A FLEXIBLE PILOT-SCALE SETUP FOR REAL-TIME STUDIES

IN PROCESS SYSTEMS ENGINEERING

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The inclusion of process control experiments in chemical engineering curriculums and the introduction of new process control experiments[1, 2, 3] indicate recognition of the importance of real-time experiments in process systems engineering. The experiments allow an instructor to reinforce and demonstrate theoretical systems concepts presented in lectures. Laboratory systems experiments in an academic setting provide students with an invaluable opportunity to familiarize themselves with important practical issues (*i.e.*, nonideality of industrial processes), such as process-model mismatch, measurement noise, inadequate number of measurements, digital measurements, actuator saturation, unmeasured disturbances, and process nonlinearity—issues often neglected in computer simulations.

This manuscript describes a low-maintenance, low-safety-risk, flexible, 0.9-m × 1.5-m × 2.4-m, pilot-scale setup that can be used for training students and carrying out research in process systems engineering. It briefly states typical applications of the setup. Detailed specific sample applications of the setup, together with real-time results, will be presented in forthcoming paper(s). The setup was built in the Department of Chemical and Biological Engineering at Drexel University and is located in the Process Systems Engineering Laboratory. The setup allows one to study a variety of process-systems engineering concepts such as design feasibility, de-

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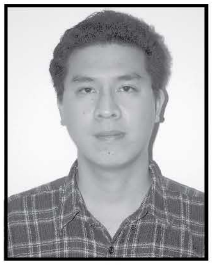

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*Current address: Fluor Enterprises, Inc., Rose Tree II, Suite 5000, 1400 N. Providence Rd., Media, PA 19603 sign flexibility, control configuration selection, parameter estimation, process and instrument fault detection and identification, controller design and implementation, instrument calibration, and process modeling. Notable features of the setup are its flexibility and low safety risk (because it uses water only). The setup can be single-variable or multivariable, mildly or strongly nonlinear, interacting or noninteracting, and/or single- or multi-tank. It has features of both apparatus # 4 and 10 described by Ang and Braatz[1]; it can be configured to be the same as apparatus #4 or 10, or a combination of apparatus #4 and 10. The setup can be used in both undergraduate and graduate process control laboratories to reinforce, through hands-on experiments, the concepts taught in process control and process analysis lectures.

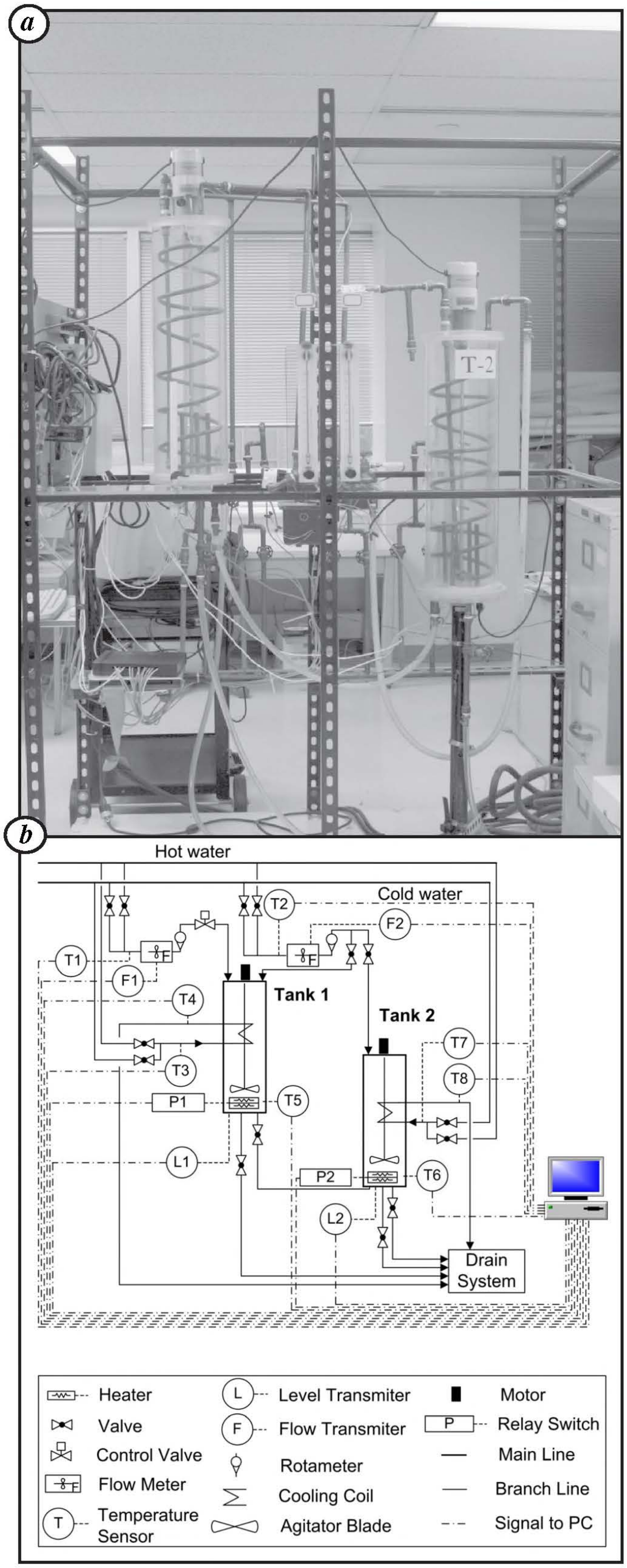


Figure 1. *The pilot-scale setup, in photograph **(a)** and schematic **(b)**.*

PILOT-SCALE SETUP

A picture of the 0.9-m × 1.5-m × 2.4-m pilot-scale setup is shown in Figure 1a, and a schematic in Figure 1b. The setup has two identical, clear-plastic, cylindrical tanks. Each tank has an outside diameter of 0.2 m and a height of 1.0 m. The tanks can be connected to each other (by easy-connect/disconnect flexible hoses) in several ways, which allows one to operate the setup as a system of a single tank, two parallel tanks, two interacting tanks in series, or two noninteracting tanks in series. The elevation of the second tank can be adjusted (via a jack) to alter the level of the interaction between the two tanks. Inside both tanks, there are helical copper tubes (*i.e.*, coiled copper tube banks) that can be used for heating or cooling, depending on the temperature of the water flowing into the copper tubes. One end of each copper tube is connected by a hose to a city water supply that is cold, hot, or a mixture of both—allowing adjustment of the inlet temperature of the water stream flowing into the copper tubes. Thermal energy can also be supplied to each tank by an electrical heater consisting of two heat cartridges inside the tank. Each tank has a variable-speed agitator.

The setup has eight resistance temperature detectors (RTDs), two flowrate sensors, two level sensors, and one control valve. The RTDs measure the temperature of the inlet and outlet streams of the tanks and the cooling/heating copper tubes. The level sensors measure the level of water in the tanks. The flowrates of two inlet streams are measured by the two online and two off-line (rotameter) flow meters. A control valve adjusts the flowrate of a water stream flowing into Tank 1.

ELECTRONIC HARDWARE

Analog Input Devices

Each of the sensors measures a process variable and generates a 4-20 mA analog signal, which is then sent to an analog input channel of a data acquisition board. The board then converts the analog signal to a digital signal. There are three types of analog instruments in this setup

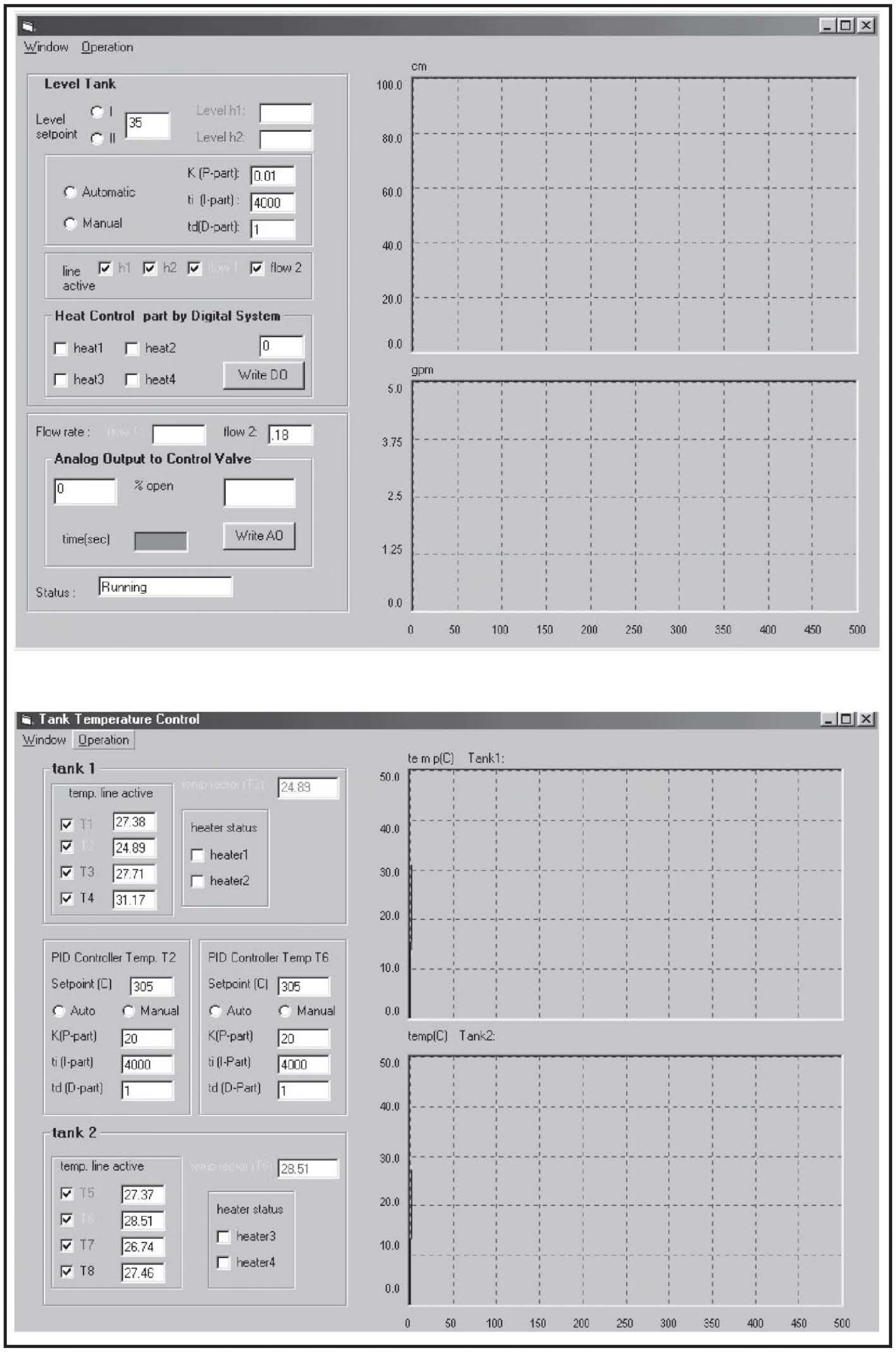
- ***Pulse-Output Flow Meter.*** *The paddle flow meter generates a positive on/off pulse signal when its rotor is rotated by the fluid flow. The pulse signal is then converted to 4-20 mA signal proportional to the flowrate (0-5 gpm).*
- ***RTD Temperature Sensors.*** *The resistance temperature detectors are connected to a Wheatstone bridge circuit that uses a reference resistor of 100 ohms, which corresponds to 0 °Celsius.*
- ***Level Sensors.*** *The level sensors used in the setup are of the pressure-transducer type. The liquid static pressure in a tank presses on the diaphragm of the transducer, generating a proportional analog signal.*

Analog Output Devices

The proportional control valve is an analog output device that receives an analog input signal (4-20 mA) and sets the flowrate proportionally. It is a fail-to-close control valve. The power of the heaters is adjusted by a solid-state relay (SSR), which is connected to a pulse-controller module (both from Omega Engineering, Inc.). The module allows simple conversion of the on/off SSR to a proportional power regulator. Therefore, the average power to the heater is proportional to the input 4-20 mA analog signal to the module. Each of the electrical heaters consists of two High Watt Density Cartridge Heaters (rated power of each: 1.5 kJ/s at 240 volts).

Data-Acquisition Board

A DAS-1701ST-DA data-acquisition board[4, 5] and an EXP-1800 extension board[6] (both from Keithley Instruments, Inc.) are used. The data-acquisition board has eight analog input channels. It receives and time-discretizes the incoming analog input signals. The expansion board allows one to expand each input channel of the data-acquisition board to eight input channels. Therefore, the data-acquisition system can support up to 64 analog input channels. It receives 12 analog signals from the eight temperature sensors, the two flow meters, and the two level sensors, and sends one analog signal to the control valve and two binary signals to the two heaters. The data-acquisition board can communicate with the central processing unit via interface software, such as Visual Basic, Visual C++ (Microsoft Corp.), and LabVIEW (National Instruments Corp.). The software then analyzes the data. A graphical user interface (GUI) is then used to present the data. In this setup, the data-acquisition application is developed by using Visual Basic as the



Level setpoint ○ I ○ II 35

Level h1:

Level h2:

○ Automatic ○ Manual

K (P-part): 0.01

ti (I-part) : 4000

td(D-part): 1

line active ☑ h1 ☑ h2 ☑ ☑ flow 2

Heat Control part by Digital System

☐ heat1 ☐ heat2 0

☐ heat3 ☐ heat4

Flow rate : flow 2: .18

Analog Output to Control Valve

0 % open

time(sec)

Status : Running

tank 1

temp. line active

☑ T1 27.38

☑ T2 24.89

☑ T3 27.71

☑ T4 31.17

24.89

heater status

☐ heater1

☐ heater2

PID Controller Temp. T2

Setpoint (C) 305

○ Auto ○ Manual

K(P-part) 20

ti (I-part) 4000

td (D-part) 1

PID Controller Temp T6

Setpoint (C) 305

○ Auto ○ Manual

K(P-part) 20

ti (I-Part) 4000

td (D-Part) 1

tank 2

temp. line active

☑ T5 27.37

☑ 28.51

☑ T7 26.74

☑ T8 27.46

28.51

heater status

☐ heater3

☐ heater4

Figure 2. *Front-end interface for the level control.*

front end and C++ as the backbone. Visual Basic can be used to create a GUI easily, and C++ used to support Windows-based input/output operations. For this setup, front-end windows for temperature control, flow control, and data storage are developed. Two of the windows are shown in Figures 2 and 3. Data from the setup can be saved as Excel files and then be imported to Matlab (Mathworks, Inc.) easily.

TYPICAL APPLICATIONS OF THE PILOT-SCALE SETUP

With the flexibility to operate in various configurations, and its many sensors and actuators, the setup allows real-time study of a variety of process-systems engineering concepts. Figure 4 shows the variables that can be measured and/or adjusted in this setup. Below is a brief description of typical real-time studies that one can perform using the setup.

Process Modeling

Given the online measurements, models including first-principles, empirical (black box), or hybrid (first-principles/empirical)[7] can be developed to describe water temperature and/or level in one or both tanks. In the case of empirical and hybrid modeling, the students can be taught model-parameter estimation as well. Hybrid model parameters include the resistances of the tank exit pipes as well as the overall heat transfer coefficients of the coiled copper tube banks. The model structure is obtained from mass and energy balances in the cases of first-principles and hybrid modeling, and from prior process knowledge (an assumption) in the case of empirical modeling. The empirical modeling can be off-line or online. In the latter case, one must use a model identification method.[7]

Process Design Analysis

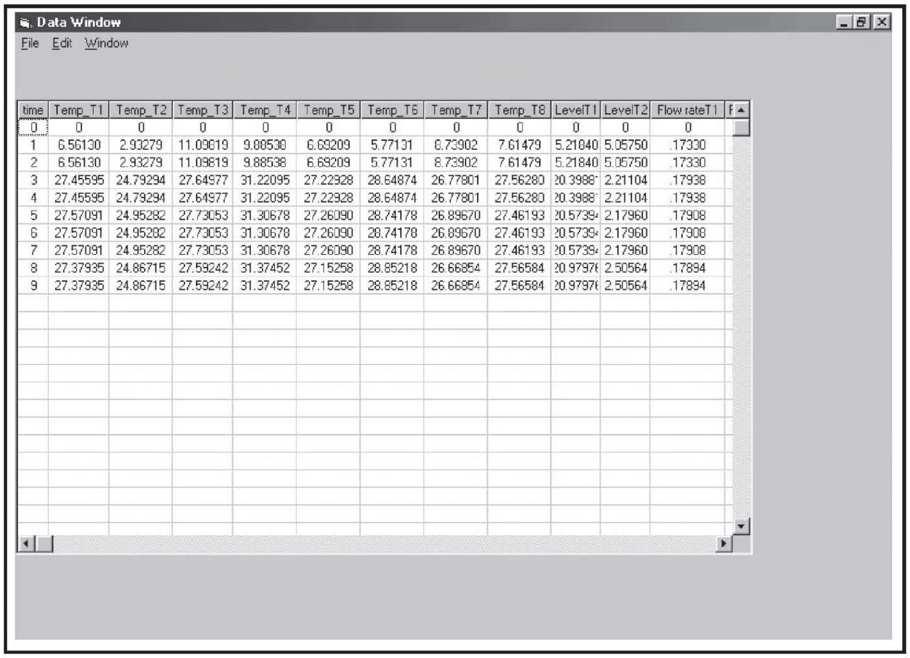
The setup can be used to analyze the following process design aspects:

- ***Feasibility.*** *Given desired steady-state values of temperature(s) and level(s), and nominal values of temperature and flowrate of the disturbance stream (inlet stream with no control valve), students are asked to evaluate theoretically and experimentally the feasibility of the design to operate at the desired steady state; that is, to check whether the design can provide heater power, water flowrate, and energy (through the heating/cooling coils) adequate to operate the process at the desired steady state.[8] For example, a desired water temperature below the city water temperature is definitely infeasible.*
- ***Flexibility.*** *Flexibility is feasibility in the presence of uncertainties such as disturbances and parameter uncertainties/variations. In this analysis, the students are asked to evaluate the feasibility of the design to operate at a given steady state when the temperature and flowrate of the disturbance stream vary within a given range.[8] Students can map theoretically the disturbance region in which the design is feasible and then verify the region experimentally.*

Process Control

The setup can be used to carry out the following process control studies:

- ***Measurement Selection.*** *Many control problems with one or more objectives can be posed, and students are*



time	Temp_T1	Temp_T2	Temp_T3	Temp_T4	Temp_T5	Temp_T6	Temp_T7	Temp_T8	LevelT1	LevelT2	Flow rateT1	F
0	0	0	0	0	0	0	0	0	0	0	0	
1	6.56130	2.93279	11.09819	9.88538	6.69209	5.77131	8.73902	7.61479	5.21840	5.05750	.17330	
2	6.56130	2.93279	11.09819	9.88538	6.69209	5.77131	8.73902	7.61479	5.21840	5.05750	.17330	
3	27.45595	24.79294	27.64977	31.22095	27.22928	28.64874	26.77801	27.56280	20.3988	2.21104	.17938	
4	27.45595	24.79294	27.64977	31.22095	27.22928	28.64874	26.77801	27.56280	20.3988	2.21104	.17938	
5	27.57091	24.95282	27.73053	31.30678	27.26090	28.74178	26.89670	27.46193	20.5739	2.17960	.17908	
6	27.57091	24.95282	27.73053	31.30678	27.26090	28.74178	26.89670	27.46193	20.5739	2.17960	.17908	
7	27.57091	24.95282	27.73053	31.30678	27.26090	28.74178	26.89670	27.46193	20.5739	2.17960	.17908	
8	27.37935	24.86715	27.59242	31.37452	27.15258	28.85218	26.66854	27.56584	20.9797	2.50564	.17894	
9	27.37935	24.86715	27.59242	31.37452	27.15258	28.85218	26.66854	27.56584	20.9797	2.50564	.17894	

Figure 3. *Front-end interface for temperature control and data storage.*

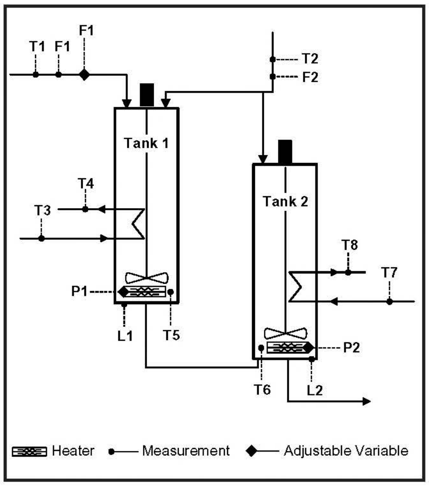


Figure 4. *Adjustable and measured variables of the setup.*

Laboratory systems experiments in an academic setting provide students with an invaluable opportunity to familiarize themselves with important practical issues (i.e., nonideality of industrial processes), such as process-model mismatch, measurement noise, inadequate number of measurements, digital measurements, actuator saturation, unmeasured disturbances, and process nonlinearity—issues often neglected in computer simulations.

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then asked to list the measurements needed to achieve the control objective. These objectives include control of temperature and/or level in Tank 1, and/or control of temperature and/or level in Tank 2. For example, for control of temperature in Tank 1, at least, the temperature measurement T5 is needed.

- ***Control Configuration Selection.*** *After choosing the necessary measurements, students can be asked to propose a set of manipulated inputs that can be used (adjusted) to realize the control objective(s). The controlled outputs should be controllable from the manipulated inputs. For example, temperatures in Tanks 1 and 2 are controllable from heater power P1 and P2. The state and/or output controllability*[7, 9] *of the control configuration can be tested.*
- ***Input-Output Pairing.*** *For multi-input, multi-output (MIMO) control problems, students can be asked to pair the inputs and outputs of the selected control configuration so that completely decentralized control can be implemented. To evaluate the level of interactions among the process variables, students can use tools such as the relative gain array,*[10] *relative orders,*[11] *and/or time delays to propose effective pairs.*[12]
- ***Controller Selection.*** *One can select a feedback or a feedback/feedforward control system depending on what control system is desired: completely decentralized (set of single-input, single-output, or SISO, controllers) or centralized (multivariable). For example, one can use the flow measurement F2 and the temperature measurement T2 (measurements of disturbance inputs), to add feedforward loop(s) to feedback control of temperature and/or level control in Tank 1. Furthermore, the controller can be: (1) a conventional controller, such as a proportional (P), a proportional-integral (PI), or a proportional-integral-derivative (PID) controller; or (2) an advanced controller such as a model-based controller.*[7, 10] *The setup can be used to understand the limitations of decentralized control and implement decouplers in reducing the effect of interactions. Further, the model-based controller can be analytical (such as an input-output linearizing controller) or numerical (such as a model-predictive controller). Whether conventional or not, adaptive features can be added to the controller.*[7, 10] *In real time, students can observe and compare the performance of different controllers, and evaluate the pros and cons of each.*

Parameter Estimation

Given the flowrate, level, and temperature measurements, students can estimate the heater powers and the heating/cooling coil-tank overall heat-transfer coefficients. In the case of the heater powers, since the heater powers are set by the computer, the values of the heater powers are known. This allows one to evaluate the accuracy of the estimated heater powers by comparing them to the actual values.

A parameter estimator that can be implemented in real-time on this setup is described by Tatiraju and Soroush.[13]

Fault Detection and Identification

The equipment can be used to demonstrate fault detection and identification.

- ***Sensor Fault Detection and Identification.*** *The setup can be used to learn sensor fault detection and identification in real-time. Noise, drift, and/or bias are added to a sensor reading, and a sensor fault detection and identification method is then used to detect the fault in the sensor and identify the fault type (noise, drift, and/or bias). An example of such a study can be found in Mehranbod and Soroush,*[14] *in which sensors L1, F1, and F2, and a PI controller to control the liquid level in Tank 1, were considered.*
- ***Process Fault Detection and Identification.*** *Partial or complete failure of one of the process actuators is an example of a process fault. A process fault detection and identification method can be used to detect an actuator failure and the type of the failure. An intentional fault can be introduced in any of the actuators, and it can be detected and identified in real time by using a process fault detection and identification method.*

Instrument Calibration

The setup has three actuators and 12 sensors. For each actuator, a calibration curve is obtained by finding the relation between the raw digital signal (that the computer sends to the data-acquisition board) and the actual value of the corresponding physical variable. For example, the control-valve calibration curve can be obtained by measuring the flowrate with the rotameter at different, constant, raw, digital signals set at the computer. For a sensor, a calibration curve is obtained by finding the relation between the raw digital signal that the computer receives from the data-acquisition board and the *actual* value of the corresponding physical variable. For example, an RTD is calibrated by placing it in beakers of water at different known temperatures and recording the value of the corresponding steady-state, raw, digital signal received by the computer. A typical calibration curve is presented in Figure 5. It shows how the flowrate of the water stream through the control valve depends on the raw digital signal.

Calorimetric Studies

The electrical heaters can be used to simulate heat of reactions. An exothermic reaction or set of exothermic reactions can be considered and simulated on the microcomputer, and the rate of heat production by the simulated reaction(s) is then sent to the heater to set the heater power to the calculated rate of heat generation. Material and energy balances for the tanks, considered with the temperature and flowrate measurements, can then be used to estimate the power to the heaters; that is, the rate of heat production by the simulated reactions.

CONCLUSIONS

This manuscript describes a low-maintenance, low-safety-risk, flexible, pilot-scale setup that can be used for training students and carrying out research in process systems engineering. It briefly states typical applications of the setup. Detailed specific sample applications of the setup together with real-time results will be presented in forthcoming paper(s). The setup allows one to study a variety of process-systems engineering concepts in real time. Among these concepts are design feasibility, design flexibility, control configuration selection, parameter estimation, process and instrument fault detection and identification, controller design and implementation, instrument calibration, and process modeling. The setup can be used to provide graduate and undergraduate students with hands-on experience and to carry out research in process systems engineering.

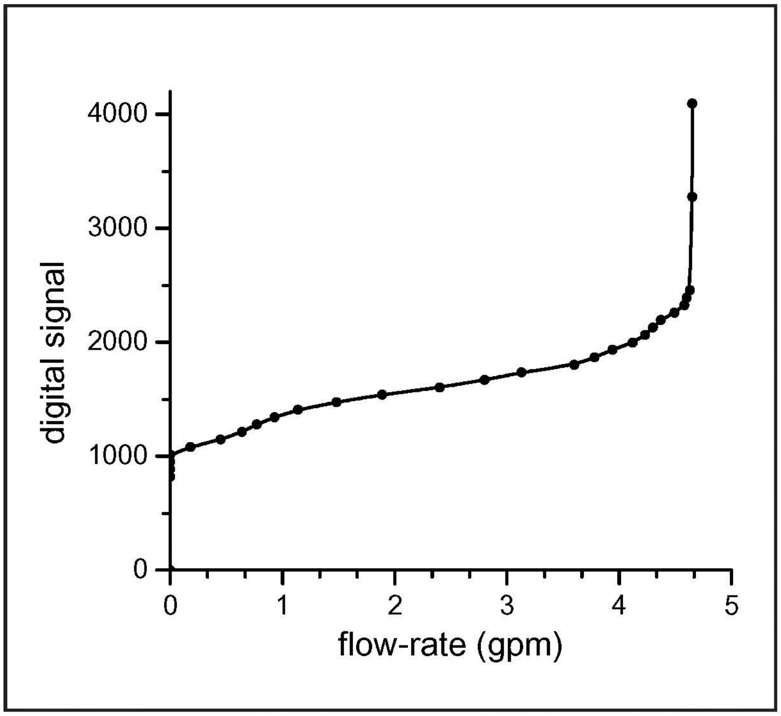

Figure 5. *Calibration curve for the control valve.*

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