The Lecture Contains:

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Resistance Thermometers

The hot wire probe referred above can be used in the constant current mode as a resistance thermometer to determine the local fluid temperature. Here we exploit the fact that the wire resistance changes with temperature. This variation is close to linear and is of the form

$$R = R_0(1 + \alpha(T - T_0))$$

A typical value of α for commonly used metals such as aluminum, gold, platinum and tungsten is 4×10^{-3}/°C. To measure resistance a small current of around 1 mA is passed through the wire and the instantaneous voltage drop $(= IR(T))$across the wire is measured. This method permits the tracking of thermal transients and fluctuations in the fluid. However it suffers from an error that occurs due to Joule heating $(= I^2R)$of the wire itself. For this reason resistance thermometers are more commonly used with circuits that employ a null method to measure resistance. The current flow in such circuits can be made extremely small.

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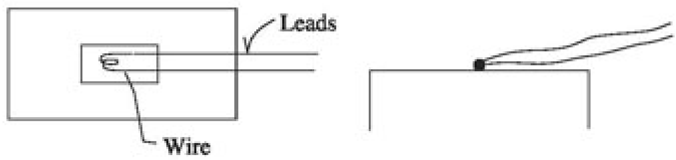

Figure 2.14: Placement of Resistance Thermometer.

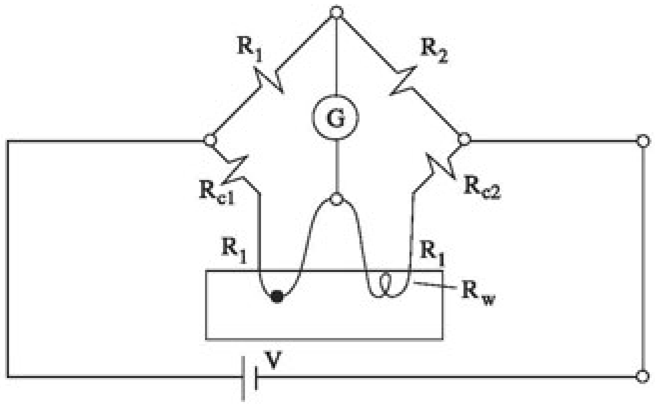

Figure 2.15: Wheatstone Bridge Setup.

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Consider the measurement of temperature of a heated surface as shown in Figure 2.14. Wheatstone bridge is commonly used for direct measurement of wire resistance, as shown in Figure 2.15 where V is the DC power source with a stability of better than 1 mV, G is a galvanometer used to check for null current, R_{c1}, R_{c2} are control resistors that reduce the current level in the circuit and R_1, R are the lead and wire resistances, respectively. The presence of R in the parallel arm of the bridge compensates for temperature gradients that will exist in the lead wires. When the bridge is balanced

$$\frac{R_1}{R_2} = \frac{R_{c1} + R_1}{R_{c2} + R_1 + R_w}$$

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Thermocouples

We describe below the use of thermocouples in temperature measurement. Their ease of operation, reliability, applicability over a wide range of temperatures (-100 to 900° C) and the ability to follow transients have made thermocouples very popular in research as well as industrial applications. Thermocouples employ a phenomenon called Seebeck effect. When two junctions formed between two dissimilar metals are maintained at different temperatures a break anywhere in the circuit will exhibit an emf called thermo-emf (Figure 2.16).

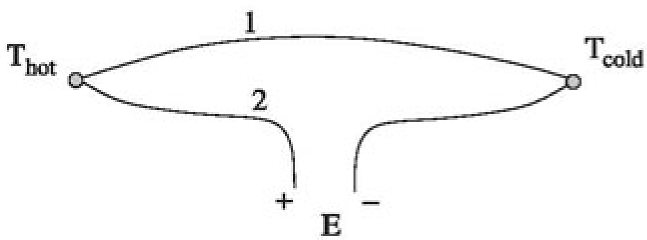

Figure 2.16: Thermocouple Arrangement.

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The thermo-emf E can be related to the higher temperature $T_{hot}(=T)$ for given values of T_{cold} (the reference temperature) as

$$E = a(T - T_{cold}) + b(T^2 - T^2_{cold})$$

or read off from calibration charts. Here T is the absolute temperature in units of Kelvin. Values of a, b depend on the choice of the reference temperature. Commonly $T_{cold} = 0^{\circ}C$ C and the reference junction is kept in an ice-water mixture. For the ice point as a reference, typical values of a and b are 1/50 mV/K and $-0.01\ mV/K^2$. Since thermo-emfs tend to be small, the voltmeter employed for this purpose must have the necessary resolution and accuracy. The thermocouple produces a voltage output in response to a temperature difference and classifies as an active transducer. Pairs of metals/alloys normally used in thermocouples are chromel/alumel, copper/constantan and iron/constantan. The bead that is formed at the junction should be clean, uniform and free of oxides. Normally every new thermocouple that is formed must be tested against an ideal reference thermocouple. The bead size can be increased by using wires of larger diameter to damp temperature fluctuations and reduced if transients need to be followed closely.

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The laws of thermocouples are symbolically given in Figure 2.17 (a-d). In Figure 2.17 (a), C could be a voltmeter whose terminals are at a uniform temperature T.

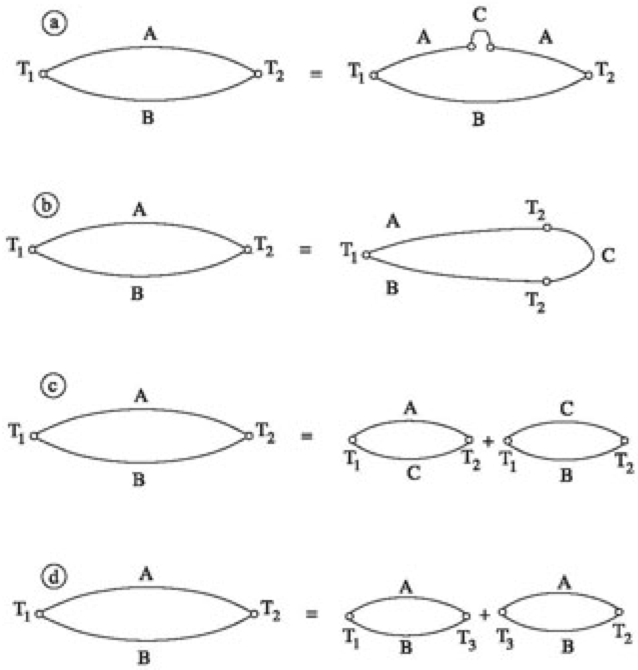

Figure 2.17: Laws of Thermocouples.

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In Figure 2.17 (b), the junction need not be formed physically at one point and instead could be distributed. Figures 2.17 (c) and (d) are respectively called the laws of intermediate metals and intermediate temperatures.

Two additional effects that influence thermocouple performance are Peltier and Thompson effects. The former is related to the heating of the junctions between dissimilar materials when a current flows through them and the latter to an emf production due to a temperature gradient along the length of the wires. Peltier effect is significant when the voltmeter measuring the thermo-emf does not have a large enough input impedance. However, thermo-emfs tend to be small and this effect is usually insignificant unless the sample whose temperature is being measured is physically small or the unknown temperature is considerably below the ambient. On the other hand, Thompson effect is an important source of error in thermocouple measurements. It can be kept small by using very short lengths of thermocouple wire and using high-conductivity copper wires to convey the thermo-emf to the measuring instrument. The thermocouple-copper junction will not result in any new emf if the laws of thermocouples described above are not violated. In particular, the copper-thermocouple and copper-instrument junctions must be at the same temperature.

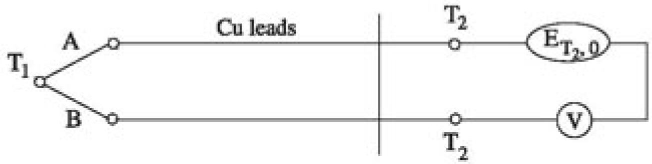

Figure 2.18: Compensation Circuit for a Thermocouple.

To use the calibration charts one of the junctions of the thermocouple must be located in an ice bath. This is inconvenient especially when multi-channel measurements are to be carried out. The circuit in Figure 2.18 eliminates the need for an ice point and compensates automatically for the room temperature. Here T_1 is the unknown temperature, A and B are the thermocouple wires, T_2 the room temperature and V the voltmeter. $E_{T_2,0}$ is a DC voltage source that produces a thermo-emf corresponding to the temperature levels T_2 and 0^oC, for the pair of materials A and B. It uses a resistance thermometer (usually a semiconductor-based thermistor) to measure the absolute room temperature and converts it into a thermo-emf using the quadratic formula referred earlier. Hence the voltmeter senses the total thermo-emf

$$V = E_{T_1,T_2} + E_{T_2,0} = E_{T_1,0}$$

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Wind Tunnels

In many experiments in fluid mechanics one requires a base flow whose velocity profile, temperature distribution and turbulence level are fully known. Specifically, most experiments require that the incoming flow be at a uniform temperature and velocity, while the velocity fluctuations are minimal. A definite disturbance is introduced in this flow and the following questions are addressed:

1. Does the disturbance level grow with time and distance?

2. What is the force developed at the site of this disturbance?

3. What are the local pressure and temperature profiles and the global heat transfer rates?

Question 2 is one of fundamental importance in aeronautics where lift and drag forces developed on aerofoil sections must be determined. Wind tunnels are used to generate the prescribed base flow in a rectangular channel that is large enough with respect to the size of the affected zone around the disturbance. In special purpose wind tunnels, the base flow may have a uniform shear (i.e., a velocity gradient) or uniform stratification (i.e., density and temperature gradient). However the common requirements for a wind tunnel are:

1. Uniform flow over a large portion of its cross-section

2. Low background turbulence level.

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A typical value of free stream turbulence level that is acceptable in force measurement is 0.1% of the mean velocity though a lower value may be required in certain studies such as those relating to hydrodynamic stability.

A sketch of a low speed open circuit wind tunnel is shown in Figure 2.19. The important components of this wind tunnel are:

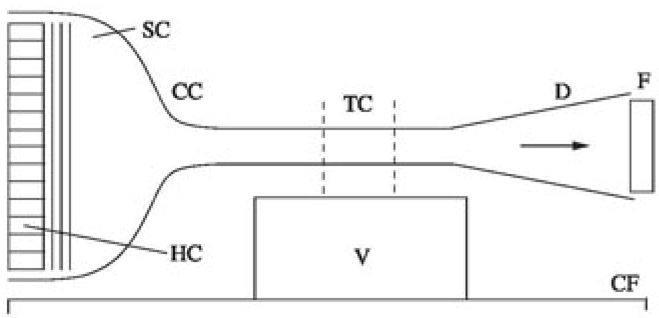

Figure 2.19: Schematic Drawing of a Wind Tunnel.

HC = Honeycomb for straightening the incoming flow.

SC = Screens for filtering out the eddies that are drawn from the ambient and those generated at the lips of the honeycomb structure

CC = Contraction cone, where the favourable pressure gradient limits the growth of the wall boundary-layers and dampens free stream turbulence

V = Vibration isolation table

TC = Test cell where the desired experiment is carried out

D = Diffuser connecting the test cell to the suction side of a fan

F = Fan that creates flow in the tunnel along with a variable speed motor

CF = Concrete floor to absorb fan vibrations

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The fan motor sizing is determined by carrying out a series of pressure loss calculations in each part of the wind tunnel. Considerations that go into the design of the wind tunnel are:

1. Low versus high speed: Low speed tunnels are those in which air may be treated as incompressible. For air at atmospheric pressure the limiting speed is one-third the speed of sound i.e., about 100 m/s. In high speed tunnels the Mach number may exceed unity. These are useful in studying shock formation in gas flows. Supersonic conditions are generally obtained as choked flow in nozzles from a high pressure reservoir. The design of the nozzle profile is critical, if supersonic speeds are required at its exit plane.

2. Open and closed circuit: In large wind tunnels the kinetic energy in the air stream is so large that it is uneconomical to discharge it into the atmosphere. In such cases the wind tunnel operates in a closed circuit and air is recirculated through the test cell. The reduced operating cost of such tunnels must be balanced against the capital cost of making a bend as well as the cost of heat exchangers that may be needed to control air temperature. For large wind tunnels an important design parameter is the energy ratio defined as the ratio of the energy in the air stream to the energy input to the fan. The former is calculated as

Dynamic pressure $\times$ Area of cross-section $\times$ air velocity

This ratio is normally in the range 3-5 in well-designed tunnels.

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