The Use of LabVIEW and Data Acquisition Unit to Monitor and Control a Bench-Top Air-to-Water Heat Pump

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ABSTRACT: A bench-top air-to-water heat pump was designed, developed, and constructed by a multidisciplinary capstone senior design team. This experimental apparatus is currently being used to demonstrate to undergraduate students some thermodynamics and heat transfer concepts and principles. A PC-based control system which consists of LabVIEW and data acquisition (DAQ) unit is employed to monitor and control this experimental laboratory apparatus. This paper provides details about the integration of the electrical/electronic component and the control system. © 2008 Wiley Periodicals, Inc. Comput Appl Eng Educ 16: 83–91, 2008; Published online in Wiley InterScience (www.interscience.wiley.com); DOI 10.1002/cae.20122

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INTRODUCTION

Recently, the assessment results of the mechanical engineering program at Indiana University-Purdue University Fort Wayne have shown that the mechanical engineering curriculum lacks "high tech" equipment and experiments. This was the feedback from our undergraduate students. The students have indicated that they would like to see more use of computer data acquisition (DAQ) systems and the availability of computers in the laboratories so they can perform on-site data analysis and calibration. Currently, there is only one mobile DAQ system that is rarely used in some of the laboratory courses. To address this concern, the authors have integrated computer DAQ in some of the existing and new experiments.

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Indiana University-Purdue University Fort Wayne is a state-supported institution. Thus makes acquiring new instructional laboratory apparatus a challenge due to typical budgetary limitations. In addition, the apparatus designed by companies specializing in education equipment may not exactly reflect the educational objective intended by the faculty. These obstacles had forced us to seek and search different venues to acquire ''high tech'' experimental laboratory apparatus for demonstrating thermodynamics and heat transfer concepts and principles. We concluded that such an apparatus can be designed, developed, and constructed ''in-house'' within a manageable budget. This can be successfully accomplished by taking advantage of the capstone senior design project and ASHRAE Undergraduate Senior Project Grant Program. The purpose of this ASHRAE's program is to fund equipment for undergraduate engineering senior projects on ASHRAE-related topics. Obtaining these types of grants to support the design, development, and construction of instructional laboratory apparatus would greatly help the normally stressed department's equipment budget. In addition, it would provide the students with quality and real life design projects to work on.

One of the new ''high tech'' laboratory experimental apparatus that was designed, developed, and constructed is a bench-top air-to-water heat pump. Integrated with this apparatus is a PC-based control system which consists of LabVIEW and DAQ unit is employed to monitor and control this experimental laboratory apparatus. LabVIEW and computer DAQ have been widely utilized to update and modernize equipment and laboratory experimental apparatus [1–7].

THE DESIGN PROCESS

The design process that the students follow in the capstone senior design project is the one outlined by Bejan et al. [8] and Jaluria [9]. The first essential and basic feature of this process is the formulation of the problem statement. The formulation of the design problem statement involves determining the requirements of the system, the given parameters, the design variables, any limitations or constraints, and any additional considerations arising from safety, financial, environmental, or other concerns.

In order for the bench-top air-to-water heat pump to function as a useful piece of laboratory equipment, the following requirements and specifications need to be met. These include requirements that will make the heat pump useful for demonstrating thermal science and fluid dynamics principles as well as ensure the heat pump will operate safely.

- Construction—The air-to-water heat pump is to be designed to operate based on a vapor-compression cycle.
- Instrumentation—The instrumentation requirements have two distinct sets of necessary specifications.

1. The heat pump must be fully instrumented with autonomous gages so that it may demonstrate its principles without needing to be hooked up to an outside computer.
2. Although it may operate without an external computer, the heat pump must also be outfitted with a DAQ bus that can be connected to an external DAQ board or software system. This bus must be able to supply to the external DAQ system the measurements that will be shown on the on-board instrumentation. In addition, the measurements must be logged by the DAQ.

- Safety—The safety considerations deal primarily with the fact that the design requires both large amounts of electrical equipment and liquids to be in close proximity. For this reason the following are required of the electrical design scheme:

1. Residual current circuit breaker.
2. Combined double pole main switch and overload cut-out.
3. All components connected to common earth conductor.

EXPERIMENTAL APPARATUS

A bench-top air-to-water heat pump, shown in Figure 1, was designed, developed, and constructed for instructional and demonstrative purposes. This heat pump was designed around the vapor-compression refrigeration cycle. The bench-top air-to-water heat pump has an intuitive user interface, reliable, safe for student use, and portable. The interface is capable of allowing DAQ by an existing laboratory computer. The unit is capable of warming the water 10°C in an open or closed configuration, and cool it back down if desired. The system fully controls and monitors the fluid properties at key points in the refrigerant and water loops.

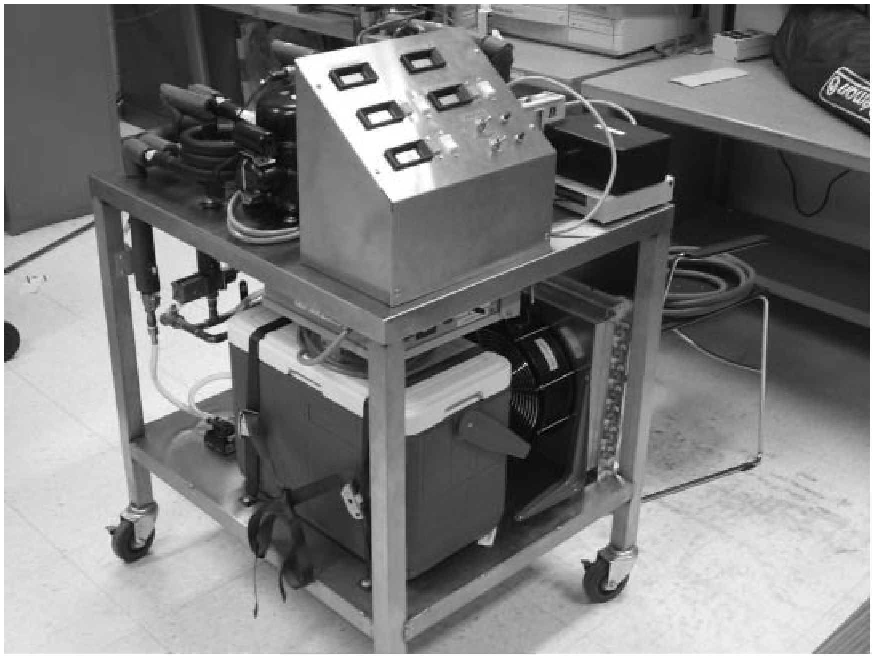

Figure 1 Experimental apparatus.

INTEGRATION OF THE ELECTRICAL/ELECTRONIC COMPONENT

The electrical/electronic part of the building process consisted of five main phases. These phases included the following: Testing low voltage designs at the component level

1. Final assembly and testing of low voltage electrical system.
2. High voltage wiring of mechanical system.
3. Integration of the electrical system with mechanical system.
4. Testing DAQ functionality.

All of the low voltage electrical components were tested for functionality before assembly into their respective circuits. This was done by applying voltages to each chip and checking output for correctness. After these individual components were tested, each of the circuits were temporarily built on a breadboard and tested to verify that they worked as expected. This was proven by applying inputs of voltages or frequencies from laboratory equipment and measuring the output voltages with a handheld meter. The microprocessors were also programmed and tested, the program can be found in the Appendix.

In the second phase of the building process, the final assembly of the low voltage electrical system was performed. All of the circuits were laid out, built, and soldered together on a perforated proto-board. The circuits were then retested with laboratory equipment to verify that building and soldering was completed correctly. Once the circuits were built and soldered, more testing was done to determine the accuracy and percentage error associated with these circuits.

The fourth phase comprised the high voltage wiring of the mechanical system. All high voltage components were wired with a common ground, the ground fault interrupter (GFI) was placed on the high voltage wire coming directly from the wall outlet to protect against large surges of current, and the double pole single throw (DPST) circuit breaker was placed directly following the GFI. In addition to these original specifications, two lights were added to show the status of the high voltage power. The first light demonstrates that the system is connected to the high voltage power and the second light confirms the system is on and operational.

The final integration of the electrical/electronic system with the mechanical system consisted of running wires from the pressure circuits to the pressure transducers, connecting the thermocouple wires to the temperature circuits, and applying low voltage power to the water pump. The final step in the electrical/electronic building process was testing the DAQ functionality. Wires were run from the control box on the heat pump unit connecting to the DAQ board via a printer cable.

After the entire system was built and operational, it was then connected to the SCB-68 break out box and then to the DAQ card, via the on-board DB-25 connector and modified printer cable. It was observed that the sensor signals dropped due to the voltage divider circuit created when the DAQ was applied to the system. To remedy this problem, fifteen LM741 operational amplifiers were employed as a non-inverting amplifier and voltage followers. The non-inverting amplifier was used to amplify (magnitude of ten) the water flow signal, as it was observed that the DAQ was having difficulty in accurately collecting the small signal. This signal isolation system was added to the cable that connects the control box to the DAQ.

TEMPERATURE MEASUREMENT

The temperature data need to be collected and monitored at nine locations in the system; four points in the refrigerant loop, four points in the water loop, and one ambient temperature reading (refer to Fig. 2). In order to collect this data, thermocouples have been chosen because of their low cost and availability. However, the non-linear characteristic of these thermocouples is a major drawback. Analog devices produce a low cost thermocouple conditioner (P/N AD597) that produces a linear voltage output with respect to temperature.

Each of the thermocouple junctions will be conditioned with a conditioning circuit. The output of the conditioning circuit will produce 10 mV/°C. This signal will be displayed directly to the on-board display and also fed directly to the DAQ. Since the input impedance of both the DAQ and the panel meter has very high impedance, the loss from each of these devices can be considered negligible. If however there is a problem with the signal having a drop we can employ a voltage follower to buffer the signal. The LED that is located on pin 9 is an open thermocouple alarm; this will light if the thermocouple is not properly connected.

Each signal will be fed into an analog multiplexer (P/N ADG408), this multiplexer will be fed a BCD number from a small flash memory-based microprocessor (P/N PIC12F675). This microprocessor will accept an input from the user from two momentary on−off switches; these switches have also been debounced by the nand gate network. The microprocessor will give a corresponding BCD output based on the action taken by the user; it will also be limited to the number of inputs that is located on the circuit. The microprocessor flowchart is illustrated in Figure 3. The microprocessor's BCD output will also be sent to a CD4511BC; this chip converts a BCD input and directly drives a seven segment LCD display that will indicate the thermocouple signal that is displayed on the panel meter. Each one of the signals will also be pulled to the DAQ board before they are multiplexed. The water loop temperature circuit is identical in operational theory to the refrigerant temperature circuit. The only difference is that the water loop circuit has one extra input for measuring ambient temperature.

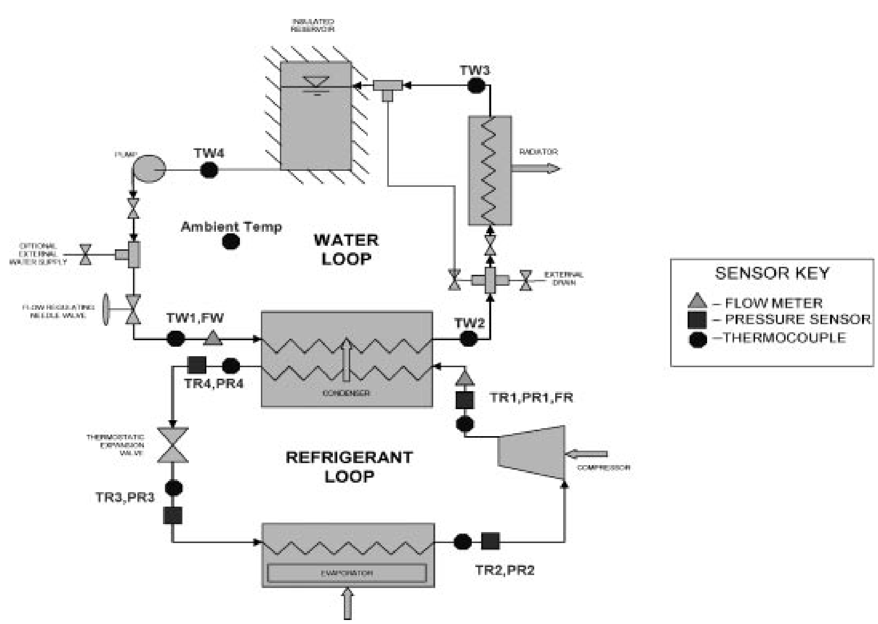

Figure 2 Schematic diagram of system and sensor locations.

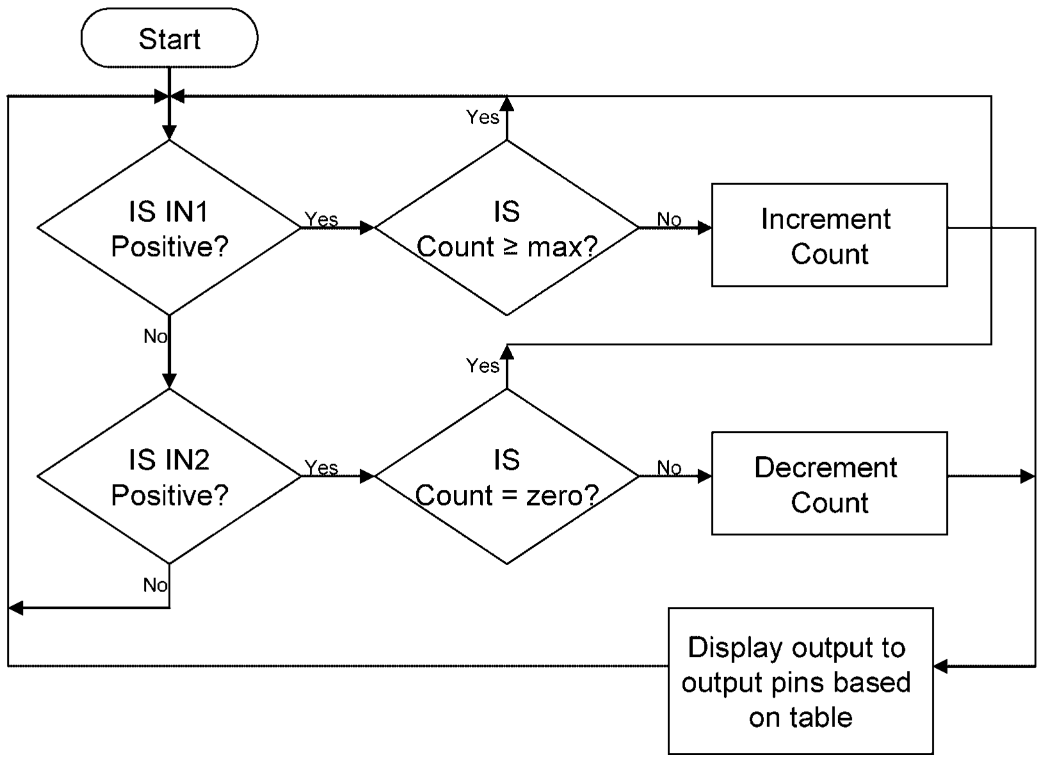

Figure 3 Flowchart for the PIC12F675 microprocessor.

PRESSURE MEASUREMENT

The pressure will only be measured on the refrigerant loop (Fig. 2). It will also only be measured at four points. The pressure transducers that have been selected for this application are the Texas Instruments 2CP5-50-1. This pressure transducer will measure gauge pressures from 0 to 300 psig, the signal output is a ratio metric signal that falls between 0.5 and 4.5 V DC. The signal can be fed directly to the DAQ board before it is fed to the analog multiplexer (P/N ADG408); because LabVIEW allows for the signals to be mapped before they are stored and displayed. The switching of the signals will occur exactly as it did in the temperature circuits with the PIC12F675 and the single seven segment display.

Before the signal is fed to the digital panel meter it needs to be fed through a network of op-amps so that it is stretched and scaled to 0−3 V DC. In order to accomplish this task the signal is fed into a summation amplifier that will add −0.5 VDC to the signal, this will offset the signal to 0−4 VDC.

The signal produced by the summation amplifier is given by

$$V_{\text{out}} = -\left[\left(\frac{R_{\text{f}}}{R_1}\right)V_{\text{in}} + \left(\frac{R_{\text{f}}}{R_2}\right)(-5)\right] \tag{1}$$

Analysis with the maximum signal input and maximum signal output yields the solution for resistor values:

$$R_{\text{f}} = 1\,\text{k}\Omega$$
$$R_2 = 10\,\text{k}\Omega$$
$$R_1 = 1.33\,\text{k}\Omega$$

These values when used with the above equation produce a shifted and scaled output signal. The output signal is now however negative and needs to be inverted. In effort to neglect the effects of the impedance from each op-amp circuit, a voltage follower is placed in between the summation amplifier and the inverting amplifier. The equation that govern the inverting amplifier is given as

$$V_{\text{out}} = -\frac{R_{\text{f2}}}{R_3}V_{\text{in}} \tag{2}$$

FLOW RATE MEASUREMENT

The two flow rate sensors that were chosen for the design are from gems sensors and are turbine type flow transducers. The refrigeration loop requires a different transducer than the water loop because of the difference in the expected flow rates. The sensor for the refrigeration loop measures flow rates from 0.37 to 4.0 GPM with a ratio metric frequency signal from 37 to 550 Hz. The sensor for the water measures flow rates from 0.26 to 2.6 GPM with a ratio metric frequency signal from 55 to 550 Hz.

Because these sensors output a frequency signal they must be converted from frequency to a linear voltage that corresponds directly to the GPM that is sensed. Analog devices have a product called AD650; this is a low cost frequency to voltage converter with extensive application notes and design tools available online. Since there are two flow meters (one for the water and one for the refrigerant), and each one of them have their own conditioning circuit, it was decided that each of these should have individual displays on the display panel. After they are conditioned, each one of the signals is fed into the DAQ as well as into a panel meter.

CONTROL SYSTEM

The control requirements of this system consist of monitoring two of the pressures (the condenser pressure and the evaporator pressure) and switching the compressor and the evaporator fan on and off, depending on the levels of the pressure transducers. In order to control this system there are a few integral components; (1) A PIC16F687, the microprocessor that will read run the control program. (2) Two solid state relays (P/N 4062RL), used for switching on and off the motors. (3) Two pressure transducer outputs (P/N 2CP5-50-1). The microcontroller runs the program that is flowcharted in Figure 4. This program utilizes the on-board 10-bit analog to digital converters to convert the pressure transducers' voltages into a usable digital value. The microprocessor compares the values that are produced from the pressure transducers to some preset values and then output control signals to the solid state relays to control the motors.

The microcontroller is programmed using the flow chart shown in Figure 4. This program starts both of the relays at zero output logic and initially checks the condenser pressure. If the condenser pressure is above the set point, both of the motors will remain at zero. The relays will remain at zero until the condenser pressure is below another preset value. Once this pressure drops to the set point the microprocessor will check the evaporator pressure, if this pressure is below a certain value the compressor will remain at zero and the evaporator pressure will continue to be polled until it rises to the specified suitable temperature. Once this temperature is achieved the compressor will be turned on and the evaporator pressure will be checked. If this pressure becomes too large the evaporator fans will remain at zero and the system will poll the evaporator pressure until it falls below the set point. Once the set point is achieved the evaporator fan will be turned on and the loop will continue to iterate at the check condenser pressure stage until the system is turned off.

DATA ACQUISITION AND SOFTWARE

The DAQ system consists of the sensor network that is outlined in Figure 4, and the DAQ board that is controlled by a computer. The board that was chosen for this project is the National Instruments PCI-6024E. This DAQ was chosen based on its ability to accept 16 analog inputs and the fact that it was already purchased by the Department of Engineering. The software used to control this DAQ board is LabVIEW by National Instruments.

A computer code that controls the DAQ board was developed (the authors are willing to send the code if requested). The DAQ was programmed to sample each channel at 10 Hz; this frequency was chosen because it will be relatively simple for the computer to deal with the small amount of data that will be produced and the system will not be changing quickly. All of the data collected will also be stored to a data file for manipulation later by the students. This will allow for a relatively small amount of stored data for easy manipulation later. Since Microsoft Excel allows for 65,536 rows of data, sampling at 10 Hz allows for the user to plot 108 min of continuous data.

Each transducer was conditioned to supply a linear voltage signal that was easily read and scaled by the DAQ. Each one of the inputs has also been scaled using the NI-DAQ Assistant; units of measure were also applied at the same time. The measurement sensitivity for each of channel is 0.008 mV, therefore Table 1 was derived to give the number of significant digits that will be produced in the data file. As can be seen from the chart, the transducers are not accurate enough to produce accurate readings out to the fullest extent of the DAQs capability.

The GUI is broken down into three distinct sections. The GUI is shown in Figure 5. The first section is titled temperature panel; it allows for the user to simultaneously view each temperature reading while monitoring a user set high temperature point for the water loop and the refrigerant loop with visual indicators (virtual LEDs). This section also allows the user to plot the data with respect to time, the transducer data can be selected by the user with a selection switch. The center section

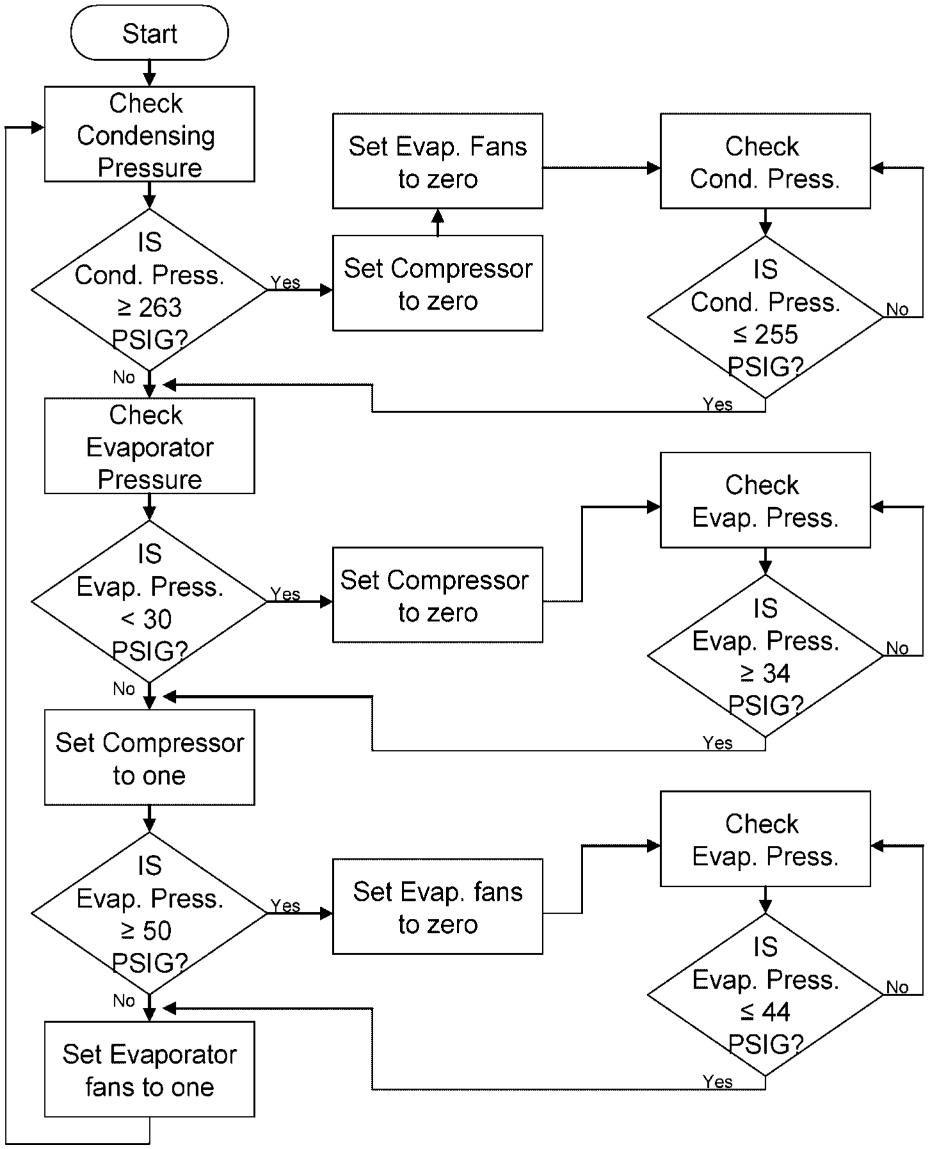

Figure 4 Flow chart for controller program.

is the flow rate section. This panel is also capable of showing the user both of the flow rates on two separate graphs, and also display the instantaneous flow rate for each sensor. The final rightmost panel is the pressure display. This display is much like the temperature display; it displays all four pressures instantaneously and allows the user to select the channel that is graphed on the screen. Each pressure is also monitored by a user high set point and alerts the user with a lamp if the pressure becomes too high at any of the points.

Table 1 Signal Breakdown for Inputs to DAQ

Measurement	Number of channels	Voltage range	Measurement range	Transducer accuracy (+/−)	Accuracy of DAQ measurement
Temperature	7	0–2	0–200	0.02	0.0008°C
Pressure	4	0.5–4.5	0–300	0.02	0.0008 psig
Flow rate (refrigerant)	1	0.26–4.0	0.26–4.0	0.03	0.000008 GPM
Flow rate (water)	1	0.26–2.6	0.26–2.6	0.03	0.000008 GPM

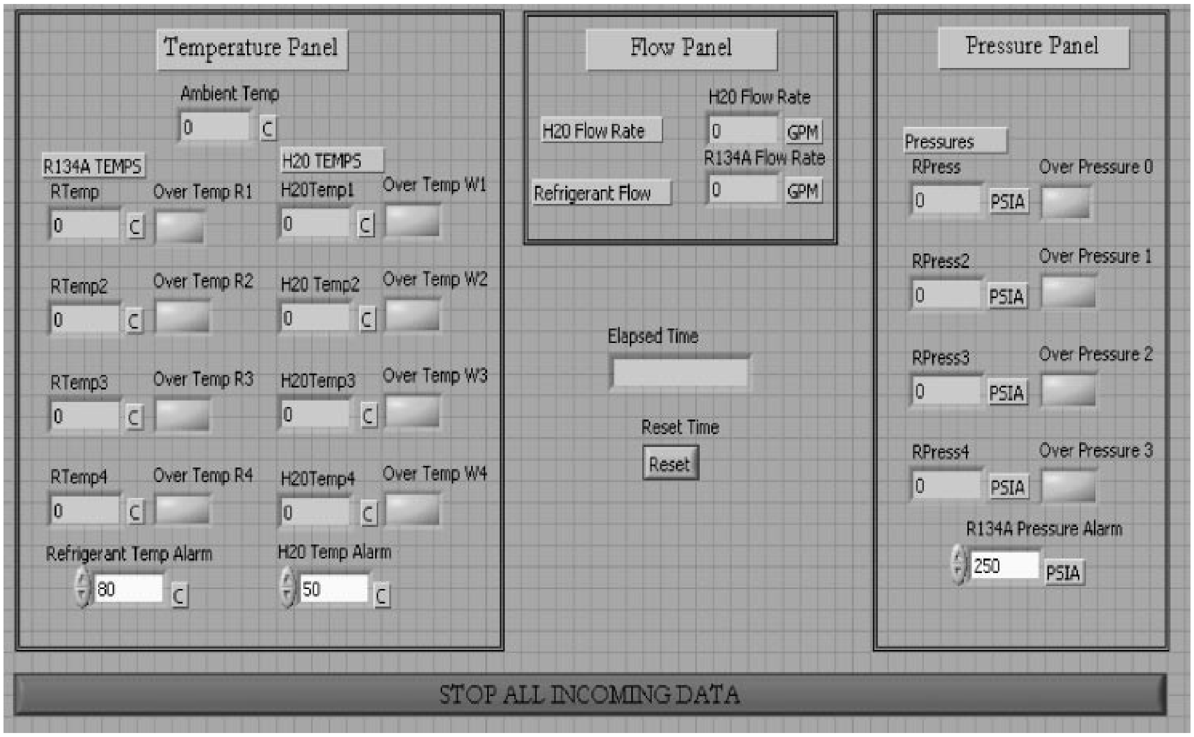

Figure 5 GUI panel for LabVIEW program.

CONCLUSION

The bench-top air-to-water heat pump experimental apparatus described in this paper is a valuable addition to the undergraduate mechanical engineering laboratory. A PC-based control system which consists of LabVIEW and DAQ unit is employed to monitor and control this experimental laboratory apparatus. The development of this unit was accomplished with zero cost to the Engineering Department at Indiana University-Purdue University Fort Wayne. This was made possible for two main reasons: the financial support from ASHRAE and the effort of a capstone senior design team. The experimental apparatus is portable.

ACKNOWLEDGMENTS

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BIOGRAPHIES

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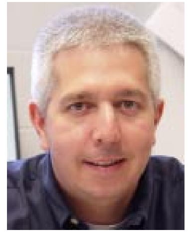

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