AIR FLOW TEMPERATURE CONTROL

by

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Summary

In this experiment, students measure the temperature of a stream of air and control it by adjusting the heating rate in a stirred-tank heater. We first learned of this sort of experiment from the work [1] of Prof. Howard Saltsburg and colleagues in the Department of Chemical Engineering at the University of Rochester. Our implementation of the experiment was directed by Prof. Richard I. Masel, with the help of several graduate and undergraduate assistants.

The experiment is one of several in our senior-level process control laboratory at the University of Illinois. However, it is the only "common" experiment, being done by all students at the same time, working in groups of two. Thus, we have several copies of the experiment. Fortunately it is very inexpensive to construct. Students use the apparatus for several purposes over a period of about eight weeks in the first part of the semester. They later proceed to more complex experiments; at this time each group in a section works on a different experiment.

An IBM PC/XT is used in connection with this experiment to perform data acquisition and control. We obtained ten PC/XTs for our control lab from IBM as part of IBM's Project Excel on the University of Illinois campus. The students use the ASYST software package from Macmillan Software Co. This is a very powerful program for digital input and output, data analysis, and graphics.

Introduction

Our motivation in developing this experiment was to provide a simple, cheap, and safe experiment with which students could be introduced to the basic ideas of digital data acquisition and control, as well as to process modeling, controller tuning, and typical control system responses. Since this experiment is done by all students in our process control laboratory (shortly to become a required course) at the same time, working in groups of two and in sections of no more than twenty, we needed many copies of the experiment. This dictated that the experiment be very inexpensive and easy to construct and maintain. Due to limitations in the control lab, this also meant that the experiment could not take much space, and should preferably be mounted on the same table used for the computer. This dictated that nothing hazardous to the computer (nor to the student) be used, and led to the choice of air (rather than, say, water) as the fluid in the experiment.

The apparatus is shown schematically in Figure 1, and is described in more detail below. A stream of air is heated in a stirred-tank heater that uses a light bulb as the heating source. The students use an IBM PC/XT with associated A/D and D/A electronics to measure the air temperature and then manipulate the AC voltage to the light bulb to adjust the heating rate.

Students use this apparatus for about eight weeks (at three hours/week) for various purposes. The first week the students familiarize themselves with the apparatus and practice using the PC/XT hardware and the ASYST software to measure, record, and graph temperature data, and to manipulate the input to the light bulb. The next two weeks they use ASYST to write a simple program to perform anticipatory ON/OFF control of the air temperature. The next two weeks the students use the apparatus to study the response of a thermocouple to a step change in temperature. This is done by heating the air in the stirred tank to a constant temperature, then quickly moving a thermocouple from room temperature air into the heated air. Both a bare thermocouple and thermocouples shielded with different types and thicknesses of tape are used. In doing this the students need to be more concerned than previously with such issues in data acquisition as sampling frequency and data smoothing. They also are able to compare their experimental data with predictions from models. Finally, the students perform an experiment in which they try to design a good PID control system for the process. They obtain a process reaction curve, use it to do initial controller tuning, then study the control system response for various values of the PID control parameters. This is an open-ended problem which leads finally to a report in which the students present their recommendations regarding the control system. As a part of this, the students also model the control system, try to relate their observed data to their models, and use the models in initial controller tuning. Over the period that the students work on the apparatus, three reports are

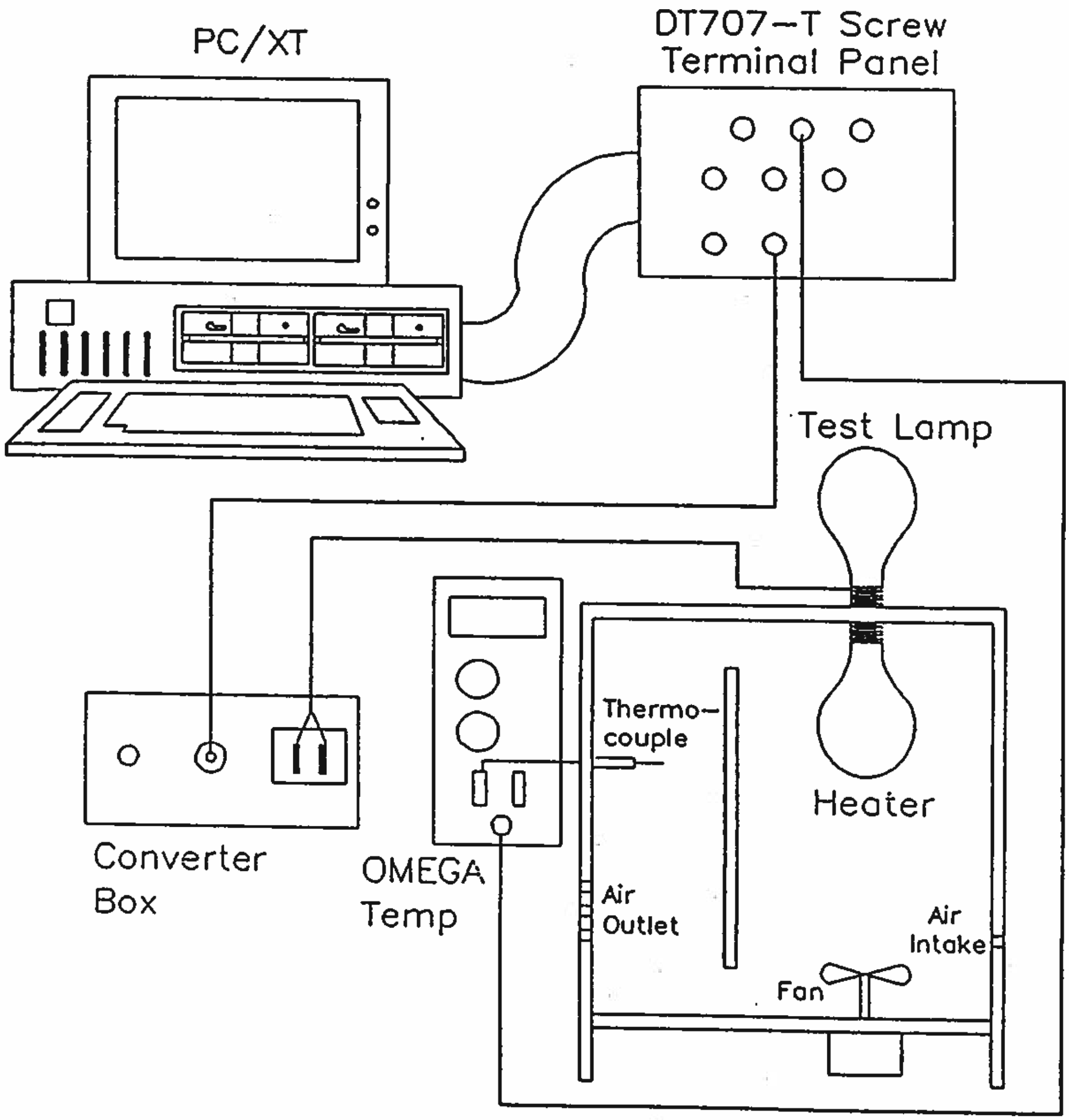

Figure 1. Schematic of apparatus.

required: one on the ON/OFF control experiment, one on the thermocouple response experiment, and one on the design of the PID control system. The last is considered a "major" report.

Theory

By the time the students begin the PID control experiment, they are familiar with the modeling of a stirred-tank heater as a first-order, linear system relating changes in outlet temperature to changes in energy input to the heating element. Of course, many assumptions are involved in such a model, one of which is neglecting the energy accumulation term for the heating element (i.e., one assumes negligible dynamic lag in the heating element). In this experiment, while there may be negligible dynamic lag in the light bulb filament, there may be nonnegligible dynamic lag in the light bulb as a whole, due to energy accumulation in the glass of the bulb. Thus, students are asked to model the system so that both $T(t)$ and $T_b(t)$, the air and bulb temperatures respectively, are treated as functions of time, and to be related to changes in $q(t)$, the energy input to the filament.

To do this, one can write an overall energy balance on the air and bulb, including the accumulation term resulting from changes in $T_b(t)$. A second energy balance, this one for the bulb alone, can also be written, and used to eliminate $T_b(t)$ from the overall balance. Thus, one obtains a second-order, linear model relating $T(t)$ and $q(t)$. In the Laplace domain this is $T(s)/q(s) = k/(1 + 2\tau\zeta s + \tau^2 s^2)$, where $k = 1/wC_a$, $\tau^2 = m_a m_b C_b/wUA$ and $2\tau\zeta = (m_a/w) + (m_b C_b/wC_a) + (m_b C_b/UA)$. The subscripts a and b indicate the air and the bulb respectively, m is mass, C is heat capacity per unit mass, w is the mass flow rate, A is the heat transfer area, and U is an overall heat transfer coefficient.

As an alternative, it is suggested to the students that it may be adequate to model the lag in the heating element simply as dead time between the energy input to the filament and the heat output of the bulb. In this case, we can easily obtain a first-order, linear model with dead time. That is, $T(s)/q(s) = k \exp(-\tau_d s)/(1 + \tau s)$, with τ_d the dead time, $k = 1/wC_a$, and $\tau = m_a/w$. In fact, process reaction curve data (see Figure 2), obtained by using the PC/XT to make a step change in the AC voltage supplied to the light bulb, and then recording the response $T(t)$, suggests that the first-order model with dead time represents the observed response fairly well.

Since the first-order model with dead time is the basis for the well-known Cohen-Coon controller tuning method for obtaining PID control parameters, this leads nicely into the next part of the experiment, namely controller tuning. Students can easily determine graphically, from their process reaction curve results, the parameters in the first-order model with dead time. The Cohen-Coon equations can then be used to determine initial estimates for the PID control parameters.

Hardware

The hardware is shown schematically in Figure 1. The main component of the experiment is a stirred-tank heater to heat the air stream. We will refer to this component here as the "air bath."

The sides, top, bottom, and back of the air bath are made of ordinary lumber, 3/4 in. thick. The side panels are 4.5 x 13.5 in., the top and bottom are 4.5 x 8 in., and the back is 9.5 x 12 in. The front is 3/16 in. thick plexiglass and is 9.5 x 12 in. An interior baffle made of lumber, 3/4 in. thick and 8 in. long, runs from the back panel to the front panel of the air bath. All interior surfaces are insulated using adhesive-backed foam rubber weather-stripping, covered by aluminum foil. The weather-stripping material is also used to form a gasket between the plexiglass front and the rest of the air bath housing.

The air intake consists of four 1/2 in. diameter holes drilled on the lower-right side, and arranged horizontally. The air outlet is three 3/8 in. diameter holes drilled on the lower-left side and arranged vertically. A metal slide mounted on the left-hand side panel can be used to cover part of the air outlet, thus allowing one to vary the air flowrate. Students may use step changes in air flowrate to test the regulatory behavior of their control systems.

The bottom panel is mounted high enough between the sides to allow room for the fan motor. The motor is 3000 rpm and 19.5 watts, and runs on 60 Hz, 115 volt AC. The particular motor used here is not well-shielded and tends to radiate 60 Hz noise that is picked up by the thermocouple wires. In order to reduce this we cover the space below the bottom panel (containing the motor), with several layers of fine metal screen.

Each copy of the experiment uses its own IBM PC/XT for digital data acquisition and control. Each system is currently equipped with 512 KB RAM, two 360 KB floppy disk drives, an IBM Enhanced Graphics Adapter, an IBM Enhanced Graphics Display, an IBM Proprinter, an IBM PC Network Adapter, and a Data Translation DT2805 data acquisition card. Most of the IBM equipment was provided by IBM as part of an IBM Project Excel grant to the University of Illinois. Other hardware was acquired with funds from the campus and the department.

It should be noted that these PC/XT systems are not dedicated to use in the control lab. When the control lab is not in operation, they are available for other uses. It should also be noted that in the process control course we also use ten IBM PC/ATs, also acquired under an IBM Project Excel grant. These are used in the control course for running control system simulation programs, and are heavily used in the senior-level process design course as well. All twenty PC systems are connected using the IBM PC Network. Another PC/AT acts as the network server; it is used extensively as a file server, and also as a server for a laser printer, a color printer, and a multicolor plotter. Students can use their local Proprinters for intermediate or draft-quality output, and then via the network get final, presentation-quality output.

The DT2805 data acquisition card is connected by ribbon cable to a Data Translation DT707-T Screw Terminal Panel, which is mounted in an enclosure that provides BNC connections to six of its eight A/D channels and both of its two D/A channels. The DT2805 provides 12 bits of resolution on these input and output channels. Two of the A/D channels are set up using ASYST to have a gain of 500, which is suitable for the thermocouple used. The D/A output channels are set up to provide a 0-10 volt DC output (other output ranges are also available), which is converted linearly to 0-120 volts AC using a simple "home-brewed" converter box. Since the power output from the light bulb is nonlinear with respect to voltage, this introduces a complication that students typically do not expect. The nonlinearity in the system is generally first discovered when students note that the model parameters obtained from process reaction curve data vary significantly depending on the initial steady state. Students are challenged to explain this behavior, and are introduced to the realities of nonlinear systems.

The thermocouple is held in place by mounting a wooden dowel through the left side of the air bath, and then passing the thermocouple wire through a small hole drilled down the axis of the dowel. The thermocouple's cold junction (reference junction) is outside the air bath at room temperature. The thermocouple is type K (alumel-chromel). Its signal goes to an OMEGA 871 digital thermometer, which provides a digital temperature reading, and an output compensated for a 0 C reference temperature, which is then connected to one of the A/D input channels on the DT707-T. The digital thermometer is not really a necessary part of the experiment, but provides a convenient way to establish a calibration between air temperature and the digital reading (on a scale from 0 to 4095) taken by the computer. Our experience is that the input signal to the PC/XT is actually somewhat less noisy if the uncompensated thermocouple signal is passed directly to the DT707-T, thus bypassing the digital thermometer. The DT707-T has its own cold-junction compensation circuit that can be used to provide a compensated input voltage to the computer. Alternatively, a temperature calibration can be established, if desired, by using the digital thermometer or some other device to make an independent temperature reading, or by feeding the thermocouple signal into both the DT707-T and the digital thermometer (careful, this introduces an additional cold junction into the circuit).

The light bulb used as a heat source is a standard 75 watt bulb, installed in a ceramic socket screwed to the top panel of the air bath. In order to reduce radiative heat transfer from the light bulb, it is painted black. A flat-black, high-temperature spray paint (often sold for use in painting barbecue grills) was used. Since the bulb used as the heating element is painted black, it provides no visual information to the student about whether the heating rate is currently high, low, or off. To do this, a lower wattage "test lamp" is installed in a ceramic socket mounted on top of the air bath. Both lamps are driven by the same AC voltage, so when the test lamp is off, the heater is off; when it is bright, the heater is on high; etc. The AC voltage for the lamps is determined by the computer via the DT707-T and the converter box.

The digital thermometer is fastened to the side of the air bath. The air bath is fastened to a table (60 x 30 in.) on which the PC/XT system, the DT707-T, and the converter box also sit.

Software

The software used is the ASYST package from Macmillan Software Co. This program provides a sophisticated, powerful, and integrated system for digital input and output, data analysis, and graphics.

Most students starting our process control lab will already have had some exposure to ASYST, since it is used in some experiments in the required physical chemistry lab courses. However, for the purposes of our lab, they need a more detailed knowledge of ASYST; thus the first two or three weeks in the lab are spent on exercises that will teach students what they will need to know about ASYST.

While we provide the students with a few special-purpose ASYST procedures (or "words" to use the ASYST nomenclature), and there are many such words provided within ASYST, we expect students to organize their own programs to use these words. For instance, to do the PID control experiment, the student will typically have to write an ASYST program that repeatedly reads A/D data, smooths this data, determines the deviation from the set point, computes a correction signal, and outputs this as D/A data. Other features the student may include in his program include real time graphical displays of data. We do not, for instance, provide the students with an ASYST program for PID control in which they are prompted for PID parameter values, and then everything else is done for them (although this could easily be done). On the other hand, we do not, for instance, expect students to deal with details of the data acquisition hardware and interfacing. Using ASYST this is not necessary; students can use single ASYST words to read an A/D channel, or to output to a D/A channel.

Finally, it should be noted that while we find ASYST to be very convenient, the experiment described here can easily be performed using other software. Basically we cannot come close to using the full power of ASYST in this simple experiment.

Results

Some sample results are shown in Figures 2-5. All these are plots of air temperature versus time, and were prepared using ASYST. All temperature data are expressed on the arbitrary scale used in taking A/D readings. This scale can be calibrated to Centigrade or Fahrenheit if desired, but this is not an essential part of the experiments described here.

Figure 2 shows a process reaction curve, obtained by making a step change in the digital output to the heater. Students can fit such output to a first-order model with dead time. Typical results for this system are dead times of five to ten seconds, and first-order time constants of 50-200 seconds. Since the system is nonlinear this variation in results is not unexpected. Values for the model parameters can then be used with the Cohen-Coon equations to determine some initial control parameter values for use in P, PI, PD, or PID control.

The students then test these parameter values, and several other parameter values, to try to determine the best control system. Since this is intended as an open-ended experiment, the students tend to try many different alternatives. They are able to do this since each run typically takes under ten minutes. In their many different runs, they generally will see some very good results, some very poor ones, and some rather average ones. For instance, Figure 3 shows a rather average response for a P control system, with some offset and fairly slow response time. Figure 4 shows a very poor result for a PID control system. Figure 5 shows a very good response for a PI control system.

This experiment seems capable of exhibiting a wide range of control system behavior.

Student Response

Though we have taken no formal survey of the control lab students at this point, the response to this experiment, and to the control lab in general seems to be positive, and increasingly so. There seem to be fewer and fewer "computer-phobic" students, and more and more students with considerable microcomputer experience.

Negative reactions from students tend to stem not from this particular experiment but from other more general aspects of the lab. For example, ASYST is a stack-oriented program. For students who have used Hewlett-Packard calculators, this presents

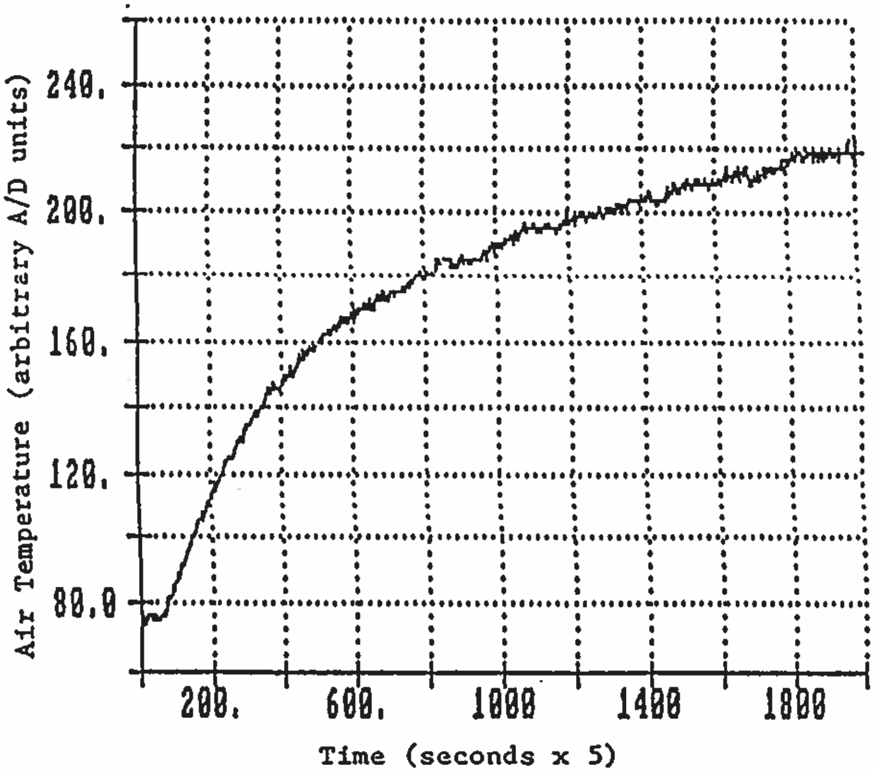

Figure 2. Process reaction curve. Temperature data are expressed on the arbitrary scale used to take A/D readings.

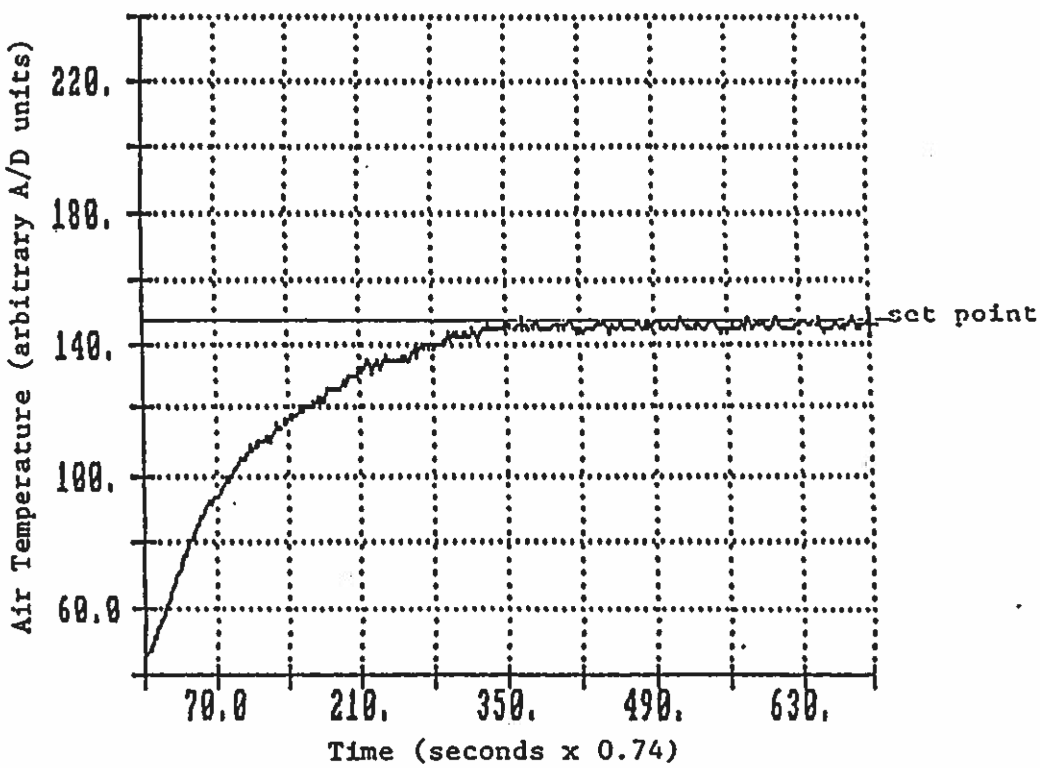

Figure 3. Response to a change in set point for a P control system with K_c = 400 (arbitrary D/A voltage units/arbitrary A/D temperature units).

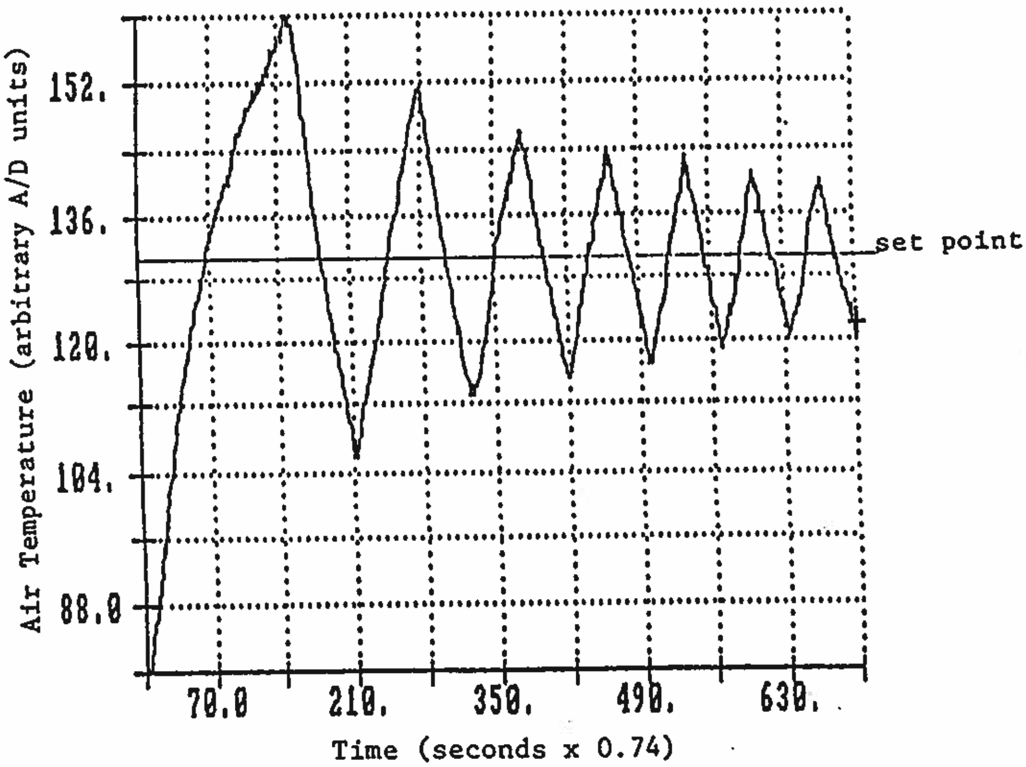

Figure 4. Response to a change in set point for a poor PID control system (K_c = 200, τ_I = 5.3 seconds, τ_D = 0.8 seconds).

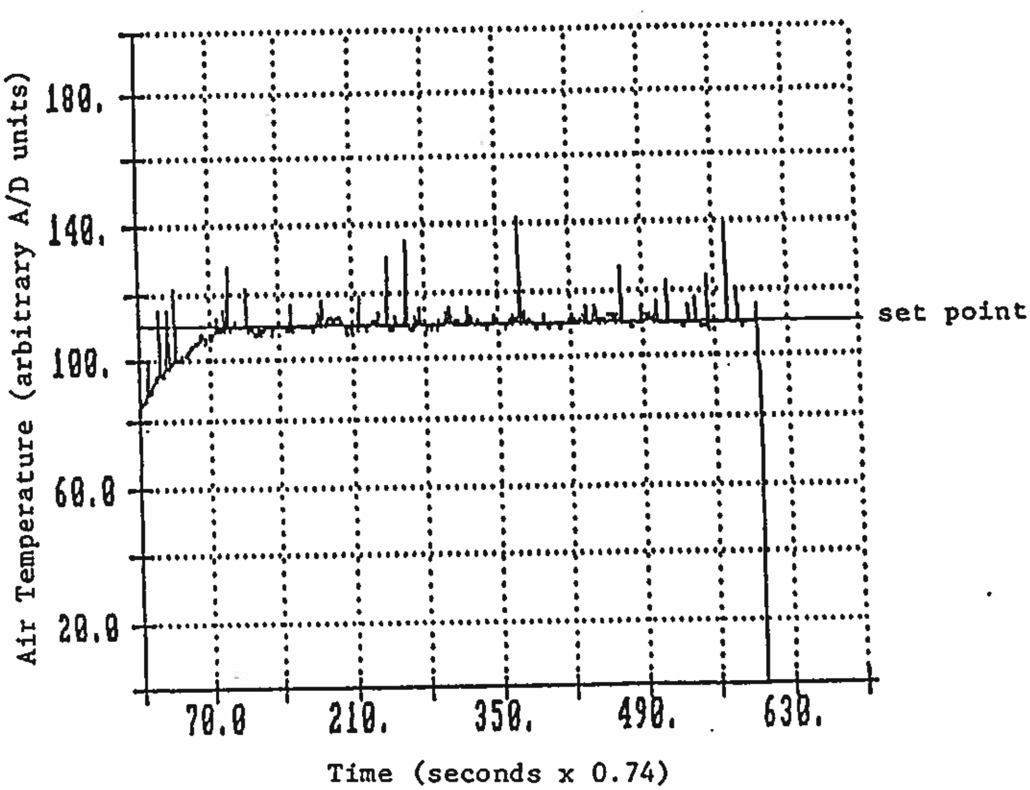

Figure 5. Response to a change in set point for a good PI control system (K_c = 8, τ_I = 100 seconds). The spikes in the curve are due to a loose connection to the sensor.

no difficulty. For those who have not, the stack concept is one that some find difficult to get used to. An alternative is to have students write programs in BASIC, using routines typically provided with data acquisition cards. However, BASIC is not used in any course generally taken prior to the control lab (while ASYST is), and it is not clear that teaching someone the essentials of BASIC is any easier than teaching someone the essentials of ASYST.

Conclusions

The air flow temperature control experiment is a safe and inexpensive way to introduce students to the basic concepts of digital data acquisition and control. It is so inexpensive that we use several copies of it. Moreover, since it can exhibit a wide range of control system response, it is well-suited to open-ended studies in which students are asked to design a control system.

Acknowledgements

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References

[1] T. Olsen, H. Saltsburg, and R. H. Heist, "Microcomputers in a College Teaching Laboratory," Part III, MICRO, 56, 38 (1983).