PC-Based Transport Laboratory Experiments

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Abstract

The transport laboratory course in Chemical Engineering at Michigan Tech has been offered to undergraduate juniors as a 2-credit required course since 2000. The laboratory equipment has been newly designed to accommodate an in-line digital computer for data acquisition. The chemical engineering faculty focused on three essential elements in selecting a system: safe, compact and inexpensive.

Based on an examination of the unit operations commonly found in modern chemical manufacturing plants, a process was designed for implementation. This consists of a flow loop with two tanks, a supply tank and a receiving tank. A ½-HP centrifugal pump is used for transfer and circulation application. The straight pipes of three different nominal sizes (1/4", 3/8", and ½") are used for the study of fluid dynamics. The angles, tees, crosses, orifice, rotameter, ball valves, gate valves, and pneumatic control valves were included for system analysis. A double-pipe heat exchanger was added for non-isothermal operations. The pneumatic control valves are operated by instrument air: one for water flow control and the other for stream flow control. The digital bench scales are used for weighing the fluid.

Thirteen experiments were designed for a one-semester course, including two or three class periods of applied engineering statistics. Some key topics include measurements of viscosity, pressure, and Reynolds number and calibrations of a DP cell and a rotameter, pneumatic control valve and steam traps. The energy losses resulting from the friction of the fluid's movement through the straight pipes, valves, and fittings are computed for the system and compared with the measured values. The operating point is identified on the pump curves with the system curve. The heat transfer coefficients are sought for the heat exchanger and displayed as a function of ΔT using an in-line PC.

1. Introduction

The chemical engineering programs at Michigan Tech requires laboratory courses such as "Unit Operations Laboratory," " Process Control Laboratory," and "Transport Laboratory." These laboratory courses give the students experience working with real chemical processes frequently found in manufacturing plants. Students also find the laboratory courses to be engaging whether they have already learned the theory or have yet to learn it, because hands-on experiments bring the theory to life for them. In this paper, "Unit Operations Laboratory" and "Process Control Laboratory" will first be briefly described, but the focus will subsequently be on the most newly developed course, "Transport Laboratory."

We offer a series of lab courses [three required labs and one optional lab]:
CM3215 Transport Laboratory [2 cr: 1-0-1 (Lec-Rec-Lab)] Required
CM4110 Unit Operations Laboratory [3 cr. 0-1-6] Required
CM4120 Chemical Plant Operations Laboratory [3 cr. 0-1-6] Required
CM4955 Process Control Laboratory [3 cr: 2-0-3] Optional

Michigan Tech offers "Unit Operations Laboratory" to the chemical engineering senior students during the Fall semester. The laboratory experiments include exercises on Polymer Flow, Pumping, Flow Rate Measurement and Friction Loss, Filtration (Batch and Continuous), Heat Exchangers, Vacuum Drying, Liquid-liquid Extraction, Distillation, Cooling Tower, Stirred Tank Reactors, and Polymer Processing. A session on Safety Auditing is also included. Weekly experiments in the unit operations laboratory are over-seen by a group of students. The selected group is trained for the safety aspects of each experiment. They then observe, report, and document any unsafe acts of their fellow students and take corrective measures to prevent them. The safety audit conducted by the students is carefully thought out and planned. Al though the university lab usually equipped with inherently safe experiments, their industrial counter parts may include dangerous processes. These exercises are designed to develop students' safety habits, both through the experience of auditing their peers and being audited by the peers.

Among these experiments, the exercises on distillation and the polymer reactor are integrated with the state-of-the-art computer system and dubbed "Chemical Plant Operations Laboratory". The distillation column is the central piece of equipment for the Solvent Recovery System and a CSTR is the key for synthesizing Polydimethyl Siloxane (PDMS). Dow Corning supplies us with the reactants and takes back the product synthesized by the students. This facility integrates a multipurpose pilot plant and a Honeywell TDC-3000 (Total Distributed Control) system. The current version has three processes: 1. a 30-gallon CSTR system, 2. a solvent recovery process, and 3. a fractional crystallization process. The first two processes have been completed and are integral parts of the Chemical Plant Operations Laboratory, another required course for seniors majoring in Chemical Engineering [Kim and Caspary, 1993, and Pintar at. el., 1998]. The third process is currently in the design stage and awaits funding.

Process control lab is designed to apply the materials taught in Process Control [CM3310] to lab experiments by actual practice. The principles of feedback control systems are reviewed and applied to various processes using on-line digital computers. The lab experiments involve control software, signal processing and conversion, data acquisition, manual/PID control, statistical process control, and tuning of direct digital control.

Engineers knowledgeable about how to operate state-of-the-art control systems have been in increasing demand in the industrial sector. Our courses aim to ensure our students are properly equipped with knowledge of the state-of-the-art computer control systems through their participation in the process control laboratory and pilot-plant operations via the unit operations laboratory.

Over the years of teaching transport processes, the unit operations laboratory, the chemical plant operations laboratory and the process control laboratory, we begin to realize that the students still lacked an understanding of several key principles. These were (1) the instrumentation behavior, or on-line measurement of physical properties such as viscosity and process variables such as pressure drop, velocity, and flow-rate; (2) statistical analysis of the data and presentation of results supplemented with proper reporting of confidence levels; (3) dynamic behavior and physical properties of steam and condensate.

The transport laboratory course was added to the chemical engineering program as a required course at the junior level beginning 2000. Each lab experiments has been designed to supplement these needs.

2. Transport lab layout

The first lab course [CM3215] is offered each semester to junior students. The laboratory course (also known as the Fundamentals of Chemical Engineering laboratory) is essentially a combination of two courses: Measurement Analysis of Data [CM3115] and Instrumentation Laboratory [CM3315]. It is structured to help the students prepare themselves for the Unit Operations Laboratory experiments.

The lab experiments are closely integrated with weekly lecture topics which are essentially a review of transport processes. Transport theory is briefly summarized for the subsequent experiment. For example, viscosity of a given sugar solution is measured in a constant water bath using a Cannon-Fenske viscometer. The kinematic viscosity thus obtained is converted to absolute viscosity. The Hagen-Poiseuille equation is reviewed and the momentum transport and shear stress are discussed. This approach gives students a solid grip on viscosity and makes it less abstractive concept.

The first experiment involves introducing to “Visio2000” so that they may construct a P&ID for the transport process. The students are exposed to the laboratory for the first time by the instructor (Figure 1). Each piece of equipment such as elbows, orifice flow meter, rotameter, DP cell, three-way valve, and ball/gate valve is to be identified and sketched for the computer-aided drawing.

There are eight identical stations in the lab and each station is assigned to a group of 2 students. The lab is capable of accommodating 128 students a year, since sixty-four students can be registered per a semester. Groups of two students conduct the experiment and collect a set of data. Each student is responsible for writing up an independent report, even though they share the same data. Furthermore, each student must independently draw the P&ID for submission as a part of the report (Figure 2).

In the lab setup, water is pumped from a 10-gal PVC supply tank through a ½" copper tube with many valves and fittings into a 10-gal PVC receiving tank. The valves and fittings include 90-degree angles, tees for directing flow and for pressure taps, ball/gate valves, three-way valves, a rotameter, an orifice flow meter with a DP cell, pneumatic control valves, and a heat exchanger. Near the discharge end of the pump there are two more straight tubes running in parallel to the ½" tube. Friction loss and pressure drop in a given length of ½" straight tube can be compared to those in the same length of ¼" or 3/8" tube. The differential-pressure (DP) cell (Honeywell ST3000 S900) for measuring the pressure drop along the flow loop is rated for a range of 0 to 100 inch in water. It provides the standard 4 to 20 mA current signals. A handheld digital multimeter (Omega) is also provided for frequent checks and calibration of output measurement. A manometer with fluid having a known density can generate the differential pressure and it is used to calibrate the DP cell. Ferric chloride, $FeCl_3$, is often used for the solution and a proper ventilation hood is recommended.

Flow rate is measured with a rotameter and orifice flowmeter. These may be calibrated via a pail-and-scale method using the receiving tank sitting on an electronic scale. The water can be routed through the heat exchanger for a heat transfer operation. A non-isothermal experiment can be carried out by using 30 psig steam and steam traps. Students can select from among two types two types of steam trap, an automatic variable orifice type (Swagelok) and an inverted bucket type (Armstrong). The condensate can be collected into a thermal weight basket and measured using an electronic CD indicator (Ohaus). The condensate flow rate can be continuously monitored through the RS-232 interface for the computer. The temperatures before and after the heat exchanger are monitored by thermocouples. The lab is also equipped with the instrument air that is needed for the operation of pneumatic control valve (Badger Research) with pressure regulator (Bellofram).

3. Computer Data Acquisition System

Each computer workstation consists of the following items.

Microcomputer

There are seven PC workstations in the lab for weekly hands-on experiments. Each is equipped with the following:

Intel Pentium microprocessor running at 250 MHz with 16M RAM
Two PCI/IDE peripheral channels for hard drive, CD-ROM drive, Zip 100 drive
SVGA color 13" monitor (1024x768)

Platform: Windows NT (4.0)

Interface cards

Each computer has plug-in boards (manufactured by National Instruments) to handle input and output signals. These include the following:

1 AT MIO16L9 for the input signals
1 AT AO6 for the output signals

Alternatively, SC-2070 (Input terminal) and CB-50 (Output terminal) boards are recommended for easy handling of I/O wires. Each station is equipped with a power source (24V@4.8A) for signal generation.

Program

LabVIEW (version 5.0) is a graphical programming tool. The term LabVIEW is an acronym for **Lab**oratory **V**irtual **I**nstrument **E**ngineering **W**orkbench (Johnson, 1995). Programs ranging from a simple function to a very sophisticated control system can be implemented by constructing block diagrams. A block diagram consists of icons and "wires" (lines) that may be placed to connect the icons in a specific way. The software automatically converts the interconnected icons into executable codes, simultaneously reporting any errors encountered. Its corresponding front panel serves as a virtual instrument (vi), mimicking the real instrument. The ***vi*** allows us to convert a computer into a useful instrument for measuring variables. It can also create a virtual strip chart recorder.

4. Lab experiments

The topics covered in a typical semester are shown in Table I. The major objectives are to solidify students' understanding of the basic theory of instrumentation, statistical analysis of data, and interpretation. Typical content of a lab experiment is illustrated in Table I.

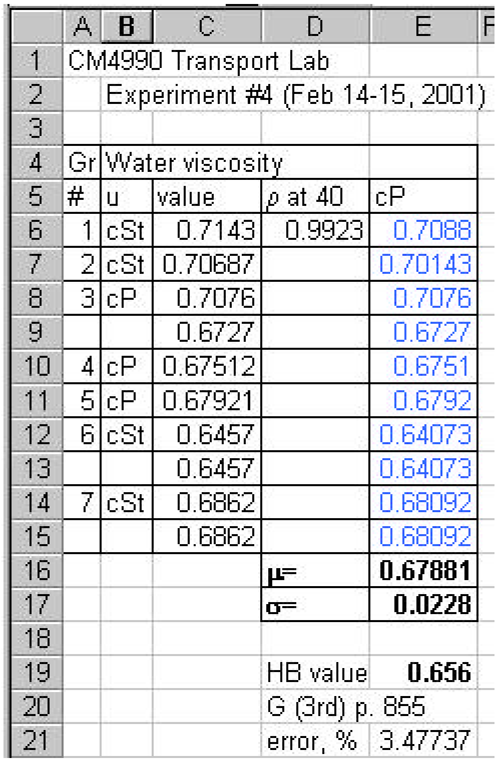
Table I. Key experiments

1. Preparation of process flow diagram (P&ID)
2. Statistical analysis of data
3. Measurement of viscosity, pressure drop, flow rate
4. Friction loss in a piping system
5. Construction of system curve in a pumping curve diagram
6. Characterization of valves and pneumatic control valve
7. Heat transfer coefficient (HTC) of a heat exchanger
8. Effect of ΔT on HTC
9. System identification and transient heat transfer

Statistical analysis of data

Viscosity is one of the primary fluid properties that is responsible for energy dissipation and generation of stresses in a fluid. It also relates shear stress to the velocity gradient. Sucrose solution of different concentrations is prepared to measure its viscosity. The instrument used for this purpose is Cannon-Fenske Routine viscometer (Cannon Instrument). It is immersed in a constant water bath at a desired temperature. The Isotemp Immersion Circulator (Fisher-Scientific) does an excellent job for this purpose. To provide a basis, distilled water at 40 C was used for the viscosity measurement. The results reported by the students are shown in Table II.

Table II. Results of viscosity measurement



	A	B	C	D	E	F
1	CM4990 Transport Lab					
2		Experiment #4 (Feb 14-15, 2001)				
3						
4	Gr	Water viscosity				
5	#	u	value	ρ at 40	cP	
6	1	cSt	0.7143	0.9923	0.7088	
7	2	cSt	0.70687		0.70143	
8	3	cP	0.7076		0.7076	
9			0.6727		0.6727	
10	4	cP	0.67512		0.6751	
11	5	cP	0.67921		0.6792	
12	6	cSt	0.6457		0.64073	
13			0.6457		0.64073	
14	7	cSt	0.6862		0.68092	
15			0.6862		0.68092	
16				μ=	**0.67881**	
17				σ=	**0.0228**	
18						
19				HB value	**0.656**	
20				G (3rd) p. 855		
21				error, %	3.47737	

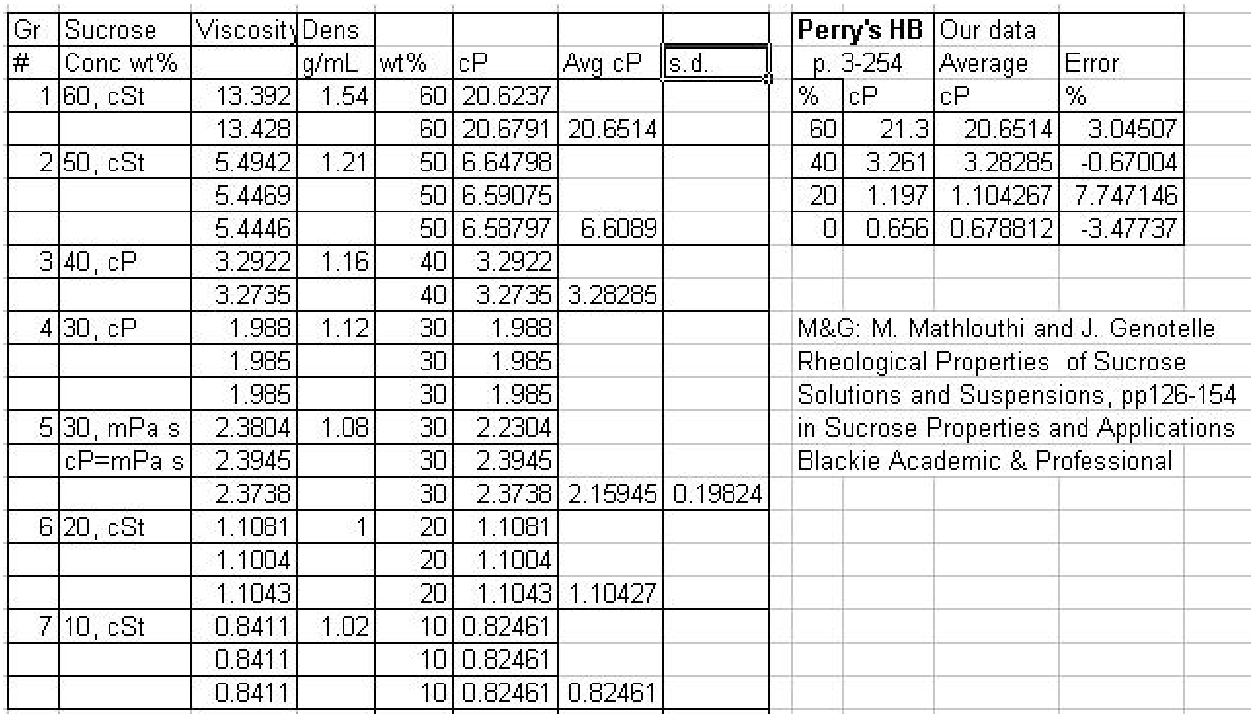
The data show that an average absolute viscosity is 0.679 centipoise (cp) with an unbiased estimator of standard deviation, 0.023. This can be compared to some previously published values of 0.656 (Bingham, 1922). We tested the published data claim at $\alpha = 0.01$. The null hypothesis, H_o, is $\mu = 0.656$ (H_1 =/ 0.656). The critical value for $\alpha = 0.01$ (two-tailed) and degrees of freedom = 9 (<- 10 – 1) is +/-3.25. The t-test is computed as:

$$t = \frac{\overline{X} - \mu}{s\sqrt{n}} = \frac{0.6788 - 0.656}{0.0228\sqrt{10}} = 3.162$$

Since the t-test value, 3.162, is less than the critical value, 3.25, we do not reject the null hypothesis. In other words, students can see that the viscosity for the 0 wt % sucrose solution (pure water) at 40 C is probably 0.625 cp as the published data claim.

Other viscosity data reported by the students for various sucrose concentrations are shown in Table III.

Table III. Measurement of viscosity for a various sucrose concentration.



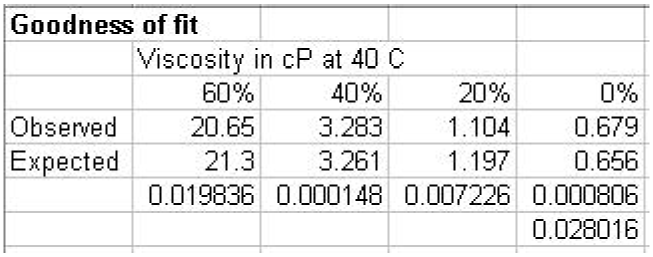
Gr #	Sucrose Conc wt%	Viscosity	Dens g/mL	wt%	cP	Avg cP	s.d.
1	60, cSt	13.392	1.54	60	20.6237		
		13.428		60	20.6791	20.6514	
2	50, cSt	5.4942	1.21	50	6.64798		
		5.4469		50	6.59075		
		5.4446		50	6.58797	6.6089	
3	40, cP	3.2922	1.16	40	3.2922		
		3.2735		40	3.2735	3.28285	
4	30, cP	1.988	1.12	30	1.988		
		1.985		30	1.985		
		1.985		30	1.985		
5	30, mPa s	2.3804	1.08	30	2.2304		
	cP=mPa s	2.3945		30	2.3945		
		2.3738		30	2.3738	2.15945	0.19824
6	20, cSt	1.1081	1	20	1.1081		
		1.1004		20	1.1004		
		1.1043		20	1.1043	1.10427	
7	10, cSt	0.8411	1.02	10	0.82461		
		0.8411		10	0.82461		
		0.8411		10	0.82461	0.82461	

Perry's HB p. 3-254 %	 cP	Our data Average cP	 Error %
60	21.3	20.6514	3.04507
40	3.261	3.28285	-0.67004
20	1.197	1.104267	7.747146
0	0.656	0.678812	-3.47737

M&G: M. Mathlouthi and J. Genotelle
Rheological Properties of Sucrose
Solutions and Suspensions, pp126-154
in Sucrose Properties and Applications
Blackie Academic & Professional

Perry's Chemical Engineers' Handbook shows that the viscosities of various sucrose solutions measured at 40 C are: 21.3 cp for 60 wt % solution, 3.261 cp for 40 wt %, 1.197 cp for 20 wt %, 0.656 cp for 0 wt % solution. Similar computations can be carried out for "Goodness of Fit" of the students' data: 20.65 cp for 60 wt % solution, 3.283 cp for 40 wt %, 1.104 cp for 20 wt %, 0.679 cp for 0 wt % solution. The critical value with $\alpha = 0.01$ and degrees of freedom = 4-1 = 3 is 11.345. The null hypothesis H_0: 21.3 cp for 60 wt % solution, 3.261 cp for 40 wt %, 1.197 cp for 20 wt %, 0.656 cp for 0 wt % solution and H1: the measurement is not the same as stated in the null hypothesis. The Chi-square value is computed as follows:

$$\chi^2 = \sum \frac{(O-E)^2}{E}$$



Goodness of fit				
	Viscosity in cP at 40 C			
	60%	40%	20%	0%
Observed	20.65	3.283	1.104	0.679
Expected	21.3	3.261	1.197	0.656
	0.019836	0.000148	0.007226	0.000806
				0.028016

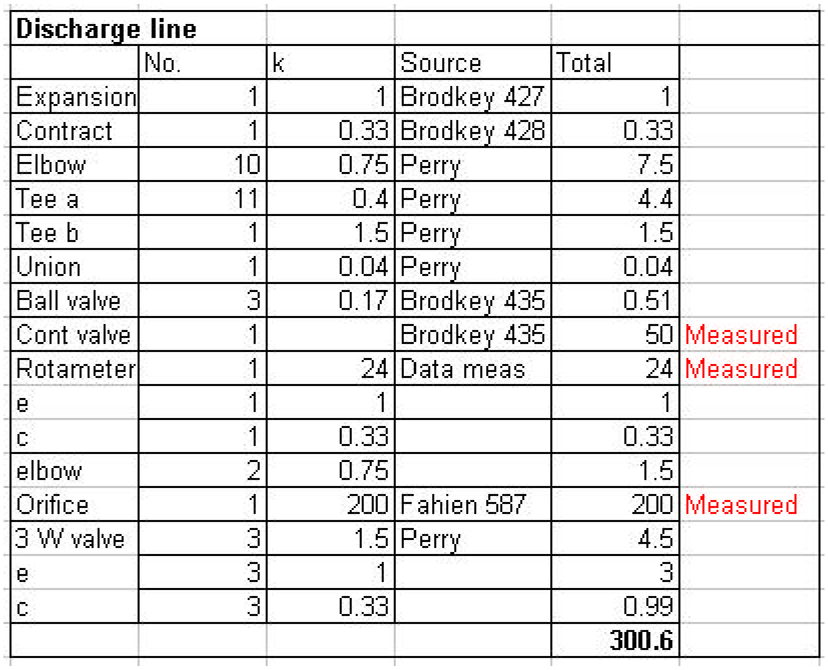
Since the Chi-square value, 0.028, is smaller than the critical value, 11.345, we will not reject the null hypothesis. That is, the handbook data are probably true. The confidence level is 99 %. Students are reminded that a probability of committing a type I error is 0.01 (or 1 %).

The data measured data by the students are plotted against sucrose concentration, along with the published data from Perry's handbook and from Mathlouthi and Genotelle (Figure 4).

Construction of system curve

The entire pumping system is analyzed to identify the operating point in the given pump performance curve. A complete list of valves, fittings, expansion, contraction, rotameter, and orifice flow meter is shown in Table IV.

Table IV. List of valves and fittings



Discharge line					
	No.	k	Source	Total	
Expansion	1	1	Brodkey 427	1	
Contract	1	0.33	Brodkey 428	0.33	
Elbow	10	0.75	Perry	7.5	
Tee a	11	0.4	Perry	4.4	
Tee b	1	1.5	Perry	1.5	
Union	1	0.04	Perry	0.04	
Ball valve	3	0.17	Brodkey 435	0.51	
Cont valve	1		Brodkey 435	50	Measured
Rotameter	1	24	Data meas	24	Measured
e	1	1		1	
c	1	0.33		0.33	
elbow	2	0.75		1.5	
Orifice	1	200	Fahien 587	200	Measured
3 W valve	3	1.5	Perry	4.5	
e	3	1		3	
c	3	0.33		0.99	
				300.6	

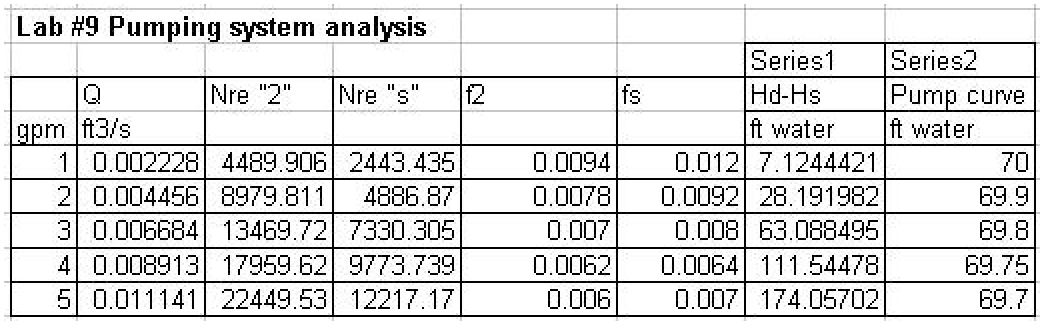
The first and second columns show the valves and fittings and their numbers. Their frictional loss in terms of number of velocity heads (K_f) is presented in the third column. Many chemical engineering textbooks and handbooks provide the relevant data for common valves and fittings. Most of these data come from a textbook (Geankoplis, 1993). Some data that are more difficult to find are for the rotameter and orifice. The other reference books are added to the 4th column. Total frictional loss is computed by multiplying the number of velocity heads by their number. The sum of the column, ΣK_2, is shown on the bottom of the 5th column to confirm the suggested data. Frictional loss of some selected equipment is measured at the operating point of pump and shown in the 6th column. Another equivalent table can be provided for the suction side of tube arrangement, producing 4.7 for ΣK_S.

The final working equation for the system is shown below.

$$H_d - H_s = z_2 - z_1 + \frac{8Q^2}{\pi^2 g}\left(\frac{1 + 4f_2 \dfrac{L_2}{D_2} + \sum K_2}{D_2^{\,4}} + \frac{4f_s \dfrac{L_s}{D_s} + \sum K_s}{D_s^{\,4}} \right)$$

The required pump heads in feet of water is given as a function of flow rate in gpm in Table V. Data in the 7th and 8th column are plotted against the data in the 1st column in Figure 5.

Table V. Pump head in feet of water vs. flow rate in gpm.



Lab #9 Pumping system analysis

						Series1	Series2
	Q	Nre "2"	Nre "s"	f2	fs	Hd-Hs	Pump curve
gpm	ft3/s					ft water	ft water
1	0.002228	4489.906	2443.435	0.0094	0.012	7.1244421	70
2	0.004456	8979.811	4886.87	0.0078	0.0092	28.191982	69.9
3	0.006684	13469.72	7330.305	0.007	0.008	63.088495	69.8
4	0.008913	17959.62	9773.739	0.0062	0.0064	111.54478	69.75
5	0.011141	22449.53	12217.17	0.006	0.007	174.05702	69.7

The pressure taps installed in many places along the tube help students to check the individual pressure drop in the equipment of interest. The data acquisition can be interfaced by an on-line computer to see the dependence of ΔT on the flow rate.

Dependence of heat transfer coefficient on ΔT

For the non-isothermal operation the water can be routed through a double-pipe heat exchanger. The utility steam is used through a pneumatic control valve manually operated by a manipulating instrument-air regulator (Bellofram). The steam condensate is collected and measured by a pail-and-scale method. The temperatures of steam, incoming water to, and outgoing water from the heat exchanger are monitored with an on-line computer.

The heat transfer coefficient (HTC) for the heat exchanger is to be computed and compared against the design value. Depending upon the steam pressure and water flow rate, the log mean temperature difference varies and the HTC for the heat exchanger changes significantly. The mass and energy balances can be performed on the steam-side as well as on the water-side. A sample case study is illustrated in Figure 6.

5. Conclusion

Even though there are many areas to be improved and modified for more sophisticated experiment, the compact lab facility is well constructed and dependable. The review of statistics helps students in interpretation of collected data and in writing reports. The DP cell is extensively studied: differential pressure, calibration, and data acquisition by computer. This played a key role in the construction of a system curve. Consequently, the students gain insight to the dependency of the energy requirement on the flow rate, and they grasp the meaning of the operating point of the pumping system. The in-line computer interface opens a new dimension to measurement and understanding of the time dependent variables. Since its inception, this lab course has added more features and met the most of the needs we initially anticipated.

6. Acknowledgments

Nam Kim and Kirk Schulz contributed in designing the initial draft of processes to be built. Romulo Almedia, David Caspary, Nicholas Greenland, and Kirk Schulz prepared the first manual. The third version was contributed by Jaya Yaddanapudi, David Caspary, Nam Kim, and Jason Keith. Dave Caspary, Lab Facilities Manager, provided the drawings and supervised the construction performed by our in-house master mechanic Jerry Norkol and Research Associate Tim Gasperich.

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Nam Kim is an associate professor of chemical engineering at Michigan Technological University. He was involved in the design of the control system for the PSCC, advises student groups on the control aspects of the solvent recovery process and supervises other unit operations experiments. He teaches process control theory and process control laboratory courses at Michigan Tech. Kim does research in the area of advanced process control (adaptive and interacting multi-variables, statistical process control, fuzzy logic, and neural networks) and energy conservation and optimization. He has a Ph.D. from Montana State University in chemical engineering. (e-mail: kimnk@mtu.edu)

Figure 1. Transport laboratory layout

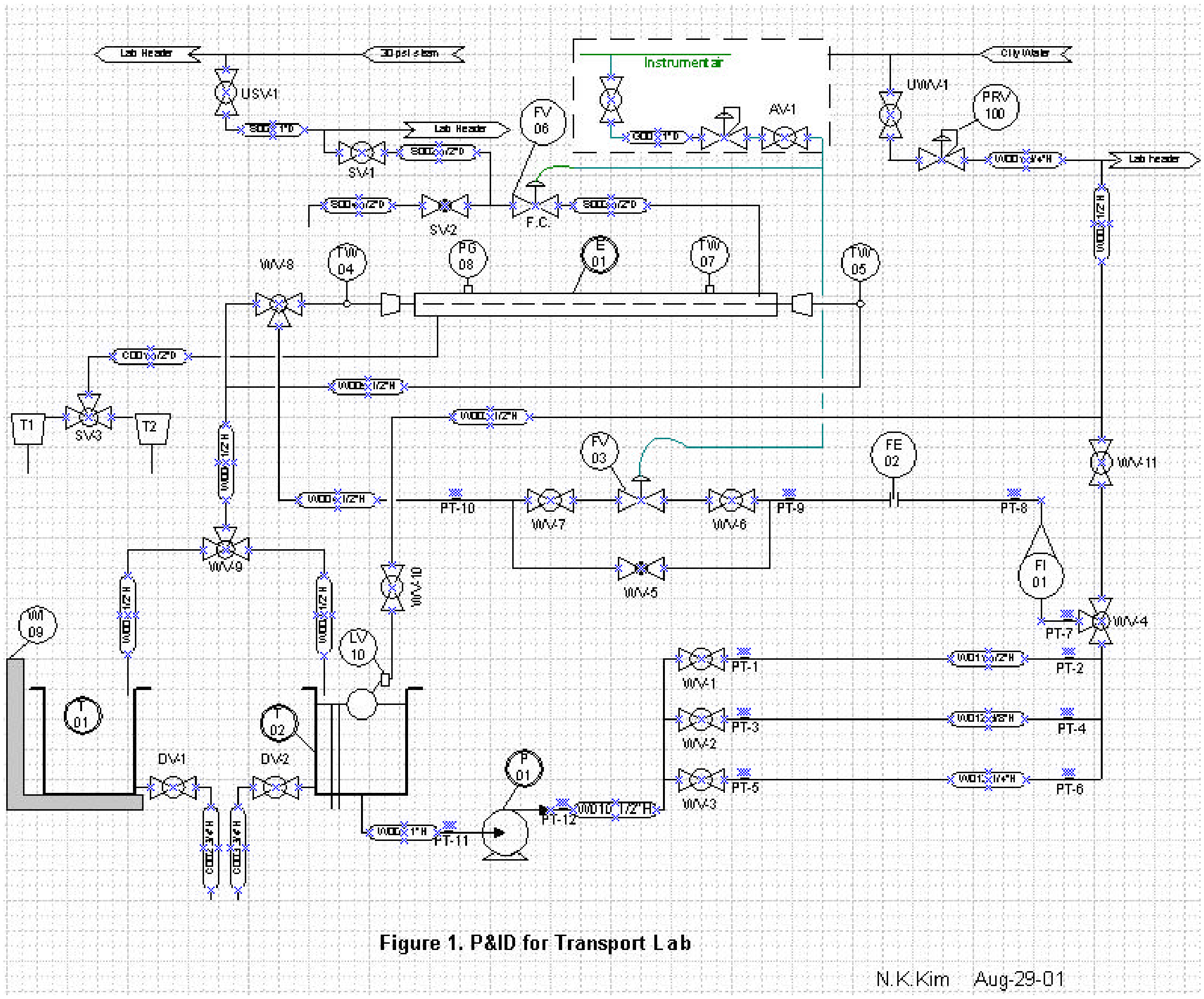
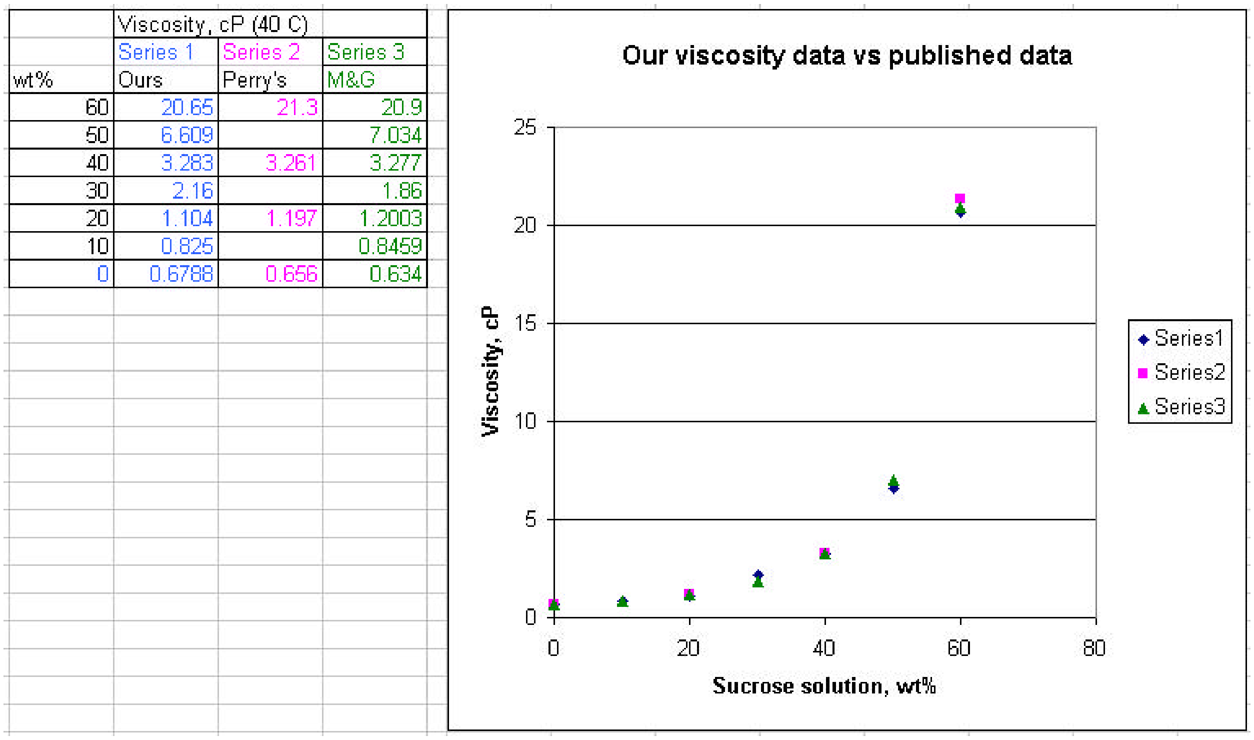


Figure 2. P & ID for the transport laboratory.

Figure 3. Computer station for on-line data acquisition.



	Viscosity, cP (40 C)		
	Series 1	Series 2	Series 3
wt%	Ours	Perry's	M&G
60	20.65	21.3	20.9
50	6.609		7.034
40	3.283	3.261	3.277
30	2.16		1.86
20	1.104	1.197	1.2003
10	0.825		0.8459
0	0.6788	0.656	0.634

Figure 4. Comparison of measured data vs. published data.

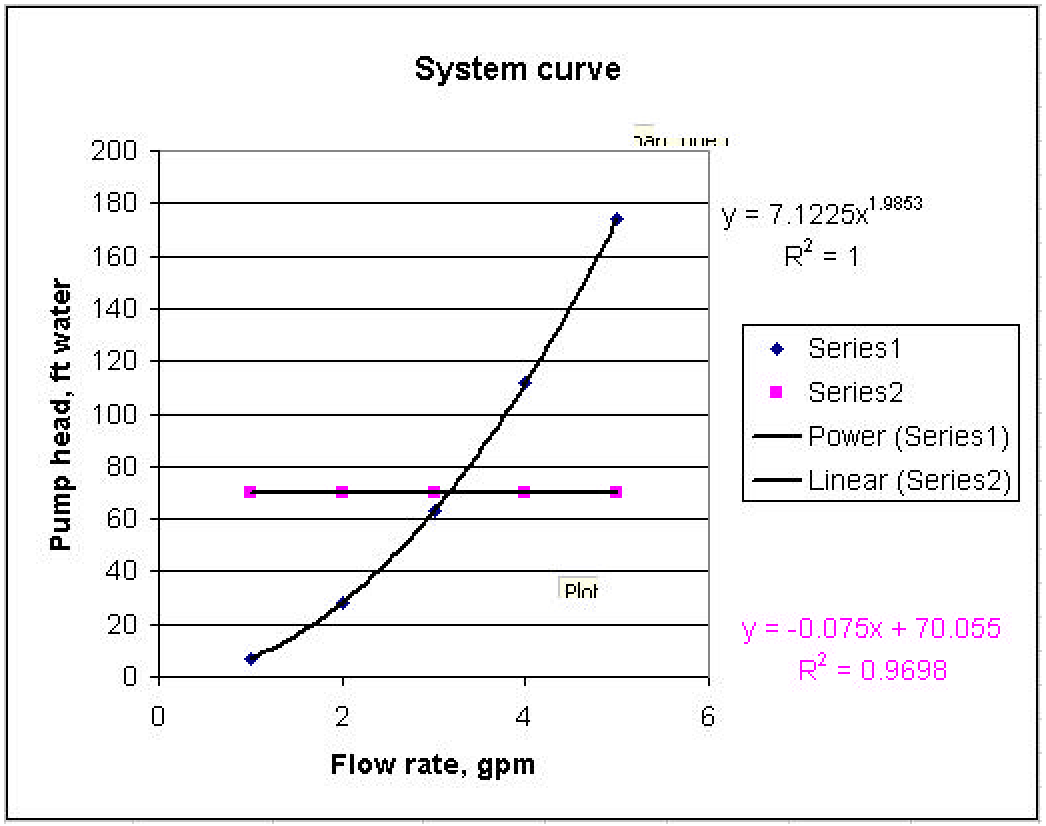


Figure 5. Construction of a system curve.

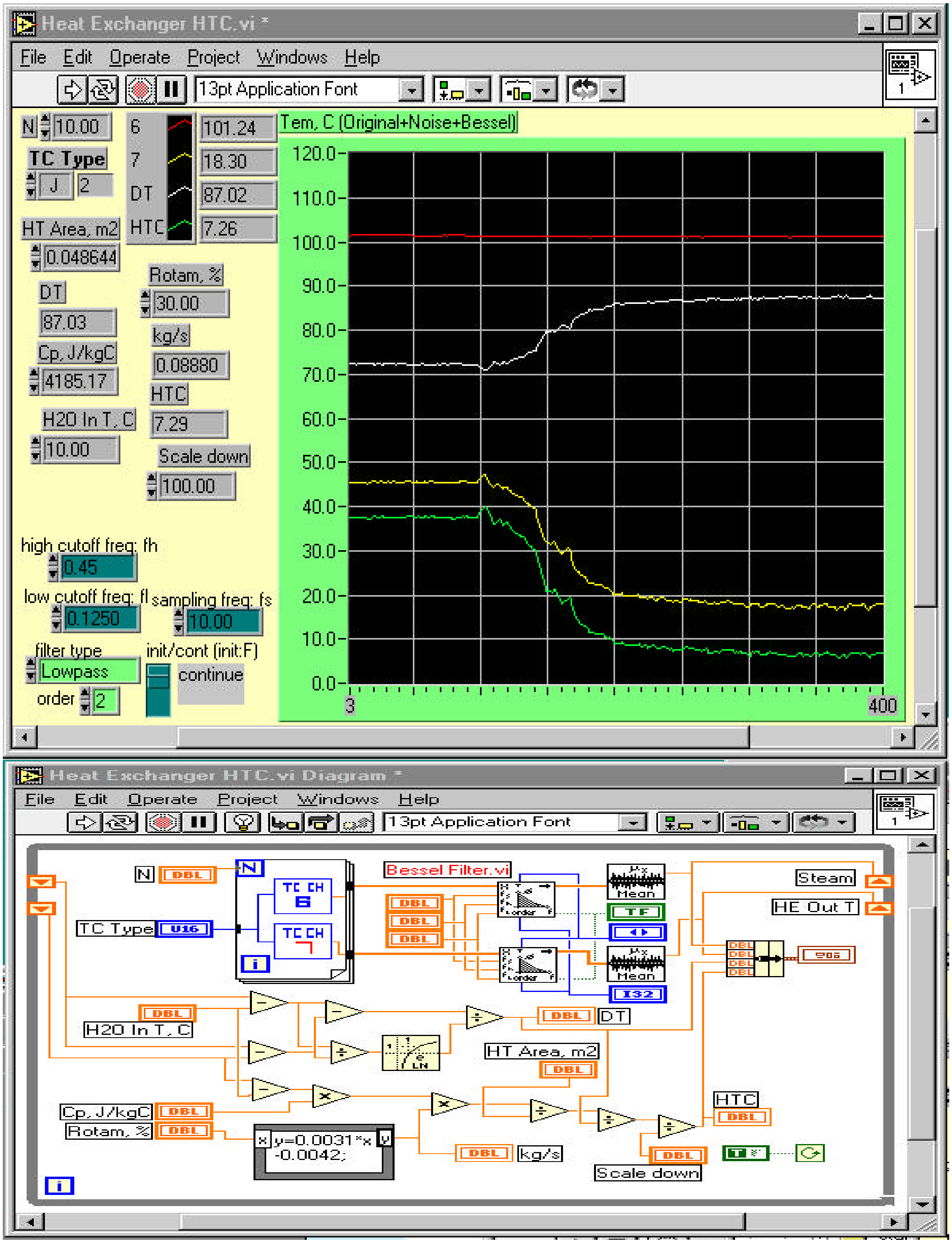


Figure 6. On-line computer data acquisition.