Innovative Mass Air Flow Measurement

Mr. Lucas Howard, Mr. Jonathan Hayes,
Mrs. Pat Buford, Dr. Wayne Helmer,

Mechanical Engineering/Electrical Engineering
Arkansas Tech University
Russellville, Arkansas

Abstract

The purpose of this project is to design and fabricate innovative air flow lab equipment using standard, low-cost components. The major equipment components are automotive mass air flow (MAF) sensors and an M68HC11EVB evaluation board. Students using the equipment will take voltage readings from an LED display of the microcontroller based output of the lab system. The MAF results will also be compared to mass air flow measurements taken from standard flow rate devices such as an orifice meter, rotameter or other reference flow rate devices. This lab equipment was designed to be used by the engineering students in courses ranging from the freshman introductory class through senior level courses.

Introduction

The faculty of the electrical and mechanical engineering departments at Arkansas Tech University is constantly trying to improve the laboratory experiences of their students. The students who use the equipment range from the inexperienced first semester to the seasoned junior and senior engineering students. Sometimes laboratory equipment that satisfies the educational needs of this diverse group of students is not economical or readily available.

To satisfy the dual requirements of diversity and cost efficiency, two students, one electrical and one mechanical, were offered special topic engineering credit to design and build this fluid flow equipment under the supervision of faculty mentors.

MAF Theory

Automotive mass airflow sensors (MAF) are used to calculate the amount of air entering the engine intake of an electronic fuel injection system. There are two types of automotive MAFs, digital and variable voltage (analog). Both use a “hot-wire” principal.

The hot-wire principal uses a resistor (usually a coil of wire) that is heated by a constant voltage. The coil of wire is placed in an airflow-sampling channel. See Figure 1. The entering the engine intake cools the wire. The wire is a positive coefficient resistor, as the temperature decreases the resistance decreases. The decrease in resistance allows more current to flow through the resistor. The induced change in voltage is sent to the computer of the vehicle to adjust the fuel flow accordingly.

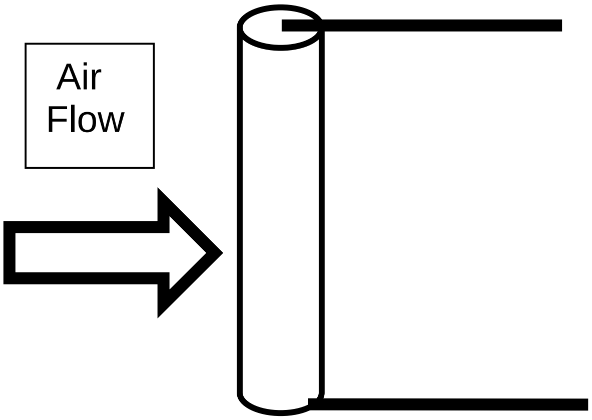

Figure 1 – Basic hot-wire probe.

Mass flow rate is found by m = ρAV (mass flow rate = density of air x cross-sectional area x velocity). The area is easily found by measuring the diameter of the entrance of the mass airflow sensor. The following steps determine the velocity.

First the supplied voltage and resistance of the resister must be known to determine the power dissipated by the resistor, P. In most cases, 12 volts are supplied. The resistance (R) can be measured using a digital multi-meter (DMM).

The equation to find P: $P = V^2/R$.

$P = q$, q is the energy removed by convection in a moving air stream.

$q = \pi\, d\, l\, h\, (T_w - T_\infty)$

<u>Where:</u>

q - power dissipated

d - diameter of wire

l - length of wire

h – heat-transfer coefficient

T_w - temperature of wire

T_∞ – ambient air temperature

The diameter, length, T_w, and T_∞ can be measured. The heat-transfer coefficient can be found. using the following equation,

$h = \mathrm{Nu}_d (k/d)$

<u>Where:</u>

k - thermal conductivity of the air

d - wire diameter

The Nusselt number, $\mathrm{Nu}_{d,}$ can be determined by the following equation. The following equation will work for most conditions including electrically heated wire in airflow.

$\mathrm{Nu}_d = (0.683)(\mathrm{Re}_d)^{0.466}(\mathrm{Pr}_f)^{1/3}$

<u>Where:</u>

Re_d - Reynolds number

Pr_f - Prandtl number

The Prandtl number is a function of the fluid temperature (see below). The Reynolds number can be determined by using the following equation.

$\mathrm{Re}_d = (u_\infty d)/v_f$

<u>Where:</u>

u_∞ - velocity of the air stream

d - wire diameter

v_f - kinematic viscosity of the air at the film temperature conditions

The kinematic viscosity can be found if the film temperature is known. The film temperature can be determined by using the following equation.

$T_f = (T_\infty - T_w)/2$

The velocity of the air stream can be found when all of the previous equations have been combined, simplified, and solved for u_∞.

After finding the velocity, determining the density of the air, and measuring the entrance diameter of the MAF, the following equation can be used to find the mass airflow.

$m = (\pi(d/2)^2)(\rho)(u_\infty)$

Where:

d - diameter of MAF sensor entrance

ρ - density of air

u_∞ - average velocity of air stream

All of the equations used in the MAF theory were found in referecnece [1] and [2].

Design

The apparatus consists of a frame with a blower, frame, air flow ducting, automobile MAF sensors, and a microcontroller. A light-emitting diode (LED) displays the voltage from the sensor. Additionally, students will input the displayed voltage to a C program or their calculators to determine the MAF.

After reviewing different designs, a design consisting of PVC pipe (for the air flow duct) and a centrifugal blower was chosen because of its simplicity and low cost of materials. The PVC pipe would channel the airflow and support the measuring devices. The needed flow rate and the pressure drop induced by the measuring devices and from frictional losses due to the pipe would determine the size of the blower.

Blower sizing

The original design was made up of three Ford MAFs (mounted in parallel to each other), a flow straightener, an orifice manometer, and a rotameter connected in series with 7.25 feet of 3-inch diameter PCV pipe. The MAFs were mounted in parallel so three student groups could take data very quickly in sequence. The pressure drop of this configuration was calculated to be 44.51 inches SP, a list of the components and corresponding pressure drops can be found in Table 1. The needed volumetric flow rate was determined to be 250 cfm. A blower that could exceed these parameters would cost anywhere from \$2200 to \$4400. Due to funding limitations a lower cost blower would have to be used. In order to use a blower with lower capabilities, the design of the system had to be changed. The initial orifice manometer and the rotameter (reference flow measuring devices) had large pressure drops, 15 inches SP and 25 inches SP respectively. It was decided that these components needed to be removed and replaced by a commercially available hot wire probe [4]. The new design consisted of three MAFs (mounted parallel to each other) and a flow straightener connected in series with 6.5 feet of 3 inch diameter PCV pipe. The pressure drop for the new design was calculated to be 3.97 inches SP, a list of the components and corresponding pressure drops can be found in Table 2. A blower-motor assembly that could handle these requirements cost around $320.

Table 1 – Original Design Pressure Drop

Component	Pressure loss (in. water)
90 deg elbows	0.92
35 deg turn	0.31
Orifice manometer	15
straws	2.22
Rotameter, King Instruments #0231	25
Entrance loss	0.31
Pipe	0.75
Total	44.51

Table 2 – Final Design Pressure Drop

Final Design	
Component	Pressure loss (in. water)
90 deg elbows	0.46
35 deg turn	0.31
straws	2.22
Entrance loss	0.31
Pipe	0.67
Total	3.97

Frame

A frame was designed to support the system. The frame had to be rigid, easy to maneuver, support the apparatus at a comfortable height for students to work on. The overall dimensions of the frame are 6.5 feet long, 23 inches wide, and 35 inches tall from 70 feet of 1.5-inch square steel tubing. The basic frame was fabricated and additional cross members and supports were added when necessary. Steel plates were welded to the four bottom corners of the frame. Caster wheels were attached to each plate.

Pipe

The pipe layout is a simple design. The three MAFs (< $30 total from E-bay) are inserted into a nominal 3 inch PVC double-wye, as seen in Figure 2. The flow straightener was composed of about 150 straws bound together with utility tape. To prevent the flow straightener from moving through the system, a wire screen was attached a foot from the end of a 2-inch pipe. The end with the flow straightener is connected to the double-wye. Rubber connectors connect an 18-inch length pipe to the 27-inch length of pipe and to a 7-inch length of pipe. Rubber connectors, allow for easy removal of the 18-inch section if an orifice manometer is to be added in the future. The 7-inch length of pipe leads to a 90° elbow. The elbow connects the horizontal line to a vertical wye. A 2-inch ball valve is connected to the single wye and serves as a by-pass valve for flow control. After the wye, the flow goes through another 90° elbow to a 3-inch to 6-inch expansion fitting, then into the blower.

Figure 2. – MAFs, frame, and blower-motor assembly

Blower and wiring installation

The blower-motor assembly is a capacitor start, single phase 115v, 1.5 hp motor with a high pressure, direct drive, radial blade blower. The wiring schedule consisted of 20 feet of 10-gage wire, conduit, conduit connectors, a switch, a conduit box, and a 120V plug. The switch and conduit box were mounted in a back corner near the blower. It was placed in a location where it would be unobtrusive but still easily accessible. The cord length from the conduit box to the plug is approximately 15 feet. This allows the frame to be placed in almost any desired location in a lab room.

Mass Air Flow Sensor and Circuitry

The MAF sensor used in the automobile industry is basically an air flow to voltage conversion device using a hot wire anemometer. Measuring mass air flow with this sensor is an application of both electrical and mechanical engineering principles.

Each MAF has a plate covering the entrance. This is to allow each group to test one MAF at a time. The MAFs have four connections located in a plastic housing. The connectors are labeled A, B, C, and D. A 12 V voltage source is connected to connection A. The ground of the voltage source is connected to connection B. Connection D is for the signal voltage. A volt meter should be connected to connections B and D, this measures the output voltage. Connection C is not used. See Figure 3 for wiring diagram. Students should not apply a voltage to a MAF when the air flow cover is in place since this will damage the platinum wire inside of the flow channel due to the no-flow situation..

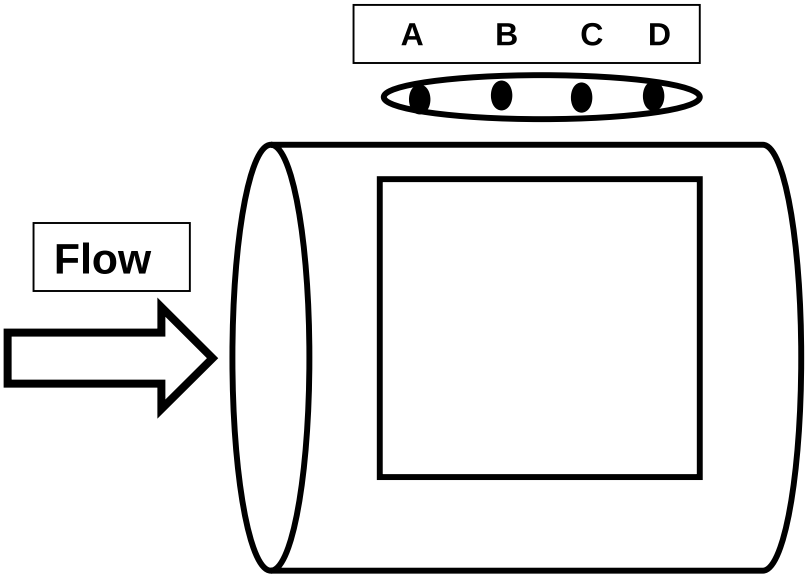

Figure 3 - Wiring connection diagram. [3]

Table 3 – Mass airflow and corresponding signal voltage

Mass Airflow (kg/hr)	Mass Airflow (lb/hr)	Vout (V)
16.77	36.89	1.02
19.19	42.22	1.09
21.41	47.10	1.16
22.93	50.45	1.30
26.26	57.77	1.35
56.43	124.15	2.14
65.51	144.12	2.18
75.07	165.15	2.29
79.61	175.14	2.27
109.11	240.04	2.56

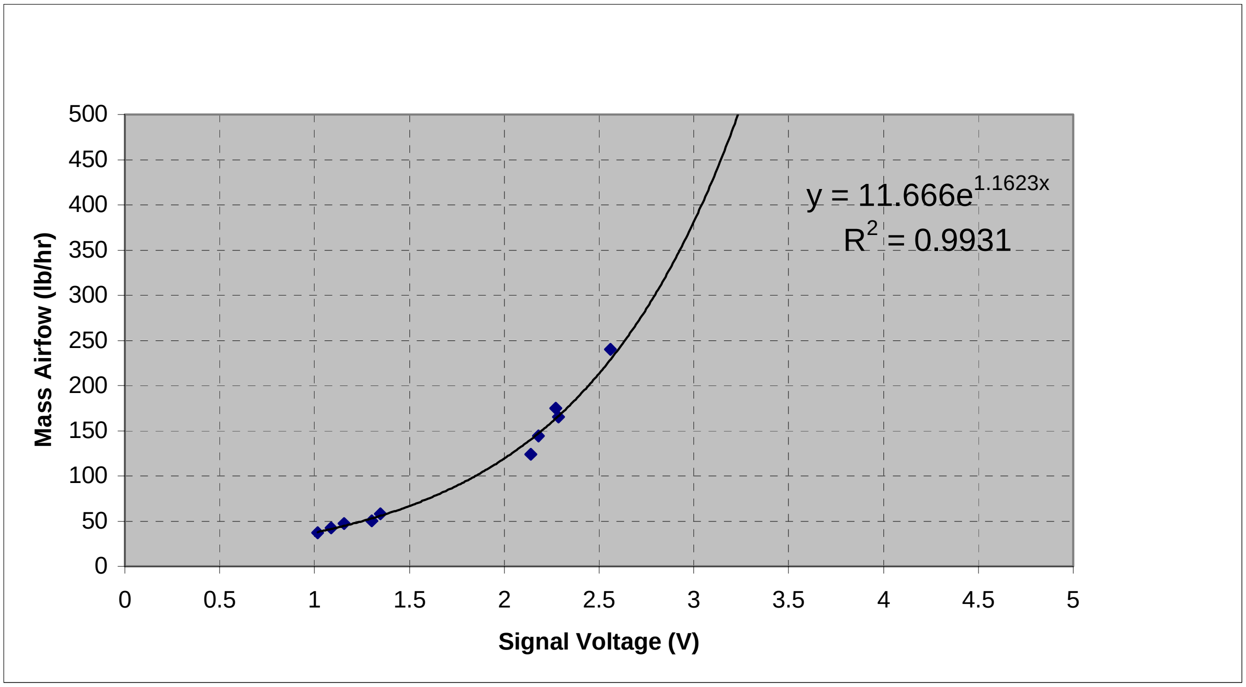

Figure 4 – Graph of typical mass airflow and signal voltage data

The data shown in the Table 3 and Figure 4 were measured and calculated in a typical student lab session. This process can be repeated for each MAF.

Microcontroller Interface

The MC68HC11 microcontroller is used as a digital voltmeter for the three MAF sensors. The program uses Port E as an A/D converter. Students input from a keypad which MAF sensor they are using in the experiment. V_{DB} (from Figure 4) of the selected MAF sensor is the input to the A/D. The first task in using the A/D converter is to generate a short delay to power up the A/D. Then the program must wait for the A/D conversion to be completed. The next step is to get the input and display the results. Unfortunately the data must be converted from binary to binary coded decimal so that it may be converted once again, this time to ASCII for display. The flowchart of Figure 5 outlines the process of a conversion of V_{DB} from a single MAF sensor to output voltage. Students input the voltage displayed to a C program or their calculators to compute the actual mass air flow. The program uses the equation of the line graphed in Figure 4 for the calculation.

Unlike the theory of the hot-wire anemometer discussed in texts, the MAF sensor used in automobiles employ complex circuitry as seen in Figure 6. It was an initial intent to have students build the simple Wheatstone bridge circuit with an amplifier and then compare their results to those obtained by the MAF sensor circuitry. Since the concept was to allow students to experience the practicality of the simple circuit, the complexity of the circuitry onboard the MAF sensor forced abandonment of this aspect of the laboratory.

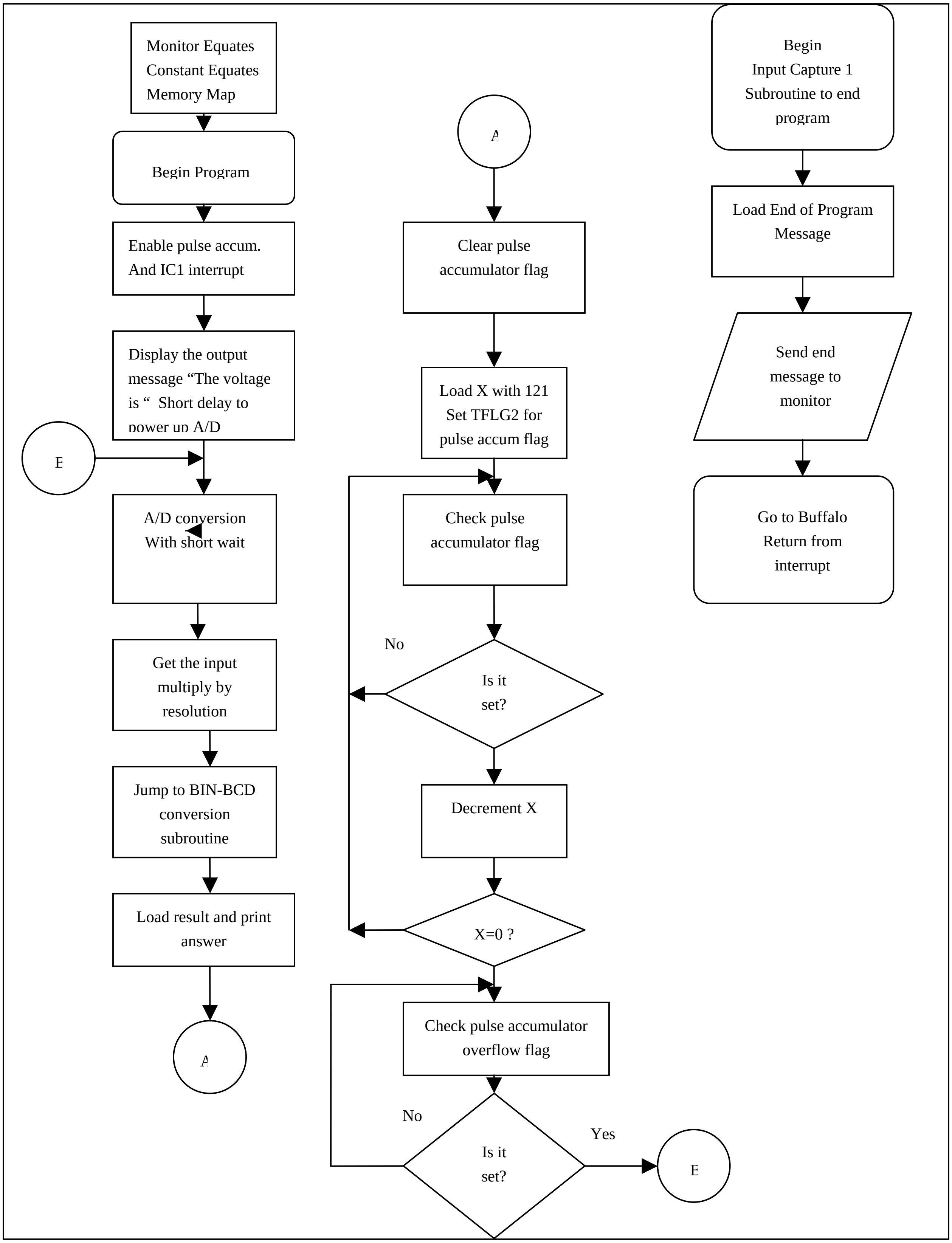

Figure 5 – Flowchart of analog to digital voltage conversion

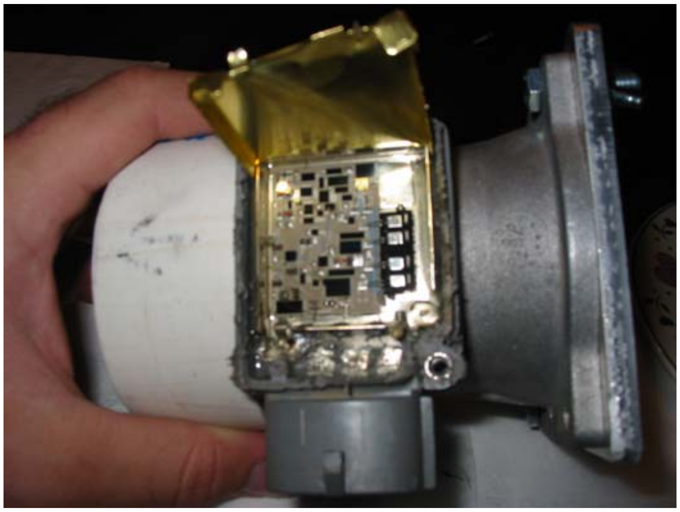

Figure 6 – MAF Sensor Circuitry

Summary and Conclusions

Air flow laboratory equipment can be extremely expensive. The uniqueness of this project is that a group of students designed and built the inexpensive (less than $1000) laboratory equipment which is then be used for years by other students in mechanical and electrical engineering laboratory experiments. It is a tremendous educational experience for both groups of students—the designers and students enrolled in the laboratory. Additionally, the design portion of this project provides an excellent opportunity for a multi-disciplinary team of both electrical and mechanical engineering students.

References

[1] Munson, Young, and Okiishi, *Fundamentals of Fluid Mechanics*, 3rd ed. Whiley, New York, 2002.

[2] J.P. Holman, *Heat Transfer*, 9th ed. McGraw-Hill, New York, 2002.

[3] Using a Mass Airflow Sensor, http://www.gecdsb.on.ca/sub/projects/ps/notemplates/wind.htm

[4] TSI Corporation. Shoreview MN. Model 8386 velocicalc portable air velocity meter.

Biographical Information

Lucas Howard is a mechanical engineering graduate of Arkansas Tech University and an sales engineer at Jack Tyler Engineering in Little Rock, Arkansas..

Jonathan Hayes is a senior electrical engineering student at Arkansas Tech University.

Patricia Buford is an assistant professor in the electrical engineering department at Arkansas Tech University. She teaches the early electric circuit course as well as the senior level control systems courses. She is a registered professional engineer in the state of Arkansas.

Wayne Helmer is a professor in the mechanical engineering department at Arkansas Tech University. He teaches both the freshman Introduction to Engineering Class as well as senior level courses in heat transfer, HVAC, and thermodynamics courses. Professor Helmer is a registered professional engineer in the state of Illinois.