4ft	2	$81.04	$162.08	47065t109	McMasterCarr
T-slotted framing; double rail 6 slot; 6ft	8	$113.28	$906.24	47065t109	McMasterCarr
T-slotted framing; single rail 4 slot; 4ft	4	$50.58	$202.32	47065t103	McMasterCarr
T-slotted framing; single rail 4 slot; 5ft	10	$53.73	$537.30	47065t103	McMasterCarr
T-slotted framing; single rail 4 slot; 3ft	6	$27.58	$165.48	47065t102	McMasterCarr
T-slotted framing; drop-in nut	20	$1.50	$30.00	47065t327	McMasterCarr
T-slotted framing; end-free nut	40	$3.89	$155.60	47065t97	McMasterCarr
T-slotted framing; mounting foot	12	$22.17	$266.04	47065t843	McMasterCarr
T-slotted framing; silver gusset braacket	10	$11.55	$115.50	47065t679	McMasterCarr
T-slotted framing; silver tee surface bracket	10	$13.93	$139.30	47065t279	McMasterCarr
Threaded mounting hanger; 1-1/2”	4	$5.97	$23.88	3006t314	McMasterCarr
Threaded mounting hanger; 2-3/8”	14	$14.14	$197.96	3006T94	McMasterCarr
Threaded mounting hanger; 2-7/8”	4	$12.99	$51.96	3006t69	McMasterCarr
Threaded mounting hanger; 1-7/8”	4	$8.99	$35.96	3006t68	McMasterCarr
Total			$2998.62		