5.1 Convection

5.1.1 Introduction

In this lab experiment you will measure the average convective heat transfer coefficient for forced convection of air past a flat disk thermistor, and develop an empirical model for evaluating the average forced convective heat transfer coefficient for this particular condition.

5.1.2 Newton's Law of Cooling

When fluid flows over a surface, where the fluid and surface are at different temperatures, heat transfer takes place. The heat transfer rate is proportional to the fluid-surface temperature difference and the surface's area. The proportionality constant is defined as *h*, the heat transfer coefficient. The equation that is developed is defined as Newton's law of cooling equation is

$$\dot{Q} = hA_s\left(T_s - T_{f,\infty}\right) \tag{1}$$

Where A_s is the surface's area (the heat transfer area), T_s is the surface temperature, and $T_{f,\infty}$ is the freestream fluid temperature. The proportionality constant is dependent on the freestream fluid properties and surface geometry.

To determine the heat transfer flux, one must know both the temperature difference between the surface and the fluid and the heat transfer coefficient. At the fluid-surface interface, the following condition must hold.

$$-k_f\left(\frac{dT_f}{dy}\right)_{wall} = h\left(T_s - T_{f,\infty}\right) \tag{2}$$

Where y is the direction normal to the surface. Upon rearranging Eq. 2, the heat transfer coefficient is solved for.

$$h = -k_f\left(\frac{dT_f}{dy}\right)_{wall} \Big/ \left(T_s - T_{f,\infty}\right) \tag{3}$$

Evaluating the right hand side requires knowledge of the fluid temperature distribution near the surface. Analogous to the velocity boundary layer, there is a thermal boundary layer. In this region close to the surface, thermal effects due to the surface are felt in the fluid. In this region there exists a temperature gradient. The heat transfer coefficient is proportional to the temperature gradient as seen in Eq. 3. To solve the temperature distribution requires solving the continuity, momentum, and energy equations. For relatively simple objects, to obtain the solution requires large computation effort on fast computers.

For an extremely simple geometry of a flat plate, a solution can be obtained. The form of the solution is

$$h_x = \frac{k_f}{x} C\, Re_x{}^n\, Pr^m \qquad (4)$$

Where x is the location on the plate with respect to the leading edge, C is a constant, Re_x is the Reynolds number based on the characteristic dimension x, Pr is the Prandtl number, and n and m are constants. Prandtl number is the ratio of kinematic viscosity to thermal diffusivity.

For more complex surfaces of similar geometry, a similar empirical correlation to Eq. 4 can be assumed.

$$Nu_x = C\, Re_x{}^n\, Pr^m \qquad (5)$$

Where Nu_x is the Nusselt number defined as

$$Nu_x = \frac{hx}{k_f} \qquad (6)$$

Through experimentation, the constants C, n, and m can be determined.

5.1.3 Description of Apparatus

The equipment used for this experiment is a fully instrumented convective heat transfer measurement system as shown in Fig. 1. No additional instruments or equipment is required for this experiment. The apparatus consists of the test section, a differential manometer, two voltmeters, air temperature readout, power supply, and air pressure regulator. A closer look of the test section is shown in Fig. 2. The test section is made of a glass tube. The air flows through the tube; where downstream of the inlet is a pitot tube for measuring the air velocity through the tube. Downstream of the pitot tube is the

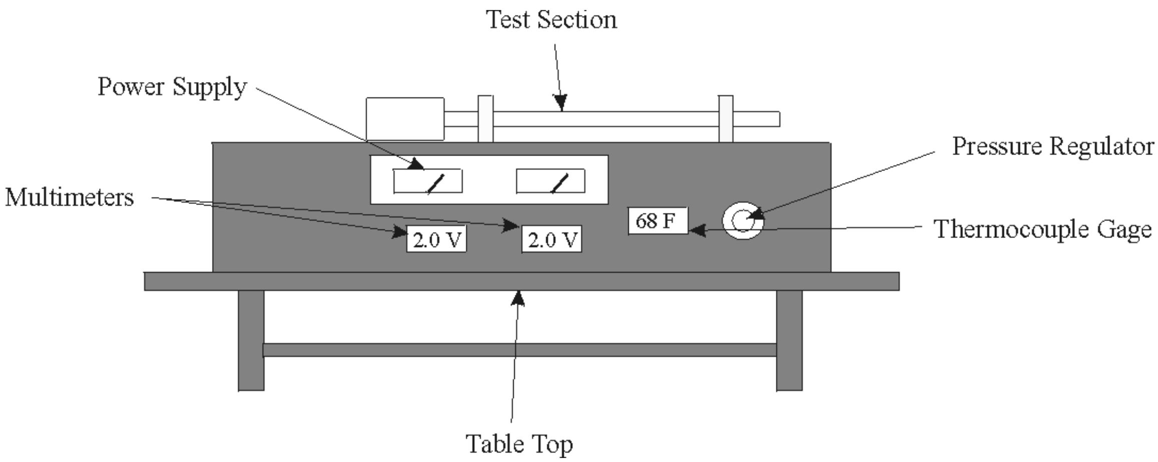

Figure 1: Schematic of Forced Convection Apparatus.

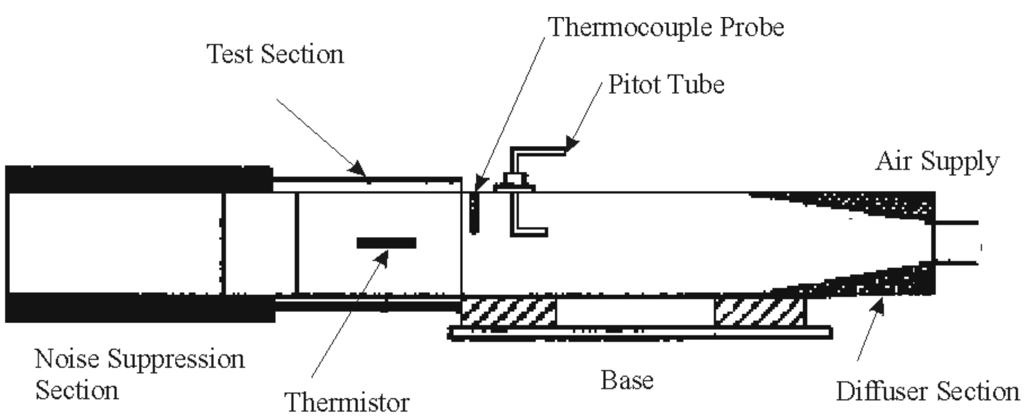

Figure 2: Cutaway of Test Section.

thermocouple for measuring air temperature. Downstream of the thermocouple is the thermistor. Power is delivered to the thermistor through the wire leads that are connected to the power supply. The thermistor is also connected to a precision resistor and one of the voltmeters. Downstream of the thermistor at the glass tube exit is a muffler to suppress the air noise.

The electrical circuit built into this apparatus to measure the heat transfer from the thermistor is shown in Fig. 3. A D.C. power supply supplies power to the thermistor and

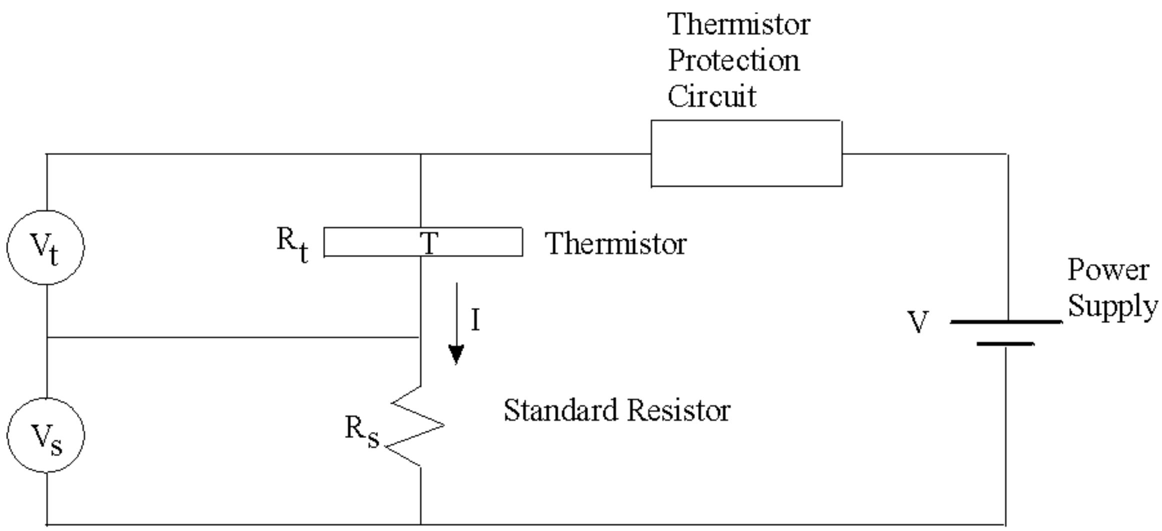

Figure 3: Electrical Circuit of Apparatus.

another resistor in series. A voltmeter's leads are connected across the thermistor to measure its voltage. Another voltmeter is used to measure the voltage across the other resistor. For a particular flow rate across the thermistor, an amount of power is supplied and dissipated by the thermistor. The amount of power delivered to the thermistor can be determined by the voltage measurements, the thermistor temperature measurement, the air temperature measurement, and the thermistor geometry.

The amount of energy dissipated by the thermistor is needed to calculate the heat transfer coefficient as shown in Eq. 1. It is calculated by

$$\dot{Q}_T = IV_T \qquad (7)$$

Where I is the circuit current and V_T is the voltage measured across the thermistor. The current is known by the standard resistor and the voltage measured across it.

$$I = \frac{V_S}{R_S} \tag{8}$$

Where V_S is the measured voltage across the standard resistor and R_S is the standard resistance. The standard resistance is 10 Ω. The resistance of the thermistor can also determined by

$$R_T = \frac{V_T}{I} = \frac{V_T}{V_S} R_S \tag{9}$$

Upon knowing the thermistor resistance, its temperature can be determined by correlations developed. The following equation is a polynomial fit relating the resistance to its temperature.

$$T = 108.08 - 1.541 R_T + 0.00679 R_T^{\,2} \tag{10}$$

where T is in [C] and R_T is in [Ω]. Combining Eq. 7 and Eq. 8 is

$$\dot{Q}_T = \frac{V_S}{R_S} V_T \tag{11}$$

The thermistor is effectively the geometry of a disc. The overall disc surface area is

$$A_s = \pi d \left(t + d / 2 \right) \tag{12}$$

Where d is the disc diameter and t is the disk thickness. The diameter is 5.08 mm and its surface area is 5.65 x 10^{-5} m^2.

5.1.4 Safety Guidelines

- Do not exceed the recommended voltage supplied to the thermistor and to the standard resistor.
- Main pressure regulator setting for air supply must not be changed without consulting the instructor.

Convection Worksheet

1. List the objectives of the experiment.

2. Before running the experiment, read the following recommendations in operating the equipment.
   - The voltage to be supplied is according to the thermistor geometries, a disc type thermistor uses 20-25 V at most.
   - When operating the DC power supply, the current knob is always at the maximum setting. Only the voltage is varied.
   - When conducting heat transfer tests, adjust V_T / V_S as close to two as possible for low velocities without tripping the thermistor protection circuit, and then vary the velocity.
   - When the thermistor protection circuit is tripped, lower the voltage from the DC power supply before pressing the reset button. However, a small voltage is necessary for the reset to work.

3. Turn-on the main power supply by flipping a switch on the right-hand side of the unit panel.

4. Supply the air to the system and adjust the pressure until seeing air flowing through the system as indicated by the inclined manometer.

5. Turn-on the power supply to the unit (on the blue panel).

6. Turn-on the power to the two digital multimeters.

7. Press the reset button to reset the circuit (lights will go off).

8. Turn the current knob clockwise to full open position and then turn the voltage knob to a few volts so V_T / V_S ratio = 2.0, or greater than 2.0.

9. Change the air velocity until the static air pressure reading from the inclined manometer in the range from 0.05 to 0.25 in H_20 (use the regulator knob). Run five different tests between this range.

10. Record the (V_T and V_S) readings and manometer readings for each airflow velocity at the steady-state condition, i.e., when the V_T / V_S reading are stabilized. Record the data in the table given on the next page.

	V_T [V]	V_S [V]	R_S [Ω]	T_a [C]	V [in of H_2O]	R_T [Ω]	T_T [C]	Q [W]	h [W/m^2-K]	Nu	Re
1											
2											
3											
4											
5											

Show the calculations for one set of data collected including uncertainty.

11. Record thermistor's voltage.

________________V

12. Record standard resistor's voltage.

________________V

13. Record standard resistor's resistance.

________________Ω

14. Record the air temperature.

________________C

15. Calculate the air density.

______________kg/m^3

16. Record the air velocity.

________________m/s

17. Determine the thermistor's resistance.

________________Ω

18. Determine the thermistor's temperature from Eq 10.

________________C

19. Calculate the convection heat transfer coefficient.

__________________W/m^2-K

20. Determine the Nusselt number based on the disc diameter. The thermal conductivity of air at 300 K is 26.2 x 10^{-3} W/m-K.

Nusselt number __________________

21. Determine the Prandtl number. The dynamic viscosity and specific heat at constant pressure of air at 300 K are 1.98 x 10^{-5} kg/m-s and 1006 J/kg-K, respectively.

Prandtl number __________________

22. Determine the Reynolds number based on disc diameter.

Reynolds number ___________________

23. Determine the uncertainty of Nusselt number.

Nusselt number uncertainty ___________________

24. Determine the constants C and n from the experimental data. Use two experimental runs. Assume that the exponent on the Prandtl number is one-third. Also determine their uncertainty.

constant C ___________________ constant n ___________________

25. Convert the above experimental data to a dimensionless form, and plot the ratio $Nu_d/Pr^{1/3}$, as a function of the Reynolds number, Re_d . Also plot the correlations for a flat plate, turbulent and/or laminar. Show uncertainty calculations on the plot.

Discussion of Results and Conclusion