Rev. 10/15 GB/GW

ChE 253M

Experiment No. 5

DIGITAL DATA ACQUISITION AND HEAT EXCHANGE

ABSTRACT

This experiment will acquaint you with methods of digital data acquisition and process control through a simple heat exchange experiment. The techniques of signal processing and measurement apply to any laboratory or industrial situation; the heat exchange equipment is used merely as a meaningful example of the power and potential of this technology. Specifically, you will:

1) Work with a data acquisition and signal conditioning system to monitor and control process parameters
2) Develop a basic understanding of factors that must be considered when designing a data acquisition process
3) Learn how temperatures can be measured using a platinum resistance thermometer
4) Learn how flow rates can be measured using a turbine meter
5) Learn how a pneumatic valve may be controlled with a computer.
6) Develop a basic understanding of feedback process control.
7) Measure the temperatures and flow rates of two water streams that pass through a shell-and-tube heat exchanger for several combinations of hot and cold water flow rates.
8) Calculate the heat transfer rates, check the energy balance, and calculate the overall heat transfer coefficients from the data in (7) above.
9) Test the effects of proportional and integral control on a water flow rate control loop.

Background

Digital Data Acquisition and Control

Digital data acquisition is the process of measuring a field variable using a digital computer, without the use of an operator to enter the data into the computer. Examples of field variables in this case are water flow rate and temperature. Digital control is the process of manipulating field variables using a digital computer. Digital data acquisition generally involves two pieces or types of equipment: a transducer and a digitizer. The transducer converts a field variable, such as pressure, temperature, flow rate, or composition, into an easily measurable electrical signal, such as a voltage, current, or frequency. The digitizer, also called an analog-to-digital converter or A/D converter, is an electronic device that converts the electrical signal (analog) into a digital value that can be conveniently processed and stored by the computer in the computer memory.

Bit Resolution

Suppose you have an 8-bit data acquisition card that reads signals from 0-10 volts (a common default range for data acquisition). The A/D converter translates your input voltage to a digital binary number that represents the analog value of the signal. It may choose among 2^8 discrete numbers that correspond to the 0-10V input range. (Each digital bit can be 0 or 1. Therefore, an 8-bit system has 2^8 total permutations.) The bit resolution is an important specification for a data acquisition card. For example, consider an 8 bit card versus a 16 bit card. The 8 bit card assigns the analog input signal to one of 256 values that linearly scale with the 0-10V range. If the analog input signal is not one of these 256 discrete values, it will simply round the value to the nearest one. The 10 V sampling range is divided into intervals of (10 V / 256) or 0.0391V. However, the 16-bit card assigns the analog input signal to one of 2^{16} (65,536) values that represent the 0-10V range. The intervals in the 16-bit card to which the analog signal must be assigned are only 10V / 65,536 or 0.000153 V apart. The 16-bit card has better resolution, hence the translated digital signal will more accurately represent the analog signal. Naturally, this performance comes at a price, so the engineer must decide what level of resolution is necessary for their application.

Suppose you have a process signal that will only range from 0-0.1 V but your A/D converter accepts signals ranging from 0-10 V. An 8-bit card will receive the signal as 0, 0.039, 0.078, and 0.1 V because of the small input signal. This is a waste of the card resolution, utilizing only 4 of 256 intervals. It is possible to use an analog voltage amplifier to amplify the voltage signal by a factor of, say, 100 before the signal enters the A/D converter. This will reduce the relative error generated by the bit-approximation. **(*See Section 4.1 for a diagram illustrating the importance of bit resolution*.)** Many data acquisition cards allow the user to employ software-controlled analog amplification before the signal enters the A/D converter, although it is sometimes advantageous to amplify the signal very close to the source.

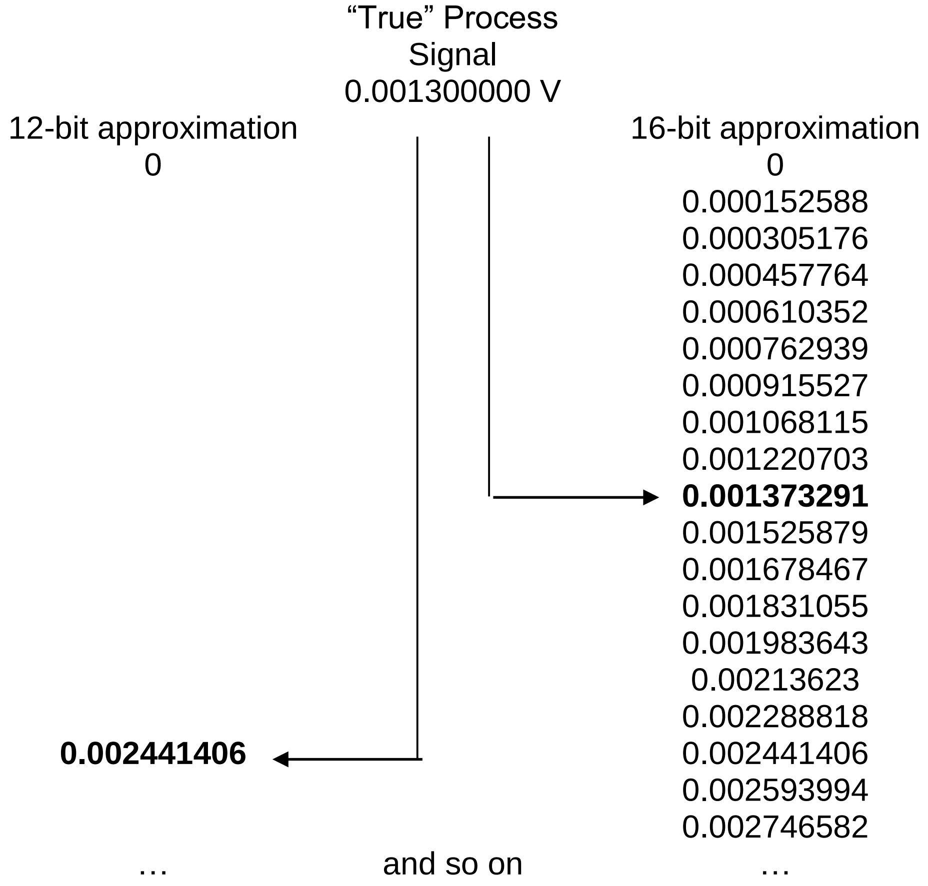
“Bit resolution” Example

Suppose we are comparing two data acquisition cards with input ranges of 0-10 V. Our process signal is 0.001300000 V. The A/D converter on the data acquisition card will have to translate this voltage to a digital value that accurately represents the true process signal.

On a 12-bit card, the 10 V input range is divided into discrete values at intervals of:
(10 volts) / (2^{12}) = 0.0024414 volts

On a 16-bit card, the 10 V input range is divided into discrete values at intervals of:
(10 volts) / (2^{16}) = 0.0001523 volts

The analog input signal (0.0013 volts) will be assigned to the closest discrete value that the data acquisition card is capable of resolving as indicated with the arrows in the diagram below:



The end result is that the 12-bit card has approximated the signal with 88% error. The 16-bit card has approximated the signal with only 6% error.

Suppose we were reasonably sure that the signal would never exceed 0.1 V. In this case, we could use an analog amplifier to amplify our signal by a factor of 100 and it would never exceed 10 V, thus staying within our 0-10 V input range for the A/D converter. If we continue the table drawn above and again locate the region of discrete values to which the input signal will be assigned, we would see the following:

“True” Process
Signal
0.0013V

Amplify to:
0.1300000000 V

12-bit approximation		16-bit approximation
…		…
		0.129089355
		0.129241943
0.129394531		0.129394531
		0.129547119
		0.129699707
		0.129852295
		0.130004883
		0.130157471
		0.130310059
		0.130462646
		0.130615234
		0.130767822
		0.13092041
		0.131072998
		0.131225586
		0.131378174
		0.131530762
		0.13168335
0.131835938		0.131835938
		0.131988525
		0.132141113
…	and so on	…

In this case, the 12-bit error has been reduced to only 0.47% and the 16-bit error is reduced to 0.0038 %!

Sampling Rate

Sampling rate is another key specification when selecting a data acquisition system. The A/D converter has a finite limit to the rate at which it can sample an analog voltage and convert it into a digital value. Typical data acquisition cards can sample more than 40,000 times per second. However, if you have a rapidly varying signal, as illustrated below, you must ensure that your sampling rate is fast enough to accurately capture high frequency changes in the signal.

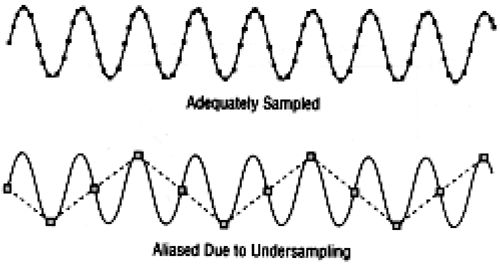


Figure 1: Importance of Sampling Rate in Data Acquisition

Other Considerations

In some cases implementing a data acquisition system is rather simple. Data acquisition cards that simply plug into an expansion slot on a PC are readily available together with the software that supports them. These units typically come prepared to measure *analog input* signals from 0-10 V. For example, consider the pressure measurement experiment studied earlier in the semester. During the pressure bleed-down experiment, you monitored the voltage output from the Schaevitz transducer with the computer to provide a record of that process variable over time. The output voltage from the pressure transducer was directly wired into a positive and negative voltage terminal on the data acquisition card.

In most cases, however, designing a data acquisition system is more complex. Many transducers do not output a simple voltage signal that varies from 0-10 V. The flowmeters in this experiment yield a frequency signal that varies to indicate the value of the process variable (explained below). In other cases, the voltage signal is extremely low – often less than a millivolt. These signals cannot be directly connected to a data acquisition board and must be "conditioned." Signal conditioning is a general term that refers to the process of relating a problematic field signal to a stable voltage signal that scales linearly with the field variable. When monitoring any of the following types of signals, some degree of conditioning may be necessary:

- Non-voltage signals such as frequencies or currents must be converted to voltages so that they may be processed by the data acquisition card.

- Low-level voltage signals require amplification. Amplification is typically done as close to the signal source as possible. Low-level voltages are often blurred by electrical interference if they are carried long distances.

- Thermocouple signals are often conditioned to correct well-known non-linearities in their voltage responses. Signal conditioning can also correct a phenomenon known as "cold junction compensation" in which thermocouple signals must be monitored with respect to a reference signal.

Many data acquisition cards also include a function commonly referred to as "analog output." These devices include a digital-to-analog converter that can generate analog voltage signals based on digital software commands. Thus they may be used as a means for the computer to control devices that respond to these analog output voltage signals. For example, in this lab, we will use the analog output to generate control voltages that will open and close the three pneumatic valves. When working with analog outputs, signal conditioning may again be necessary. Many process devices are designed to respond to current signals. In these cases, the voltage output from the data acquisition card must be translated into a current signal in order to control the device.

In this lab, we are using a National Instruments PCMIO-16-E-4 12-bit data acquisition card with a sampling rate of 500,000 Hz. Signal conditioning is handled by a series of electronic modules that plug into an expandable chassis system. Specifically, we are using National Instruments' SCXI modular signal conditioning system. Each module in the SCXI chassis serves a specific function. The first module from the left processes the platinum RTD signals (explained below). The second module converts frequency signals from the turbine flowmeters into voltage signals. The third module converts analog output voltage signals into current signals that control the pneumatic valves. The last module is unused in this lab.

Temperature Measurement

Four platinum resistance temperature devices (RTDs) are used to measure temperature in this experiment. An RTD is a temperature-sensing device whose resistance increases with temperature. Platinum is the most common RTD material and has a nominal resistance of 100 Ω at 0 °C, and a linear temperature coefficient of 0.38 Ω/°C. RTDs are noted for good stability as well as excellent accuracy over a wide temperature range.

However, an RTD output can not be directly connected to an A/D voltage converter. It is necessary to pass current through the RTD in order to infer the resistance from a voltage drop which *can* be processed through an A/D converter in a data acquisition system. Recall Ohm's Law: $V=IR$ so that if we apply a fixed, known current (I) through a resistor and measure the voltage drop (V) we can calculate R. Since this current will cause the RTD to internally heat, it is advisable to use a very low current – we use 0.15 mA in this experiment. In addition, by immersing the RTD in a large volume of fast flowing fluid with excellent contact for heat transfer, the trivial amount of internal heat generated by the RTD is quickly carried away by the flowing fluid. When measuring a static gas with low heat transfer rates, the self-heating effect may be more significant and a RTD may not be a wise choice for temperature measurement. The resistance of the RTD is measured by the above procedure and converted to a temperature by the heat exchanger software using a standardized correlation curve known as the Callendar-Van Dusen equation:

$$R_T = R_0\left[1 + AT + BT^2 + C(T-100)^3\right]$$

where R_T is the resistance of the RTD at temperature = T, R_0 is the resistance of the RTD at 0 °C, A, B, and C are the Callendar-Van Dusen coefficients shown below, and T is the temperature in °C.

Table 1: Callendar-Van Dusen Coefficients for Standard American RTDs

A	3.9692×10^{-3}
B	-5.8495×10^{-7}
C[1]	-4.2325×10^{-12}

[1] *C = 0 if T > 0 °C*

Flow Measurement

Two turbine flowmeters are used to measure volumetric flow rate. In these devices, a vaned rotor turns as fluid flows through the meter. Over a certain range of flow rates, the rotation rate varies linearly with volumetric flow rate. This rotation is detected with a magnetic pickup device, resulting in electronic pulses as the flowmeter rotor spins in the flowing fluid. This signal is typically interpreted as a frequency; i.e. number of electronic pulses per second (Hz). Calibrations are performed to establish a correlation between frequency and flow rate. The pulse frequency signal is converted to voltage by a National Instruments SCXI-1126 frequency conversion signal-conditioning module in the SCXI chassis. The output voltage is a known linear function of the input signal frequency.

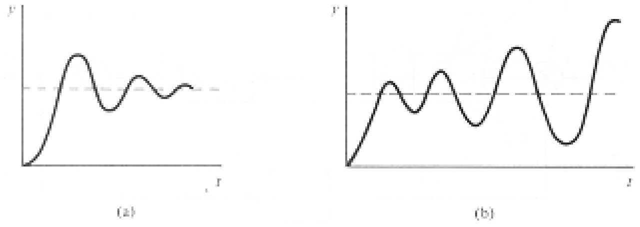
Process Control – Basic Principles

This lab provides an excellent opportunity to demonstrate some basic principles of process control. It is not the intent of this section to become mired in the mathematical details of how process control systems function – that will be covered in your process control course (ChE 360). Here we simply want you to see first hand how powerful a simple process control system can be and how it operates in a common application.

Process control systems are quite prevalent in everyday life, although you may not think of them in such terms. One of the most common types of process control is feedback control. In such a system, we have a variable that we would like to control. We control this variable by manipulating some other variable. When you set your thermostat to cool your house in the summer, you are using a simple feedback control system. Your thermostat monitors the temperature of your house. When the temperature exceeds the set point, it turns on the air conditioner as necessary to cool the house to the temperature you desire. An important feature of any process control system is its ability to overcome disturbances from a dynamic, changing environment. Disturbances are effects that may cause you to deviate from a set point even if your control variables are held constant. As you generate heat inside your house from cooking, or the sun heats your house from the outside, the thermostat's feedback control returns you to the set point temperature you have chosen by leaving the air conditioning on as necessary to overcome the disturbance. However, as we will learn in this lab, the simplistic control scheme described above is inadequate for many important industrial applications.

Consider a sensitive chemical process where the temperature must remain at 100 °C to maximize conversion. This temperature is monitored in the center of a large reaction vessel. Large band heaters are clamped around the outside of the vessel. Suppose you are heating the vessel during start-up with a simple on/off control scheme as outlined above. You begin at room temperature and the heater remains on until the temperature sensor reaches 100 °C. But at this point when the heater turns off, there is still a temperature gradient between the heaters and the temperature sensor mounted in the tank. Upon equilibration, the temperature will exceed 100 °C. Similarly, as the tank cools while the heaters are turned off, the outer walls will fall below 100 °C before the temperature sensor detects the drop. It takes some finite period of time for the heaters to respond and warm up to 100 °C and during this time, you will experience further cooling. The end result is a cyclic, unsteady temperature variation.

Sophisticated control systems can deal with these problems automatically. They can *anticipate* the need for heating before the temperature falls below 100 °C by watching the temperature history over time. By anticipating temperature trends, the controller can take "preventive" action to compensate for these trends and damp the oscillation. A well-designed process control system can compensate for any process disturbance and quickly return the process variable to the set point as shown on the left side (a) of Figure 2 below. On the other hand, a poorly designed process control system can fluctuate wildly and lose control of the process variable as shown on the right side (b) of Figure 2.



(a) (b)

Figure 2: Controlling a Process Variable

The purpose of a process control system is to achieve and maintain a set point. That is, the process control system manipulates a particular process variable to reach and maintain a desired flow rate, temperature, or other process variable of interest. In this lab we need to control the flow rate of a water stream. The flow rate is our controlled variable. The computer manipulates the position of a pneumatic valve to change the flow rate, hence valve position is our manipulated variable. During the experiment, our process may be subject to disturbances. Disturbances are unpredictable fluctuations that may change our flow rates. In this case, our system can experience sudden changes in water pressure as other users open and close valves. We need a control system that maintains a chosen flow rate in spite of any such disturbances. It must do so by manipulating the position of the inline valve appropriately. We may think of this system in the following diagram notation:

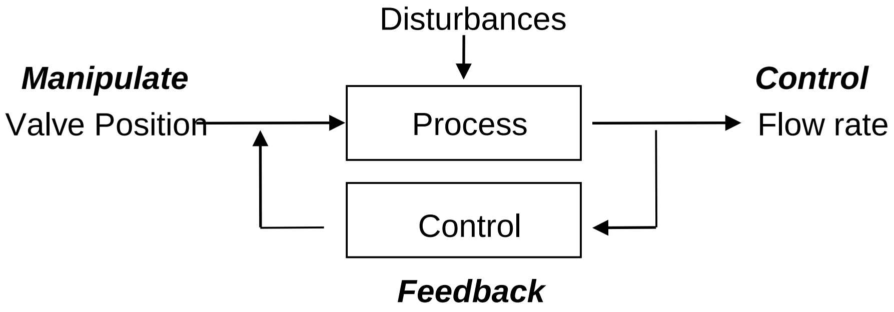


Figure 3: Schematic of a Feedback Control Scheme

In the heat exchanger system, the box labeled “Control” is handled by the computer. We will be using *proportional-integral control*, also referred to as PI control. Some processes also add a component known as derivative control, hence the more common term “PID” control.

Proportional control works in the following manner. Suppose we have an established steady state flow rate F_s that was achieved with our metering valve in position V_s. Then, another user on our water line opens up a large supply valve causing the line pressure to drop. If nothing is done to our control valve, we will experience a drop in the flow rate to some new, lower value F while holding valve position V_s. The control system must compensate by changing V_s in some way. One simple control law we may choose to implement is the following:

$$V = -\alpha(F - F_s) + V_s$$

We want to minimize the flow rate error ($F-F_s$) by changing the value of the valve position (V). The constant α in the above equation dictates how much the valve position must change relative to the steady state position (V_s) to compensate for the disturbance. This simple control scheme is known as *proportional control*. The parameter α is known as *proportional gain*. A proportional gain set too high causes the controller to overcompensate by taking overly drastic action to correct the error, while a low proportional gain will cause the controller to act too slowly, allowing the system to be out of specification for a long period of time.

By design, a control scheme that is based only on a proportional correction will always result in a steady-state offset error, although this error is significantly reduced in comparison to a system with no control. Integral control can then be used in conjunction with proportional control to drive this error to zero. The idea is simply that control action is taken even if the error is very small over a long period. You can think of integral control as a constant summation function that is constantly adding up the error and providing feedback proportional to the total rather than the error. This enables the controller to correct for accumulation of small errors over time (cumulative error). Integral control is often referred to as the 'memory' of a controller.

The characteristic parameter used to manipulate the integral control is known as reset rate. As you increase the reset rate, you are increasing the rate at which the integral control attempts to eliminate offset errors. If this rate is too low, the control will be ineffective at eliminating a steady offset error. However, if this rate is too high, the integral control may lose control of the system by failing to allow enough time for re-equilibration after control action is taken.

Derivative control monitors the rate of approach to the setpoint, and is most commonly used to prevent “overshoot.”

In this lab, you will observe the effects of proportional gain and reset rate on the control of a process variable. Many of the control phenomena described above will be demonstrated.

Valve Operation

Analog output from the data acquisition card is used to move three valves to the control the flow rates of the hot and cold streams and the flow rate of steam used to heat the hot stream in a secondary heat exchanger. These three valves are repositioned in a manner based upon the updated value of the process variable they are controlling. The difference between the measured flow rate and the set point is used to determine the magnitude and direction of valve motion that is required, based on a proportional-integral control algorithm.

The data acquisition card produces a voltage that corresponds to the valve position required to maintain the setpoint. This voltage signal is converted to a current signal using a National Instruments SCXI-1124 module on the SCXI chassis. The resulting current signal is used to drive an electrical-to-pressure transducer or E/P transducer. This transducer is an electrically driven pressure regulator in which an input supply pressure is down-regulated to a value that depends linearly upon input current. This computer controlled air pressure may be used to operate a pneumatic control valve that may open to varying degrees in order to regulate the flow rate into the heat exchanger.

Heat Exchange: The Heat-Transfer Coefficient

The overall heat-transfer coefficient for a shell-and-tube heat exchanger, *U*, is defined by the following equation:

$$Q = U \cdot A \cdot F_G \cdot \Delta T_{log\ mean}$$

where,

Q = rate of heat transfer, BTU/hr

U = overall heat transfer coefficient, BTU/hr-^{o}F-ft^2

A = area of tubes, ft^2

F_G = correction factor for $\Delta T_{\text{log mean}}$

$\Delta T_{log\ mean}$ = log mean temperature difference

The rate of heat transfer can be calculated by the sensible heat gained by the cold fluid and by that lost by the hot fluid. The area can be calculated from tube geometry. The factor F_G is a correction for the $\Delta T_{log\ mean}$ term for multipass heat exchangers, and for heat exchangers where there is cross-flow (see Chapter 15 in McCabe and Smith [Ref. 1] for more information on this subject).

APPARATUS

The main heat exchanger is of the shell-and-tube type and has chilled water on the shell side and hot water on the tube side. Chilled water is provided by the University chilling station, and city water is heated in two parallel secondary heat exchangers using medium pressure steam as the hot stream. Heating of the city water stream is accomplished by controlling the flow of steam to the secondary heat exchangers.

The primary heat-exchanger specifications are as follows:

Total outside tube area for heat transfer = 56 ft^2
Number of tubes = 116
Tube characteristics: Admiralty metal, ID = 0.331 in, OD = 0.375 in, #24 BWG
Shell characteristics: ID = 6 in, L = 5 ft, one pass with nine transverse baffles
Tube arrangement: triangular, P_T = 0.453 in, staggered, normal leakage
Tube side: hot water
Shell side: chilled water

The flow rates of the cold and hot water flow rates are measured by turbine meters that were discussed previously. Inlet and outlet temperatures for both streams are measured with platinum resistance thermometers. Software written using National Instruments' Lab View programming system is used to monitor process conditions and provide control of the hot and cold water flow rates and the hot water temperature. Each data point plotted is an average of 1000 samples from the A/D converter.

You will need to set the hot and cold stream flow rates using this software. The hot stream will generally be left at 35 °C. Change the value of the flow rate setpoint you wish to change by clicking the up and down arrows next to the set point value. (Alternatively, you may click inside the box with the number, delete the current value, enter your new set point, and press enter to record the change.) In order to activate a control loop, the switch beneath “Control” must be set to “ON” for the flow rate or temperature of interest.

The control loops are set to operate as PI controllers with the derivative action set to zero. The ***P*** term is the proportional gain for proportional control while the ***I*** term is the reset rate for integral control. These two parameters will be varied for the hot water flow rate in the second part of the lab.

PROCEDURE

Part A – Determining the Heat Transfer Coefficient

1. Ensure that the power is on for the **Dell computer**, the **SCXI signal conditioning chassis**, and the DC power supply for the frequency amplifier.
2. Set the instrument air supply pressure to 20 psig.
3. Trace the path of the city water stream. Ensure that all manual valves are open. At least one will be closed when you begin this lab.
4. Trace the path of the chilled water stream. Ensure that all manual valves are open for this stream as well. Again, at least one will be closed when you begin this lab.
5. Trace the path of the medium pressure steam. Ensure that all manual valves are open for the steam. The steam is often left in the open position to allow condensate to drain. SAFETY NOTE: All valves and pipes that contain steam may be VERY HOT. Use caution around the apparatus, especially when open or closing any valves.
6. Locate the “HEAT EXCHANGER” icon on the computer desktop and double-click to load the software.
7. The system will ask you to verify what you have completed the above steps. Simply answer OK when prompted.
8. It is necessary to briefly preheat the secondary steam heat exchangers that will be used to warm the incoming city water stream. Without this step, condensate may accumulate in the steam side of the heat exchangers which will prevent the hot water stream from being heated to the proper set point. The software has an automatic preheat routine that will allow steam to flow through the secondary exchangers for 30 seconds. It will then send you to the main operating screen with the hot stream temperature set for 35 °C and the city water set for 30 GPM. Unless otherwise directed by the TA, you should select the automatic preheat routine. ***While running the heat exchanger, the city water flow rate set point should always be at least 25 GPM and the hot stream temperature set point should be at least 35 °C.*** This will ensure that the system does not overheat while preventing excess condensation in the heat exchangers.
9. You should hear water flowing and you will likely hear the pneumatic valve opening and closing as necessary to achieve the hot water flow rate setpoint. Observe the response of the valve position relative to flow to see how the control loop automatically narrows in on the proper setting.
10. Set the chilled water flow rate to 25 GPM. Enable control for the “Chilled Water Flowrate Control Loop” by setting “Control” to “ON.” Again, you will hear the valve open and water will begin to flow.

11. Set the city water flow rate to 34 GPM. Allow the system to operate until all flow rates and temperatures have reached steady-state. Record the four stream temperatures for the heat exchanger and record the hot and cold flow rates.
12. Find the steady state equilibrium stream temperatures for 16 total combinations of hot and chilled water flow rates via the following matrix:

	HW = 28 GPM	HW = 34 GPM	HW = 38 GPM	HW = 40 GPM
CW = 25 GPM		*done above*		
CW = 30 GPM				
CW = 35 GPM				
CW = 40 GPM				

Part B – Evaluation of Process Control Parameters

You will now vary the proportional and integral control parameters for the hot water flow rate control loop.

1. Turn off the control loops for the hot water temperature and the chilled water flow rate. *All procedures outlined below apply to the hot water control loop!*
2. Set the flow rate to 32 GPM.
3. Set the integral (I) and proportional (P) control terms to 0.
4. Change the flow rate to 40 GPM. You will notice that we now have no controlling action to drive the process variable towards the setpoint. Record your observations.
5. Enable proportional control by setting P = 0.7500. This proportional gain is excessive for our system. You might think of this as the process overreacting to any deviation from the setpoint. Record your observations.
6. Return the proportional control to P = 0.0100 and the integral control to I = 0.0020.
7. Allow the flow rate to stabilize.
8. Set I = 0 to disable integral control. Set P = 0.0400. Change the setpoint to 30 GPM. Record your observations.
9. Now, enable the integral control by setting I = 0.0005. You should see that this change helps correct the offset. Record your observations.
10. Increase the reset rate to I = 0.0020. This level of integral control does a better job of pulling the process variable back towards the setpoint. Record your observations. What if we increase the integral control even more to correct the process variable even faster?
11. Increase the reset rate to I = 0.150. Watch what happens to the stability of the system. Record your observations. You will observe an important process control phenomenon known as *integral windup.* At this control level, the integral control does not wait long enough to see the results of corrective action in the process variable. It tries to drive the process back faster than the process variable can respond to control changes, and thus it loses control of the system.

RESULTS

In your report include the following for all sixteen heat exchanger trials:

1) For all sixteen heat exchanger trials, a table showing the volumetric flow rate, the mass flow rate, the inlet temperature, the outlet temperature, the temperature difference, and the rate of heat transfer, for both hot and cold streams. Also report the ratio of Q_{hot} to Q_{cold}.
2) For all sixteen heat exchanger trials, a table showing the hot stream volumetric flow rate, the cold stream volumetric flow rate, and the experimentally calculated overall heat transfer coefficient. Graph these results on a single graph as four curves with four points per curve.
3) Report your observations from Part B. Please use both graphic and written descriptions of your observations.

DATA ANALYSIS

1) Please **analyze** and **interpret** the results! Just reporting some tables and graphs and rewriting the numbers into a sentence does not demonstrate your understanding of the subject. This may include analysis of any observed trends, comparison with theoretical expectations and discussion of significance of measured and calculated values.
2) What should be the ideal ratio of Q_{hot} to Q_{cold}? Should the heat lost by one stream equal to the heat gained by the other? What are the possible sources of error in measuring this ratio? Which do you expect to be greater, Q_{hot} or Q_{cold}?
3) Comment on the effect of flow rate on the heat transfer coefficients.
    a) Do they change?
    b) Is there a trend to the change?
    c) How can you account for this trend (hint: boundary layer?)
4) Comment on the necessity of the $\Delta T_{log\ mean}$ (LMTD) factor, and justify the value for the correction factor F_G you use in your calculations.
5) Comment on the roles of proportional and integral control parameters and the performance of the controller when parameters are varied. Describe what happens to the performance when you change these values.
6) Please take care to use the proper units. Pick one system and stay with it!

REFERENCES

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2) J.O. Hougen; Measurements and Control Applications; 2nd Ed., Instrument Society of America, Pittsburg, (1979), p. 159.
3) W.L. McCabe and J.C. Smith; *ibid*, p. 405.

4) W.L. McCabe and J.C. Smith; Unit Operations of Chemical Engineering; 3rd ed., *ibid*, p. 301.
5) G. Stephanopoulos; Chemical Process Control; Prentice-Hall, Englewood Cliffs, (1984).

Appendix

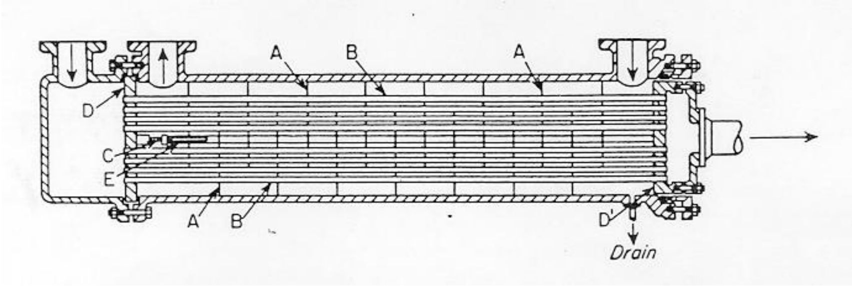

Figure 1: Internal Diagram of a Single Pass 1-1 Counterflow Heat Exchanger. A, baffles; B, tubes; C, guide rods; D,D', tube sheets; E, spacer tubes [4].

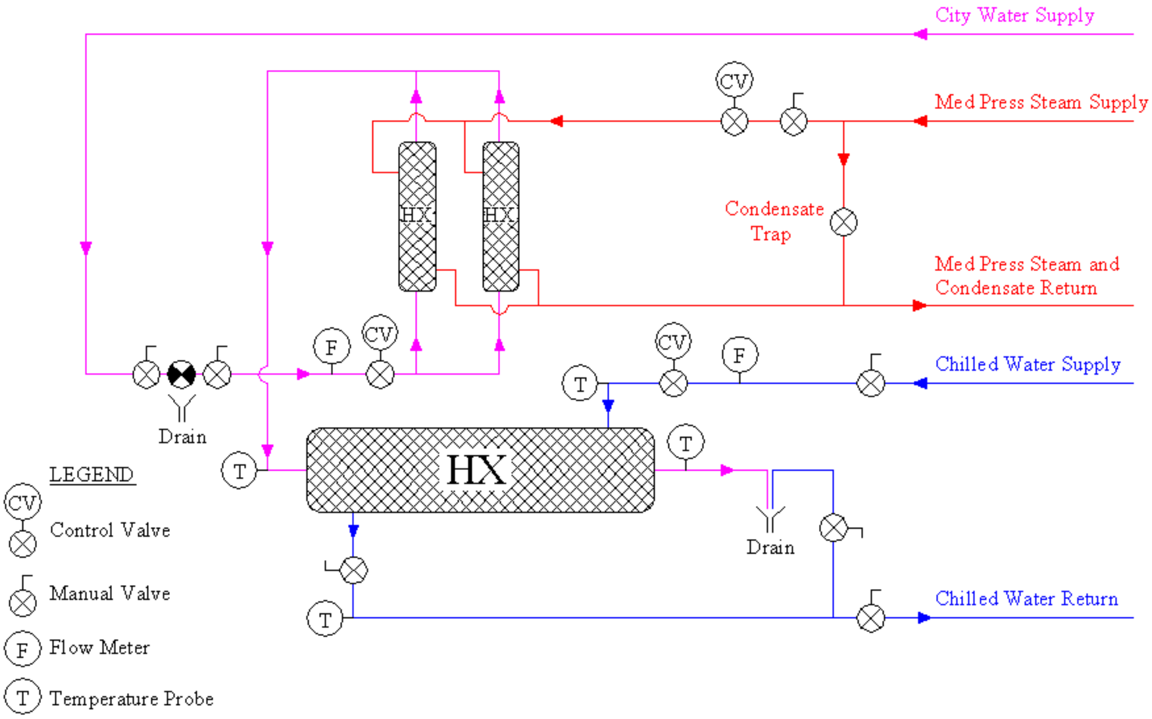

Figure 2: Experimental Setup Schematic. Control lines not shown.