Apparatus

Figure 1 is a photograph from in front and slightly above the apparatus. The duct holding the fan and heat sink is in the upper right corner of the photo. The lower right quarter of the photo shows the Arduino and prototype shield (far right), a thermocouple conversion board (center) and the MOSFET board for controlling the heater power (center left). Below the thermocouple and MOSFET boards is a screw terminal that distributes 12 VDC power to the heater, fan and Arduino. The power supply that connects to the screw terminal via a barrel jack is not shown.

The left side of Figure 1 shows a small control panel with toggle switches to turn the fan and heater on and off. The control panel also has rotary potentiometers that allow the fan speed and heater power to be adjusted. Figure 2 is an isolated photograph of the control panel. An LCD panel displays numerical indicators of fan speed, heater power and heat sink temperature. The fan speed and heater setting are displayed as 8 bit values, i.e., in the range 0 to 255. The temperature display is the temperature at the base of the heat sink in °C.

Figure 3 indicates the width $W$, length $L$ and height $H$ parameters of the heat sink. In addition, let $n_W$ and $n_L$ be the number of fins in the $W$ and $L$ direction, respectively. Table 1 lists the physical characteristics of the six heat sink assemblies available for testing for the six assemblies available to students for testing. Each heat sink in an experiment is identified with a single letter tag, A-F. Students use the tag and Table 1 to obtain the physical dimensions of the heat sink in the apparatus in their particular experiment. The resistance of the heater (resistor) is labelled on base of the heat sink, and also listed in Table 1.

The heater power leads and thermocouple are attached via (separate) screw terminals on the
Figure 2: Control panel with toggle switches and potentiometers for adjusting fan speed and heater power, and an LCD panel for displaying fan setting, heater setting and heat sink temperature.

Figure 3: Geometric parameters of the heat sinks.

thermocouple board and the MOSFET board, which are in turn securely mounted on the main platform of the apparatus.

Figure 4 is a close-up view of one of the six heat sink assemblies, each of which consists of an aluminum heat sink, a support pedestal and a base. Figure 5 is a photograph of the base and support pedestal, which are laser-cut from 3.2 mm (1/8 inch) thick plywood. The pedestal has a smaller footprint than the heat sink, so it is not visible in Figure 4. The pedestal is attached to the plywood base by wood glue. The pedestal provides a pocket for the power resistor acting as a heater. The power resistor is attached to the heat sink with a screw. The pedestal also provides a substrate for embedding the thermocouples which have their metal junctions in contact with the bottom of the heat sink. Figure 5 shows three thermocouples embedded in grooves cut partway
Figure 4: Heat sink assembly. Power to the heater (a power resistor) is supplied by the red and black wires visible on the left side of the photo. Red and pale yellow wires (with yellow heat shrink) visible on the right side of the photo are 30 gage K-type thermocouples. Three thermocouple junctions are located at the interface between the plywood base and the bottom surface of the heat sink. The position of the heat sink in the duct is determined by mating tabs at the edge of the plywood base to tabs in acrylic rails attached to the inside walls of duct.

Figure 5: Thermocouples embedded in the heater support pedestal. The thermocouple wires are epoxied into small grooves machined into the surface of the pedestal.
across the pedestal. The thermocouples are secured with epoxy and located so that the junction protrude slightly above the surface of the pedestal. Through-holes in the pedestal and base are aligned to allow four screws inserted from the bottom of the base to secure the metal heat sink to the heat sink assembly.

The user locates the heat sink assembly in one of 7 axial locations in the duct by mating the tabs on the side of the heat sink assembly into a corresponding set of slots on two acrylic rails that are glued to the inside walls of the duct. Seven discrete axial positions are possible. For most positions the user simply reaches into the open end of the duct. The top of the duct is also removable to aid in positioning the heater assembly closer to the fan.

Table 1: Physical parameters of the heat sink assemblies.

<table>
<thead>
<tr>
<th>Tag</th>
<th>$R$ (Ω)</th>
<th>$H$</th>
<th>$L$</th>
<th>$W$</th>
<th>$n_W$</th>
<th>$n_L$</th>
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<td>10</td>
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<td>11</td>
<td>12</td>
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<td>0.67</td>
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</table>

Experimental Measurements

The apparatus allows you to conduct several different experiments. We recommend that you choose either experiment A or experiment B described below.

Preliminary Checklist: Please Read Before Coming to the Lab

Before attempting any measurements, work through the checklist for the apparatus. The checklist should take 5 minutes to complete, and doing so will help to avoid wasting much more time working with a system that might be misconfigured or collecting data while making inappropriate adjustments to the system.

Experiment 0: Transient response to a change in operating conditions.

Each time the operating condition of the apparatus is changed, the temperature of the heat sink will undergo a transient change to the new equilibrium temperature. The thermal mass of the heat sink and that available power and fan speed result in a transient that may take up to 8 or 10 minutes of more to decay.

Expect to wait at least 10, and possibly 12 or 15 minutes for the transient caused by changes in operating condition of the system to decay.

The actual time for your system depends on the physical size (mostly the mass) of the heat sink, the heat power setting and the fan speed setting.

It is instructive to record data during at least one of the temperature transients. Doing so requires you to write down both the temperature and time at which the temperature was recorded.
Figure 6: Typical transient response after changing power setting to the heater. Discrete jumps in temperature values are due to the 0.25°C resolution of the thermocouple sensing chip.

Making a measurement every 30 seconds will give you 20 data points for a 10 minute transient, which should be sufficient.

Figure 6 shows a typical transient response of the heat sink thermocouple after two step-changes in power setting. When the power level is changed, the temperature response is an exponential decay to a new steady state value. If the heat sink can be treated as a lumped mass – an assumption that should be tested – the model for the temperature transient $T(t)$ is

$$T = T_{ss} + (T_i - T_{ss}) e^{-t/\tau}$$

where $T_{ss}$ is the steady state temperature of the heat sink, $T_i$ is the initial temperature, and $\tau$ is the thermal time constant of the heat sink in the air stream. If the heat sink can be treated as a lumped mass, the time constant is

$$\tau = \frac{mc}{hA}$$

where $m$ is the mass of the heat sink, $c$ is the specific heat of the heat sink material, $h$ is average (over the surface) convective heat transfer coefficient, and $A$ is the surface area of the heat sink. In this experiment you can change $h$ by . . . (how?). Different heat sinks will have different surface areas.

**Common Operation for Steady-State Experiments**

Refer to the annotated image of the control panel in Figure 2. Both the fan and the heater are controlled by on/off toggle switches and potentiometers. The fan and heater settings are displayed on the LCD panel along with the temperature at the base of the heat sink. The fan speed and heater power are qualitatively indicated by two LEDs. The brightness of the green LED increases with fan speed. The brightness of the red LED increases with heater power.
The following steps are used to measure one operating condition of the apparatus.

1. Connect a 12 VDC power supply to the plug on the front of the device. This should cause the LCD to flash a start-up message and then display values of the 8-bit PWM settings of the fan speed and heat power, along with the temperature of one of the thermocouples at the base of the heat sink. Figure 2 shows a typical display.

2. Turn on the fan by flipping the toggle switch upward. The fan should start immediately. Adjust the fan speed by turning the potentiometer.

3. Turn on the heater by flipping the toggle switch upward. Turn the heater control potentiometer to adjust the power input to the heater. Monitor the temperature display on the LCD panel.

4. Wait for the temperature indicated on the LCD panel to stabilize. For moderate to high fan speeds, steady state should be achieved in 10 to 15 minutes.

   Record the four numbers on the LCD panel
   - Fan setting: a value between 100 and 255
   - Heater setting: a value between 0 and 255
   - Temperature at the base of the heat sink: adjacent to $T$
   - Temperature of thermocouple amplifier chip: adjacent to $T_r$

The preceding steps are common to steady-state measurements. For the purposes of this experiment, we will use $T_r$, the temperature of the thermocouple amplifier chip, as a surrogate for the ambient air temperature, $T_a$.

**Experiment A: Heat transfer coefficient as a function of heater power**

The goal of this experiment to measure the heat transfer coefficient as a function of the power input at the base of the heat sink. Referring to the common procedure listed on page 6, Experiment A involves first setting a fixed fan speed – common procedure step 2 – and then repeat these steps

1. Set the heater power: common procedure step 3

2. Wait for steady state and record data: common procedure step 4

Do not change the fan speed.

**Experiment B: Heat transfer coefficient as a function of fan speed**

The goal of this experiment to measure the heat transfer coefficient as a function of the fan speed. Referring to the common procedure listed on page 6, Experiment B involves first setting a fixed heater power – common procedure step 3 and then repeating these steps

1. Set the fan speed: common procedure step 2

2. Wait for steady state and record data: common procedure step 4

Do not change the heater power.
Figure 7: PWM signal to control power to the heater. The duty cycle, $\tau_0/\tau_c$ is variable.

Common Data Analysis

The fan and heater are controlled by PWM signals from the Arduino. The PWM setting is an 8-bit value, where 0 corresponds to zero supply voltage and 255 corresponds to maximum supply of 12 VDC.

In the current version of the apparatus, the PWM setting of the fan is the only indicator of the fan flow rate or air speed.

Power input to the heater is

$$Q_{in} = \frac{V_{in}^2}{R}$$  \hspace{1cm} (3)

where $V_{in}$ is the effective voltage input and $R$ is the resistance of the power resistor. Table 1 lists values of $R$ for the resistors used as heaters.

The power is controlled by a PWM (Pulse-width modulation) circuit that supplies a square-wave signal as depicted by diagram in Figure 7. $V_s$ is the supply voltage (12V), and $\tau_0/\tau_c$ is the fraction of time that the power is on. $\tau_0/\tau_c$ is called the duty cycle.

The electrical energy supplied to the heater in one period of the PWM cycle is

$$E_1 = \int_0^{\tau_c} \frac{V_{in}^2(t)}{R} dt = \int_0^{\tau_0} \frac{V_{in}^2(t)}{R} dt + \int_{\tau_0}^{\tau_c} \frac{V_{in}^2(t)}{R} dt$$

The second integral on the far right-hand-side is zero since $V_{in} = 0$ for $\tau_0 < t \leq \tau_c$. Thus, the electrical power delivered during one PWM cycle is

$$E_1 = \frac{V_s^2}{R} \tau_0$$

and the average power delivered during one cycle is

$$P = \frac{E_1}{\tau_c} = \frac{\tau_0}{\tau_c} \frac{V_s^2}{R}$$  \hspace{1cm} (4)

The LCD control panel displays the power setting as an 8-bit value, $p$, where $0 \leq p \leq 255$, and $p$ is proportional to the duty cycle.

$$\frac{p}{255} = \frac{\tau_0}{\tau_c}$$

Therefore, the power input to the heater is

$$P = \frac{p}{255} \frac{V_s^2}{R}$$  \hspace{1cm} (5)

Remember that the value of $p$ is adjusted by turning the power control knob on the control panel and $V_s = 12V$ from the power supply.
In steady state, we expect
\[ Q_c = hA(T - T_a) \] (6)
where \( Q_c \) is the convective heat loss, \( h \) is a constant called the heat transfer coefficient, \( A \) is the surface area of the heat sink, and \( T_a \) is the ambient temperature. Not all of the electrical input power is lost by the heat sink to the air flow. Some of the heat is conducted out of the power leads and a smaller amount is conducted out of the thermocouple leads. Some additional heat is lost by radiation. Let \( Q_o \) be the heat loss by these other modes (conduction and radiation). The total power input \( Q_{\text{in}} \) is the sum of the convective loss and the other losses.
\[ Q_{\text{in}} = Q_c + Q_o \] (7)
Substituting Equation (7) into Equation (6) and rearranging gives
\[ T = T_a + \frac{Q_{\text{in}}}{hA} - \frac{Q_o}{hA} \] (8)
Thus, we expect a linear relationship between \( T \) and \( Q_{\text{in}} \), with a constant offset due to \( T_a \) and \( Q_o \). Note that the loss term, \( Q_o \), is also likely to be a weak function of \( T \) and the air flow rate because conductive heat losses down the heater and thermocouple leads will be affected by the air flow over those exposed (but electrically insulated) wires.

**Experiment A: Heat transfer coefficient as a function of heater power**

**Experiment B: Heat transfer coefficient as a function of fan speed**