1   Objective

The objective of the laboratory exercise is to measure the convective heat transfer coefficient for a single block attached to a simulated printed circuit board. The block simulates a low-profile package for an electronics device. It is approximately 5 cm square in the plan view, and 0.64 cm thick in the direction normal to the simulated circuit board. The block is heated by a thin film heater that is supplied with a low DC current. The block is placed in one of the three small wind tunnels in the thermal management laboratory.

For this laboratory exercise, the block apparatus is already instrumented. You will perform measurements at two velocities. The data is collected with the BenchLink Data Logger and the Agilent 34970A DMM/Switch. You will create a data reduction routine that accounts for the conduction and radiation losses from the block. You will report the heat transfer coefficient and its uncertainty for the two operating conditions of your experiment.

2   Apparatus

Figure 1 is a sketch of the experimental apparatus. A single, heated block is mounted on a simulated printed circuit board (PCB). The board is attached via short stand-offs to the bottom hatch of a small wind tunnel. A fan at the outlet of the wind tunnel draws air through the inlet and then the test section.

By adjusting the damper of the wind tunnel, the flow rate of air over the heated block is varied. The heat transfer coefficient from the block to the air is computed from measurements of the air temperature, the block temperature, and the convective heat loss from the block.

Figure 2 is a sketch of the heated block assembly. It is formed as a sandwich construction of two 5.08×5.08 cm square aluminum blocks that are 3.2 mm
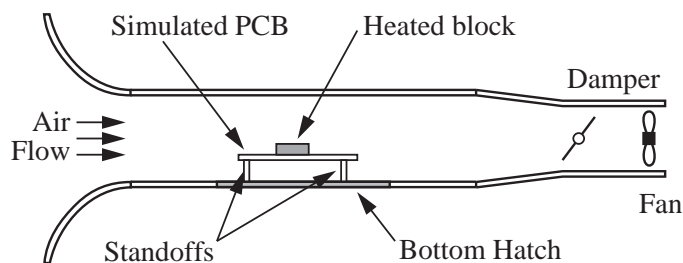

Figure 1: The experimental apparatus consists of a single heated block mounted on a simulated printed circuit board (PCB). The PCB is attached to the bottom hatch of a small wind tunnel.
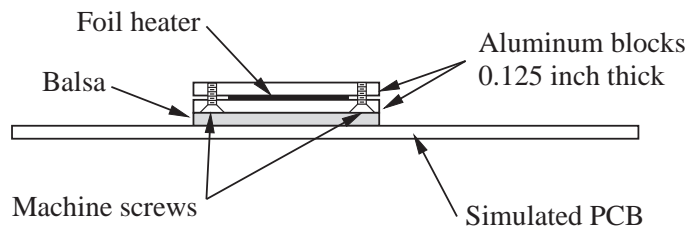
Figure 2: Construction of the heated block.

thick. Between the aluminum blocks is a foil heater manufactured by Minco[1].

A block of balsa separates the heater assembly from the simulated PCB. The balsa provides thermal isolation (reducing the conduction heat transfer to the board) and some vertical spacing so that the heated block is not sitting directly on the simulated PCB.

3   Heat Transfer Analysis

The heat transfer coefficient of the block is computed from

$$h = \frac{Q_{\text{conv}}}{A(\bar{T}_s - T_a)} \tag{1}$$

where Q_{conv} is the convective heat loss from the block, $\bar{T}_s$ is the average surface temperature of the block, T_a is the inlet air temperature, A is the surface area of the block involved in convective heat transfer.

As depicted in Figure 3, the electrical power dissipation in the heater leaves the block via convection, conduction and radiation. A steady-state energy balance on the block gives

$$Q_{\text{conv}} = \dot{E}_{\text{in}} - Q_{\text{rad}} - Q_{\text{cond}} \tag{2}$$

where $\dot{E}_{\text{in}}$ is the electrical energy input from the heater, Q_{cond} is the conduction loss into the mock PCB, and Q_{rad} is the radiation heat loss to the surroundings. A more detailed examination of the heater assembly is necessary for devising estimates of Q_{rad} and Q_{cond}.

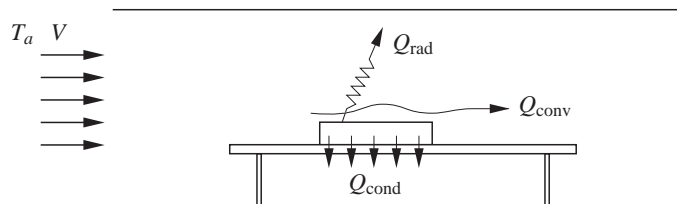[1]Minco Products Inc., 7300 Commerce Lane, Minneapolis MN 55432-3177, `www.minco.com`.

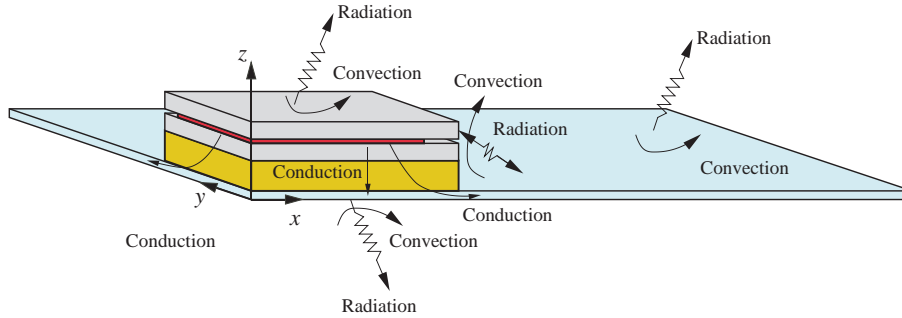Figure 3: Simplified view of heat loss mechanisms for the heated block.

Figure 4: Multiple heat flow paths from the heater to the ambient.

3.1   Radiation and Conduction Losses

Figure 4 is a schematic representation of the heat flow paths from the heated block to the ambient. The diagram is a cut-away view, where the origins of the x and y axes are at the geometric center of the block in a plan view.

Electrical energy dissipated by the heater flows by conduction to the surface of the upper and lower halves of the aluminum block. Heat is lost by convection and radiation from the top and side surfaces. Heat is also conducted downward through the simulated PCB, or laterally outward through the simulated PCB. In both cases the heat conducted to the simulated PCB is lost via convection and radiation to the ambient. Further complicating this situation is a small amount of radiation between the edges of the block assembly and the simulated PCB. The heat transfer from the edges of the block assembly — either by radiation to the simulated PCB, or radiation and convection to the ambient — will be small because the surface area of the edges is small compared to the surface area of the top and bottom of the alumnimum block assembly.

The radiation heat loss from the top surface of the upper alumninum block can be estimated with

$$Q_{\mathrm{rad}} = \epsilon_b \sigma A_{\mathrm{rad}}(\bar{T}_s^4 - T_{\mathrm{amb}}^4) \tag{3}$$

where ϵ_b is the emissivity of the block surface, σ is the Stefan-Boltzmann constant, $\bar{T}_s$ is the average, (absolute) surface temperature of the block, and T_{amb} is the temperature of the ambient surfaces that are exchanging heat with the block via thermal radiation. Equation (3) is based on the assumption that the block is surrounded by a black-body environment at T_{amb}. Although this is a highly idealized model, the alternatives rapidly increase in complexity. If the radiation correction is small, i.e. if $Q_{\mathrm{rad}}/Q_{\mathrm{conv}} \ll 1$, then the errors in the radiation model will make small contributions to the uncertainty in the calculation of h.

3.1.1   Thermal Network Model

The conceptual model in Figure 4 corresponds to the thermal network model in Figure 5. The network is rather complicated because many heat flow paths are shown. Nonetheless, the network is a simplified model of the multiple mode

(convection, radiation, conduction) and three-dimensional heat transfer in the block assembly. After first considering of the various heat flow paths in Figure 5, a simplified network model will be developed.

In the network model in Figure 5 the foil heater is represented by the node labelled T_h. The electrical energy dissipated as heat can flow by conduction to the top and bottom halves of the block, and by conduction down the copper lead wires. The heat flowing toward the top half of the block is either lost by convection and radiation at the edges, or convection and radiation at the top surface. In this experiment, the heat loss by convection at the top surface is much larger than the heat loss by convection and radiation at the edges.

Heat flowing down into the lower half of the block assembly can be lost by convection and radiation at the edges, or it can be conducted down into the balsa layer. Heat conducted into the balsa layer can be lost as convection and radiation at the edges of the balsa (not shown in Figure 5) or conducted down into the simulated printed circuit board. Heat flowing through the printed circuit board is either spread laterally (heat flow path not shown in Figure 5) or conducted down to the lower surface where it is lost by convection and radiation.

3.1.2   A Simplified Network Model

The thermal network model in Figure 5 is more complicated than it needs to be. Some reasonable simplifications can be made that will not severely compromise the accuracy of measurements for the quantities needed to compute h. If heat lost from the edges of the assembly are neglected, an energy balance on the heater node in Figure 5 gives

$$Q_{\mathrm{conv}} = \dot{E}_{\mathrm{in}} - Q_{\mathrm{rad}} - Q_{\mathrm{lead}} - Q_b \tag{4}$$

where Q_{lead} is the heat loss along the heater lead wires, and Q_b is the heat loss by conduction downward into the simulated printed circuit board. Comparing Equation (2) and (4) shows that

$$Q_{\mathrm{cond}} = Q_{\mathrm{lead}} + Q_b. \tag{5}$$

The heat loss along the leads can be estimated as

$$Q_{\mathrm{lead}} = \frac{T_h - T_a}{R_{\mathrm{lead}}} \tag{6}$$

where R_{lead} is the thermal resistance of the copper lead wires.

The heat loss through the base can be estimated with

$$Q_b = \frac{T_{s,b} - T_{p,a}}{R_{b,\mathrm{tot}}} \tag{7}$$

where $T_{s,b}$ is the surface temperature of the bottom block (between the block and the balsa), $T_{p,a}$ is surface temperature of the simulated printed circuit board exposed to the air, and $R_{b,\mathrm{tot}}$ is the total resistance between $T_{s,b}$ and $T_{p,a}$. The value of $R_{b,\mathrm{tot}}$ is the sum of the conductive resistance of the balsa, the conductive resistance of the simulated PCB, and the contact resistance between the balsa and the simulated PCB.
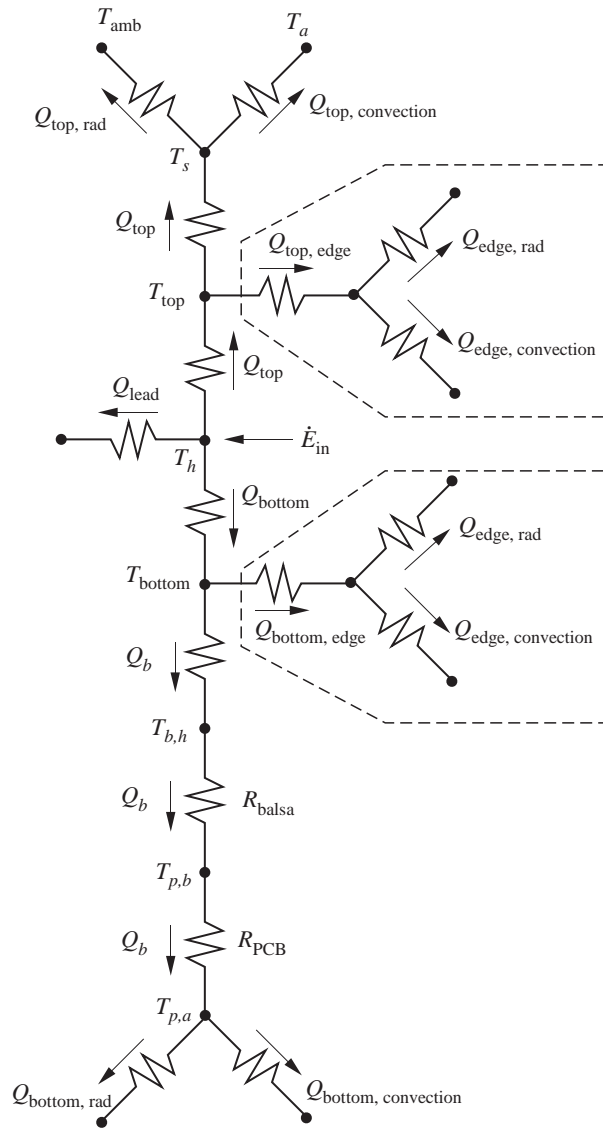
Figure 5: Thermal network model of heat flow paths from the heater to the ambient. Portions of the network surrounded by dashed lines are neglected in the simplified model.
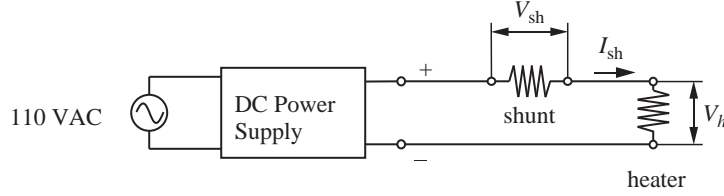
Figure 6: Power supply circuit for the heated block.

A better formula for estimating Q_b is

$$Q_b = \frac{T_{t,b} - T_{b,b}}{R_b} \tag{8}$$

where $T_{t,b}$ is the temperature of the top surface of the balsa, $T_{b,b}$ is the temperature of the bottom surface of the balsa, and R_b is the thermal resistance of the balsa. Equation (8) is likely to be more accurate than Equation (7) because there are no large contact resistances along the heat flow path[2].

3.2 Heater Power Input

Figure 6 is a schematic of the power supply circuit. The power input to the heater is controlled by an adjustable DC power supply. The power dissipated by the heater can be evaluated with $I_h^2 R_h$ or V_h^2/R_h or $V_h I_h$, where I_h is the current flowing through the heater, R_h is the resistance of the heater, and V_h is the voltage across the heater. The power dissipation is not computed from formulas depending on R_h, because the resistance of the heater varies somewhat with temperature.

A more reliable way to measure the power dissipation is to obtain an independent measure of the current flow. This is achieved by adding a second resistor, called a *shunt resistor*, in series with the heater. The resistance of the shunt resistor is small compared to R_h so that the shunt resistor does not dissipate appreciable power. Because of the low power dissipation the temperature of the shunt resistor, and therefore, its resistance, remains constant.

The power input to the heater is

$$\dot{E}_{\text{in}} = V_h I_h \tag{9}$$

The heater current is measured with a precision, current sensing resistor[3] with a nominal resistance of $0.005\,\Omega \pm 1$percent. The resistance of the shunt resistor should be measured before the experiment is carried out. The voltage drop across the shunt V_{sh} resistor is easily measured, and the heater current is

$$I_h = I_{\text{sh}} = \frac{V_{\text{sh}}}{R_{\text{sh}}}$$

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[2]There is a contact resistance between each thermocouple and the balsa. However the balsa is soft, and the force applied to attach the block to the simulated PCB will embed the thermocouple in the wood. This will have the effect of increasing the area of contact between the thermocouple and the balsa. It will also reduce the effective thickness of the balsa, which will tend to reduce the effective thermal resistance between the thermocouples.

[3]4LPW Series, IRC Wire and Film Technologies Division, 736 Greenway Rd., PO Box 1860, Boone NC 28607, www.irctt.com.
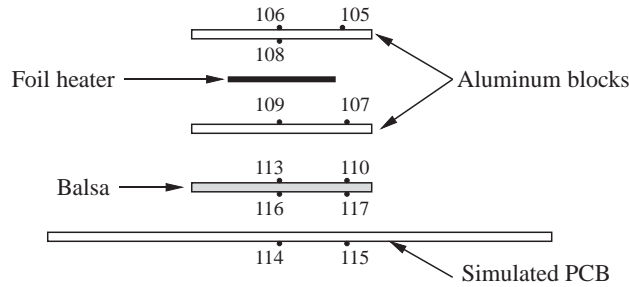
Figure 7: Locations of the thermocouples in the apparatus. Numbers in the diagram correspond to channels of the Agilent 34970A DMM/Switch. Refer to Table 1 for descriptions of these channels.

where R_{sh} is the resistance of the shunt resistor. Therefore,

$$\dot{E}_{\mathrm{in}} = \frac{V_h V_{\mathrm{sh}}}{R_{\mathrm{sh}}}. \tag{10}$$

3.3   Thermocouple Locations

Use of Equation (1) and (2) requires measurement of several temperatures. An instrumented block and simulated PCB are provided with several fine gage thermocouples already installed. Additional thermocouples will need to be fabricated and located to measure the air temperature, and the wall temperature used in the radiation correction.

Figure 7 shows the locations of the thermocouples that are installed in the apparatus. The three digit numbers are the channel numbers for the Agilent 34970A DMM/Switch unit. The list of channel numbers and the corresponding terminal numbers on the 50 pin terminal block are listed in Table 1.

Empty rows in Table 1 are available for sensors that you may install. Note that Channel 102 and Channel 112 are unused. You can use this pair of channels to make a four wire resistance measurement for a second thermistor. Figure 8 shows the how channel pairing is used for a four-wire resistance measurement with the Agilent 34970A.
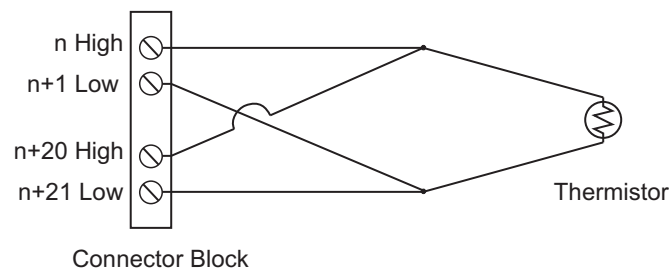
Figure 8: Channel pairing for a four-wire resistance measurement with the Agilent 34970A DMM/Switch. The screw terminals on the left are on the 50 pin connector block. The starting pin number is n.

Table 1: Wiring assignments for the single block heater lab. The *Ch. #* column indicates the channel number for the Agilent DMM/Switch. The *High terminal* and *Low terminal* columns are the numbers of the screw terminals on the 50 pin connector blocks. "TC" is an abbreviation for thermocouple.

Ch. #	High/Low Terminals		Signal	Description
101	1	2	4-wire resistance	Thermistor in the primary zone box. Paired with Channel 111.
102	3	4		
103	5	6	Voltage	V_{sh}, voltage across the shunt resistor.
104	7	8	Voltage	V_h, voltage across the heater.
105	9	10	Voltage	TC on outer edge of top surface of block
106	11	12	Voltage	TC on center of top surface of block
107	13	14	Voltage	TC on outer edge, between bottome block and heater
108	15	16	Voltage	TC on center, between top block and heater
109	17	18	Voltage	TC on center, between bottom block and heater
110	19	20	Voltage	TC on outer edge, between bottom block and balsa, taped to balsa
111	21	22	4-wire resistance	Thermistor in the primary zone box. Paired with Channel 101.
112	23	24		
113	25	26	Voltage	TC on center, between bottom block and balsa, taped to balsa
114	27	28	Voltage	TC on center of bottom surface of simulated PCB
115	29	30	Voltage	TC on edge of bottom surface of simulated PCB
116	31	32	Voltage	TC on center, between bottom block and simulated PCB, taped to balsa
117	33	34	Voltage	TC on edge, between bottom block and simulated PCB, taped to balsa
118	35	36		
119	37	38		
120	39	40		

4   Laboratory Procedure

The laboratory exercise requires you to complete the following tasks

1. Complete the set-up of the apparatus.

2. Shakedown the sensors to prepare for making measurements.

3. Configure the BenchLink Data Logger for the heat transfer measurements.

4. Run the Experiment.

Detailed steps for each task are given in the following sections. Note that the heater is not turned on until *after* the BenchLink software is configured and running (step 3, above).

4.1   Complete the Apparatus

The block assembly has a heating element and thermocouples attached to it. You do not need to add sensors to the assembly. Please be careful with the block assembly.

In order to complete the apparatus you will need to fabricate and install thermocouples used to measure T_a, the air temperature upstream of the block, and T_{amb}, the ambient temperature for thermal radiation exchange with the block surface.

1. Fabricate at least two thermocouples that will be used to measure T_a and T_{amb}.

2. Attach the thermocouples to copper extension wires and place the junction in the zone box. Do not disconnect any of the wires from the terminal strip in the zone box. Attach the extension wires to appropriate terminals on the 50 pin terminal block.

3. Install the T_a and T_{amb} thermocouples at appropriate locations in the wind tunnel. Use tape or some other non-permanent and non-damaging method of attachment.

4. Install a thermistor in the zone box (if one is not already installed), and attach the leads to the 50 pin terminal block.

5. Add the pin and channel assignments for the thermocouples and thermistor to Table 1.

6. Insert a thermal anemometer probe in the probe holder of the wind tunnel. Use the nylon screw to *gently* fix the probe in position. Make sure the red dot on the probe tip faces directly upstream. Cover any holes in the probe holder with duct tape so that air is not sucked through the probe hold and into the wind tunnel.

4.2   Shakedown

The purpose of this shakedown procedure is to make sure that the sensors are behaving as expected. Before investing time in collecting steady-state heat transfer data, it is wise to check for easily fixable errors such as open circuits and reversed thermocouple polarity.

Perform the following steps *before* you turn on the power to the heater.

1. Measure and record the resistance on all sensor channels. Thermocouples should have a very low resistance, say 200 Ω or less. The resistance measurements can be done manually with the controls on the front panel of the Agilent 34970A, or you can use a custom setup of the BenchLink Data Logger software.

2. Measure and record the EMF of all thermocouples. The EMF of the thermocouples should be close to zero if the test apparatus has been sitting undisturbed for a couple of hours. Perform a quick conversion to verify that the thermocouple emf corresponds to a junction temperature close to ambient temperature.

3. Make sure the BenchLink Data Logger is on, and scanning all channels with sensors attached.

4. With the wind tunnel fan off, turn on the heater by turning on the power supply to no more than 8 VDC. Carefully monitor the heater temperature.

5. After one minute of operation with the heater on (or sooner if the heater temperature exceeds 45 °C), turn off the heater power. Inspect the EMF values of all thermocouples. Any thermocouple that is close to or embedded in the heater assembly should have a positive EMF, meaning that it is at a higher temperature than the zone box. Any thermocouple with a negative EMF is likely to have its polarity reversed.

4.3   Configure the BenchLink Data Logger

The heat transfer experiment will take some time to reach thermal equilibrium. You may want to use one scan rate while your monintor the system for steady state (say one reading per 10 or 15 seconds) and another scan rate for recording data once steady state has been reached (say one reading per 3 or 5 seconds). Switching the scan rate will require you to restart the data logger. Complete the following steps *before* turning on the heater.

1. Turn on the Agilent 34970A.

2. Launch the BenchLink application.

3. Follow the instructions in the separate handout titled "Agilent 34970A Data Logger Software". Be sure to use the appropriate channel settings (either DC voltage or resistance) for the sensor list in Table 1.

4. Set the scan interval to at least 10 seconds.

5. Configure the graphics window for plotting the heater temperature and any other temperatures of interest. Add a text box to display the EMF of at least one thermocouple adjacent to the heater.

6. Start scanning *before* turning on the heater.

4.4   Run the Experiment

Collect data for two velocities. Make sure the BenchLink Data Logger is on, and it is scanning all channels with sensors attached.

To reduce the time necessary for the apparatus to warm up, you can turn on the heater with the wind tunnel fan turned off. Do this *only* while carefully monitoring the heater temperature. When the heater temperature approaches $45\,°\mathrm{C}$, or when the heater temperature stabilizes (whichever comes first), turn on the fan and adjust the damper to get the desired velocity in the wind tunnel.

After the initial warm-up period, complete the following steps.

1. Record the ambient conditions and the start time for the experiment.

2. Wait for the thermocouple readings to stabilize, indicating that the system has attained steady state operation.

3. After the system has reached steady state, let the Benchlink Data Logger record at least 40 scans.

4. Record the stopping time for the operating condition.

5. Switch the damper to a new air velocity, and return to step 1.

5   Data Analysis

1. Export the raw data from the BenchLink database.

2. Use the MATLAB program provided, or use Excel to compute the average and standard deviation of each sensor reading at each operating condition.

3. Develop a procedure for computing the heat transfer coefficient h, defined in Equation (1). Calculate h for each operating condition.

4. Use sequential perturbation to compute the uncertainty in the heat transfer coefficient, δh.

6   Report

Your report should include the following.

- A block diagram of sensor location and wiring. Do not strive for geometric fidelity. A block diagram shows the topology of the connections. It is not a dimensional drawing.

- Describe the data reduction procedure for computing h and δh.

  ▷ List all equations used in data reduction and uncertainty analysis.

  ▷ Define all symbols (variables and constants) in words.

  ▷ Provide a listing of your MATLAB program or spreadsheet for data reduction. These can be in an appendix.

  ▷ If you use a spreadsheet, provide a manual example of the data reduction procedure for computing h.

  ▷ List the averaged raw data.

  ▷ Provide a table of all inputs to the uncertainty analysis. These inputs should include the calibration uncertainty and random uncertainty of each sensor. Provide an estimate of uncertainty in any calculated quantity used to compute h. For example, estimate the uncertainty in the thermal resistance of the heater leads, and the thermal resistance to conduction through the bottom of the heater assembly.

- Present the final results in table such as the following.

V (m/s)	h (W/m^2/°C)	δh (W/m^2/°C)	$\dot{E}_{\text{in}}$ (W)	Q_{conv} (W)	Q_{cond} (W)	Q_{rad} (W)

- Discuss the trend in the h as the air velocity is changed.

- Comment on the quality of your data. Could you improve the quality of your results by repeating the experiment with some changes? If so, what would those changes be? Are there questionable measurements (or measured values) used in the data reduction?

- Recommend improvements for the experiment based on your results.