Sub Module 2.2

Thermoelectric thermometry

Thermoelectric thermometry is based on thermoelectric effects or thermoelectricity discovered in the 19th century. They are:

- **Seebeck effect discovered by Thomas Johann Seebeck in 1821**
- **Peltier effect discovered by Jean Charles Peltier in 1824**
- **Thomson effect discovered by William Thomson (later Lord Kelvin) in 1847**

The effects referred to above were all observed experimentally by the respective scientists. All these effects are reversible unlike heat diffusion (conduction of heat) and Joule heating (due to electrical resistance of the material) which are irreversible. In discussing the three effects we shall ignore the above mentioned irreversible processes. It is now recognized that these three effects are related to each other through the Kelvin relations.

Thermoelectric effects:

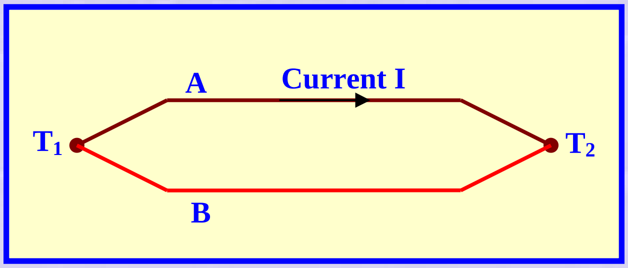

Figure 4 Sketch to explain Peltier effect

Consider two wires of dissimilar materials connected to form a circuit with two junctions as shown in Figure 4. Let the two junctions be maintained at different temperatures as shown by the application of heat at the two junctions. An electric current will flow in the circuit as indicated with heat absorption at one of the junctions and heat rejection at the other. This is referred to as the Peltier effect. The power absorbed or released at the junctions is given by $P = \dot{Q}_P = \pm\pi_{AB} I$ where π_{AB} is the Peltier voltage (this expression defines the Peltier emf), $\dot{Q}_P$ is rate at which the heat absorbed or rejected. The direction of the current will decide whether heat is absorbed or rejected at the junction. For example, if the electrons move from a region of lower energy to a region of higher energy as they cross the junction, heat will be absorbed at the junction. This again depends on the nature of the two materials that form the junction. The subscript AB draws attention to this fact! The above relation may be written for the two junctions together as

$$\pi_{AB}(T_1, T_2) = \pi_{AB}\big|_{T_1} - \pi_{AB}\big|_{T_2} \qquad (3)$$

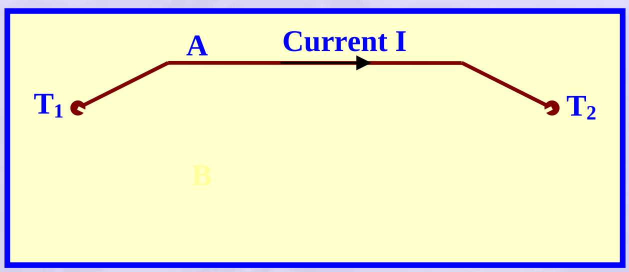

Figure 5 Sketch to explain Thomson effect

Note that the negative sign for the second term on the right hand side is a consequence of the fact that the electrons move from material A to material B at junction 1 and from material B to material A at junction 2.

Consider now a single conductor of homogeneous material (wire A alone of Figure 4) in which a temperature gradient exists. The current I is maintained by heat absorption or heat rejection along the length of the wire. Note that if the direction of the current is as shown the electrons move in the opposite direction. If $T_2 > T_1$, the electrons move from a region of higher temperature to that at a lower temperature. In this case heat will be rejected from the wire. The expression for heat rejected is $\dot{Q}_T = I\int_{T_2}^{T_1} \sigma_A dT$ where $\dot{Q}_T$ is the Thomson heat and σ_A is the Thomson coefficient for the material. A similar expression may be written for the Thomson heat in conductor B.

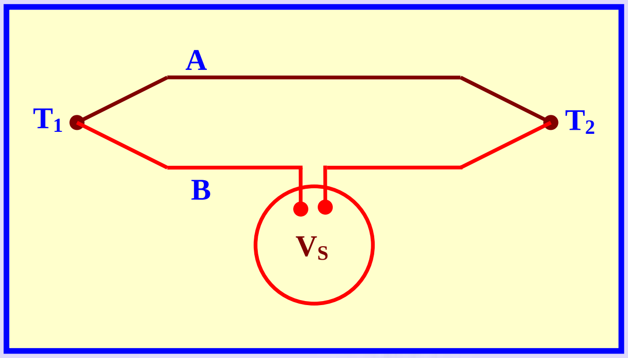

Figure 6 Sketch to explain the Seebeck effect

If we cut conductor B (or A) as indicated the Seebeck emf appears across the cut. This emf is due to the combined effects of the Peltier and Thomson effects. We may write the emf appearing across the cut as

$$\begin{aligned} V_S &= V_P + V_T = (\pi_{AB})_{T_2} - (\pi_{AB})_{T_1} + \int_{T_1}^{T_2} \sigma_A \, dT + \int_{T_2}^{T_1} \sigma_B \, dT \\ &= (\pi_{AB})_{T_2} - (\pi_{AB})_{T_1} + \int_{T_1}^{T_2} (\sigma_A - \sigma_B) dT \end{aligned} \qquad (4)$$

We define the Seebeck coefficient α_{AB} through the relation $\frac{dV_s}{dT} = \alpha_{AB}$. In differential form, Equation 4 may then be rewritten as (assume $T_2 - T_1 = dT$)

$$\begin{aligned} \frac{dV_s}{dT} &= \alpha_{AB} = \frac{d\pi_{AB}}{dT} + (\sigma_A - \sigma_B) \\ &\text{or} \\ dV_s &= d\pi_{AB} + (\sigma_A - \sigma_B) dT \end{aligned} \qquad (5)$$

Kelvin relations:

Since the thermoelectric effects (Peltier and Thomson effects) are **reversible** in nature there is no **net entropy change** in the arrangement shown in Figure 4.

The entropy changes are due to heat addition or rejection at the junctions due to Peltier effect and all along the two conductors due to Thomson effect. The entropy change due to Peltier effect may be obtained as follows:

At junction 1, the entropy change is $s_{P1} = \frac{\dot{Q}_{P1}}{T_1} = I\frac{\pi_{AB}}{T_1}$. Similarly at junction 2 the entropy change is $s_{P1} = \frac{\dot{Q}_{P2}}{T_2} = I\frac{\pi_{BA}}{T_2} = -I\frac{\pi_{AB}}{T_2}$. Again if we assume that the temperature difference is $T_2 - T_1 = dT$ the net change in entropy is $ds_P = Id\left(\frac{\pi}{T}\right)$. The net change in entropy due to Thomson heat in the two conductors may be written as $ds_T = I\frac{\sigma_A - \sigma_B}{T}dT$. Combining these two we get

$$ds = ds_P + ds_T = I\left[d\left(\frac{\pi}{T}\right) + \frac{\sigma_A - \sigma_B}{T}dT\right] = 0$$
$$= I\left[\frac{d\pi_{AB}}{T} - \pi_{AB}\frac{dT}{T^2} + \frac{\sigma_A - \sigma_B}{T}dT\right] = 0 \quad (6)$$

The total entropy change is equated to zero since both the thermoelectric processes are reversible. The current I can have arbitrary value and hence the bracketed term must be zero.

From Equation 5 $(\sigma_A - \sigma_B)dT = dV_s - d\pi_{AB}$. Introducing this in Equation 6 we get

$$\frac{d\pi_{AB}}{T} - \pi_{AB}\frac{dT}{T^2} + \frac{dV_s}{T} - \frac{d\pi_{AB}}{T} = 0$$

or

$$\pi_{AB} = T\frac{dV_S}{dT} = T\alpha_{AB} = T\alpha_S \quad (7)$$

We have renamed the Seebeck coefficient as α_S according to normal practice.

Differentiating Equation 7 we get $d\pi_{AB} = Td\alpha_s + \alpha_s dT$. Introduce this in Equation 5 to get $dV_s = Td\alpha_s + \alpha_s dT + (\sigma_A - \sigma_B)dT = \alpha_S dT$ or

$$(\sigma_A - \sigma_B) = -T\frac{d\alpha_s}{dT} \quad (8)$$

Equations 7 and 8 constitute the Kelvin relations.

How do we interpret the Kelvin relations?

The Seebeck, Peltier and Thomson coefficients are normally obtained by experiments. For this purpose we use the arrangement shown in Figure 6 with the junction labeled 2 maintained at a suitable reference temperature, normally the ice point (0°C). The junction labeled 1 will then be called the measuring junction. Data is gathered by maintaining the measuring junction at different temperatures and noting down the Seebeck voltage. If the measuring junction is also at the ice point the Seebeck voltage is identically equal to zero. The data is usually represented by a polynomial of suitable degree. For example, with Chromel (material A) and Alumel (material B) as the two wire materials, the expression is a quartic of form $V_S = a_1 t + a_2 t^2 + a_3 t^3 + a_4 t^4$ where The Seebeck voltage is in μV and the temperature is in °C. An inverse relation is also used in practice in the form $t = A_1 V_S + A_2 V_S^2 + A_3 V_S^3 + A_4 V_S^4$. Two examples follow. We shall see later that the coefficients in the polynomial are related to the three thermoelectric effects.

Example 2

- *For the Chromel-Alumel pair the Seebeck voltage varies with temperature according to the fourth degree polynomial*

$$V_S = 39.44386\,t + 5.8953822\times10^{-3}\,t^2 - 4.2015132\times10^{-6}\,t^3 + 1.3917059\times10^{-10}\,t^4$$

- *The Seebeck voltage is in μV while the temperature is in °C. Discuss the behavior of this thermocouple near the ice point.*

  - *It is clear that, near the ice point, the Seebeck coefficient (it is also called the thermoelectric power) is*

$$\alpha_s = \frac{dV_s}{dt} \approx 39.4\ \mu V/°C$$

  - *Using the Kelvin relations, we also have the following:*

1. $$\left(\sigma_A - \sigma_B\right) = \left(\sigma_{Chromel} - \sigma_{Alumel}\right) = -T\frac{d\alpha_s}{dT} = -T\frac{d^2V_S}{dT^2}$$

2. $$\pi_{A-B} = \pi_{Chromel-Alumel} = T\alpha_S \approx 39.44386\,T$$

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- *Note that T in the Kelvin relation is in Kelvin and t in the polynomial is in 0°C. Also note that* $\frac{d}{dT} \equiv \frac{d}{dt}$. *Hence the second derivative of the Seebeck voltage is given by*

$$\frac{d^2V_S}{dT^2} = \frac{d^2V_S}{dt^2} = 2a_2 + 6a_3t + 12a_4t^2$$

- *Near the ice point we may take t = 0 and write*

$$\left(\sigma_{Chromel} - \sigma_{Alumel}\right) \approx (-2)(0.0058953822)(273.15)$$
$$= -3.2206 \ \ \mu V.$$

and

$$\pi_{Chromel-Alumel} = T\alpha_S = (273.15)(39.44386) = 10774.1\ \mu V \approx 0.0108\ V$$

Example 3

- *The thermocouple response shown below (Copper Constantan thermocouple with the cold junction at the ice point) follows the law $V_S = a\,t + b\,t^2$. Obtain the parameters a and b by least squares. Here t is in ^oC and V_S is in mV.*

Temperature, ^oC	37.8	93.3	148.9	204.4	260
V_S, mV	1.518	3.967	6.647	9.523	12.572

- *Since the fit follows the form specified above, it is equivalent to a linear relation between E= V_S/t and t. Since V_S/t is a small number we shall work with 100 V_S/t and denote it as y. We shall denote the temperature as x. The following table helps in evolving the desired linear fit.*

	x=t	$y=100V_S/t$	x^2	y^2	xy	y_{fit}
	37.8	4.015873	1428.84	16.12724	151.8	4.036073
	93.3	4.251876	8704.89	18.07845	396.7	4.24048
	148.9	4.46407	22171.21	19.92792	664.7	4.445255
	204.4	4.659002	41779.36	21.7063	952.3	4.649661
	260	4.835385	67600	23.38094	1257.2	4.854436
Sum:	744.4	22.22621	141684.3	99.22085	3422.7	6.638481
Mean =	148.88	4.445241	28336.86	19.84417	684.54	4.445181

(Note: I have used EXCEL to solve the problem)

- *The statistical parameters are calculated and presented in the form of a table:*

Variance of x=	*6171.606*
Variance of y=	*0.084001*
Covariance =	*22.73252*
Slope of fit line =	*0.003683*
Intercept of fit line =	*3.896856*

- *Using the fit parameters the calculated values of y_{fit} are shown in the last column of the first table. Reverting back to t and V_S, we get the following relation:*

$$V_S = t(0.003683\,t + 3.896856)/100 \approx 0.03897t + 3.683 \times 10^{-5} t^2$$

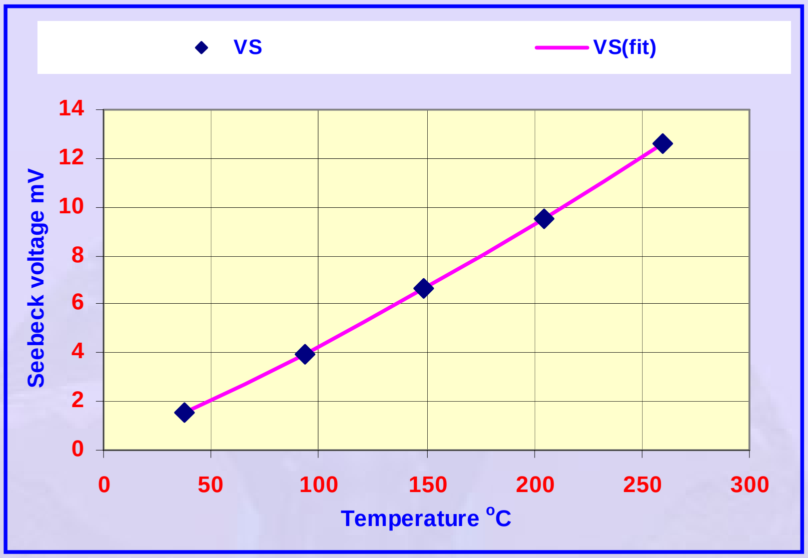
- *We compare the data with the fit in the table below:*

t	*V_S*	*V_S(fit)*
37.8	*1.518*	*1.526*
93.3	*3.967*	*3.956*
148.9	*6.647*	*6.619*
204.4	*9.523*	*9.504*
260	*12.572*	*12.622*

- *Standard error of the fit with respect to data may be calculated as*

$$\sigma_{Err} = \sqrt{\frac{(V_S - V_S(fit))^2}{3}} = \sqrt{\frac{0.003774}{3}} = 0.035\,mV$$

- *The 3 in the denominator is the degrees of freedom. A plot is made to compare the data and the fit. It is clear that the thermocouple behavior* *is mildly nonlinear. The standard error of fir translates to approximately ±1 °C!*



- *The inverse relation may similarly be obtained by fitting a linear relation between* $\frac{t}{V_S}$ *and* V_S*. This is left as an exercise to the student. The result obtained is* $t = 25.173V_S - 0.3769V_S^2$ *with a standard error of* $\sigma_t = \pm 2.209\,°C$.

Example 2 has shown that the thermoelectric data may be expressed in terms of global polynomial to facilitate interpolation of data. A simple quadratic fit has been used to bring home this idea. In practice the appropriate interpolating polynomial may involve higher powers such that the standard error is much smaller than what was obtained in Example 2. As an example, the interpolating polynomial recommended for the K type thermocouple with the reference junction at the ice point is given as:

$$V_S = 39.44386\,t + 5.8953822 \times 10^{-3} t^2 - 4.2015132 \times 10^{-6} t^3 + 1.3917059 \times 10^{-10} t^4$$

This is a fourth degree polynomial and passes through the origin. The Seebeck voltage is given in μV and the temperature is in °C. Using Kelvin relations, the appropriate parameters are calculated near the ice point as:

$$\alpha_s = \frac{dV_s}{dt} = 39.444\mu V / {}^o c$$

$$\pi_{AB} = T\alpha_S = 273.15 \times 39.44 = 10774.1\mu V$$

$$\sigma_A - \sigma_B = -T\frac{d\alpha_S}{dt} = 273.15 \times 2 \times 0.005895 = -3.22064\mu V$$

The variation of the Seebeck coefficient over the range of this thermocouple is given in Figure 7 below.

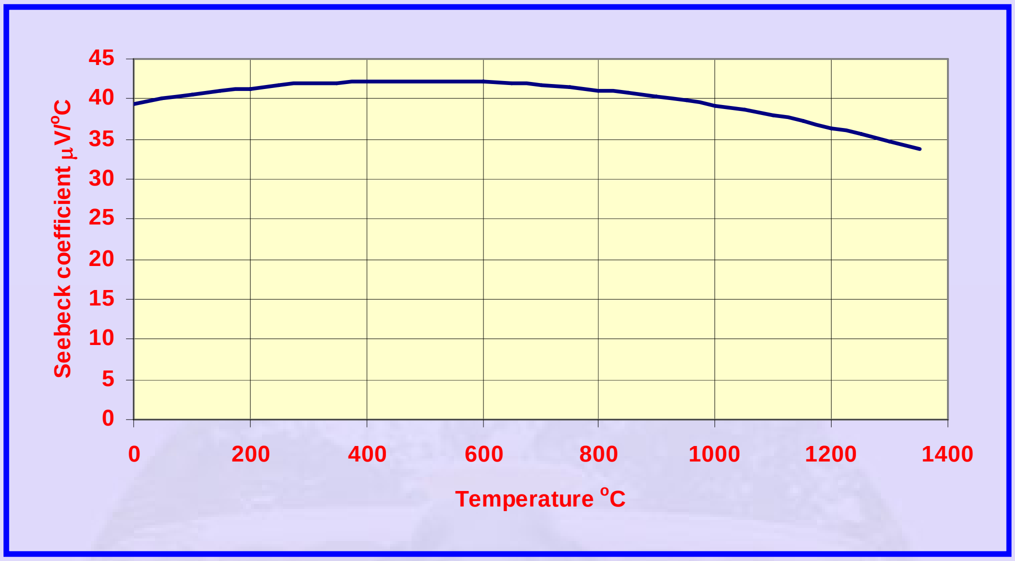


Figure 7 Variation of Seebeck coefficient with temperature for K type thermocouple

A short excerpt from a table of Seebeck voltages is taken and the corresponding fit values as calculated using the above fourth degree polynomial is given in Table 3. Note that the voltages in this table are in mV.

Table 3 comparison of actual data with fit

t	V_S	V_S(fit)
37.8	1.52	1.499
93.3	3.819	3.728
148.9	6.092	5.990
204.4	8.314	8.273
260	10.56	10.581
371.1	15.178	15.237
537.8	22.251	22.276
815.6	33.913	33.874
1093.3	44.856	44.879
1371.1	54.845	54.827

The maximum deviation is some 0.102 mV. The standard error is approximately ±0.053 mV! This translates to roughly an error of ±1.2°C.

The above shows that the three effects are related to the various terms in the polynomial. The Seebeck coefficient and the Peltier coefficients are related to the first derivative of the temperature. The contributions to the first derivative from the higher degree terms are not too large and hence the Seebeck coefficient is a very mild function of temperature. In the case of K type thermocouple this variation is less than some 2% over the entire range of temperatures. The Thomson effect is related to the second derivative of the polynomial with respect to temperature. The value of this is again small and varies from -3.22 V at 0°C to a maximum value of +31.16 V at 1350°C.

On the use of thermocouples for temperature measurement

We shall be looking at basic theoretical aspects and practical aspects of measurement of temperatures using thermocouples. General ideas are explored first followed by important practical aspects. Simple or basic thermocouple circuit used for temperature measurement is shown in Fig. 8.

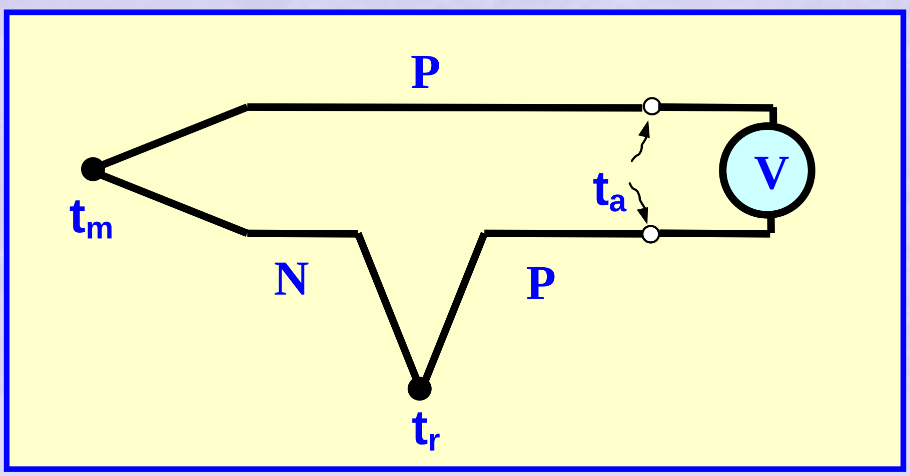


Figure 8 Simple thermocouple circuit

The basic thermocouple circuit consists of a wire of P type material (P stands for positive) and a wire of N type material (N stands for negative) forming a measuring junction and a reference junction as shown (more about P and N materials will be given later). The voltmeter is connected by making a break in the P type wire as shown. Thus two more junctions are formed between P type wires and connecting leads of the voltmeter. As we shall see later the voltmeter will indicate the correct Seebeck voltage corresponding to t_m if the two extra junctions formed with the voltmeter are at the same temperature. If $t_m \succ t_r$, the voltmeter will indicate a positive voltage, the way it is connected.

We now look at the temperature variations along the wires that make up the simple circuit shown in Fig. 8. It is likely that the thermocouple wires pass through a region of uniform temperature (eg. the laboratory space) a short distance away from the junctions that are maintained at the indicated temperatures. The state of affairs is schematically shown in Fig. 9. It is clear that the temperature varies significantly within a short distance from the measuring and reference junctions (the variation is determined by the thermal properties of the wire and the nature of the ambient) and comes to the ambient temperature. Recall that the thermoelectric effects (Peltier and Thomson) are confined to either the junctions or to the region along the wires that have a temperature variation along them. Those regions along the wire that are isothermal do not give rise to *any* thermoelectric effects. Hence it is possible to change the simple circuit shown in Fig. 8 to a practical circuit shown in Fig. 10.

In the practical circuit the thermocouple wires are long enough to see that the end away from the junctions is at the room temperature. Copper wires are used as shown in the largely isothermal region. Apart from the measuring and the reference junctions there are six more junctions that are formed!

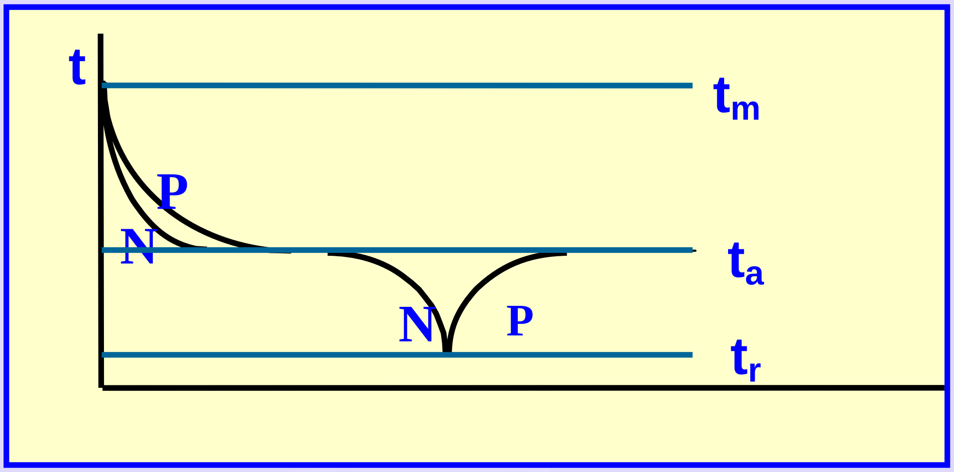


Figure 9 Temperature variations along the wires

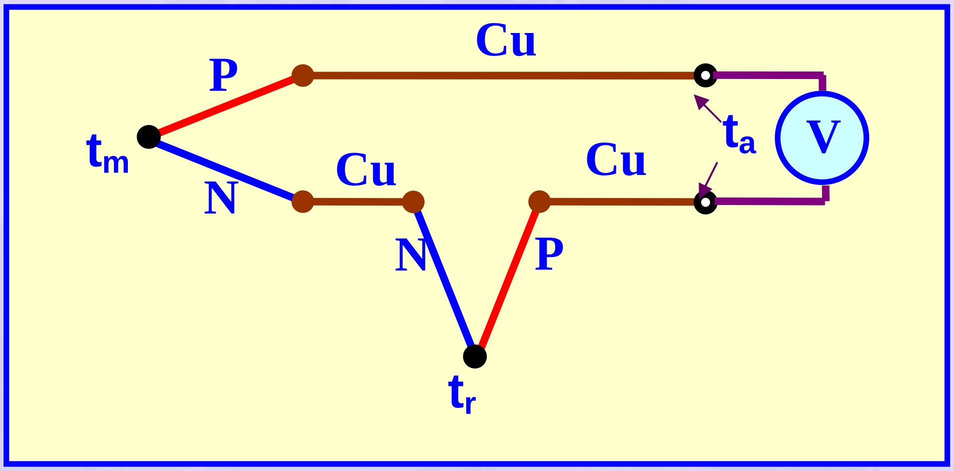


Figure 10 Practical thermocouple circuit

We shall now look at these junctions in the light of three laws of thermoelectric circuits that are discussed below.

Laws of thermoelectric circuits

I. Law of homogenous materials

A thermoelectric current cannot be sustained in a circuit of a single homogenous material however it varies in cross section by the application of heat alone

II. Law of intermediate materials

The algebraic sum of the thermoelectric forces in a circuit composed of any number of dissimilar materials is zero if all the junctions are at the same temperature

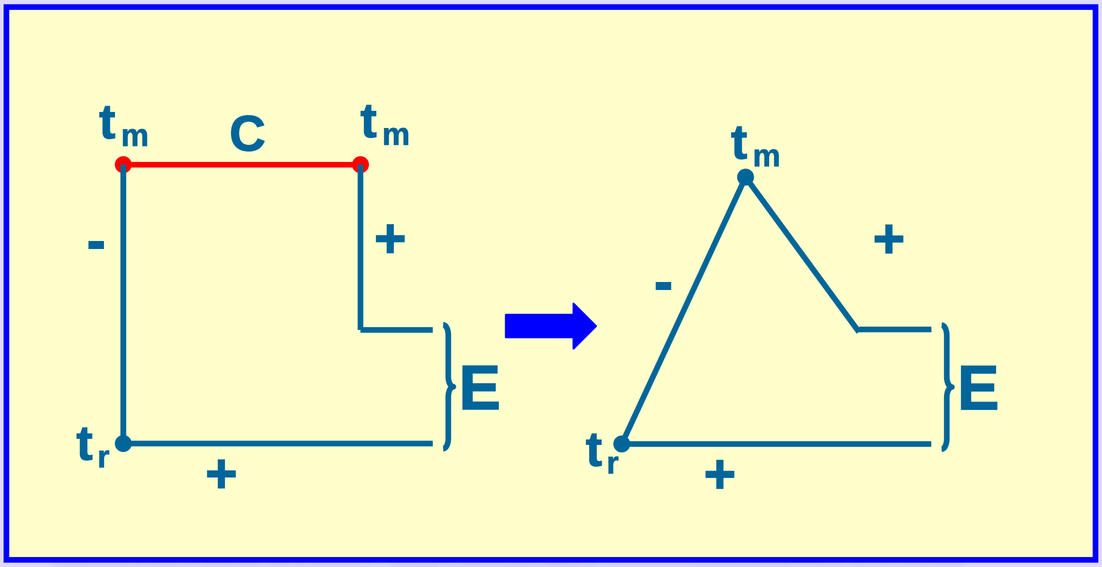


Figure 11 Explanation of the law of intermediate materials

The law is explained with reference to Fig. 11. The Seebeck emf E developed is independent of the fact that a third material C forms two junctions with the + and – materials as shown in the first part of Fig. 11. Since the material C is isothermal the situation is equivalent to a single measuring junction between the + and – materials as indicated in the latter part of the figure.

III. Law of successive or intermediate temperatures

This law is explained with reference to Fig. 12. **The Seebeck voltage is E_1 with the measuring junction at t_1 and the reference junction at t_2. The Seebeck voltage is E_2 with the measuring junction at t_2 and the reference junction at t_3. Then the Seebeck voltage is $E_3=E_1+E_2$ with the measuring junction at t_1 and the reference junction at t_3.** Utility of this law will be brought out later.

Now we get back to the practical thermocouple circuit shown in Fig. 10. The six extra junctions that are formed are all at a uniform temperature equal to the ambient temperature. The laws of thermoelectricity enunciated above guarantee that these do not have any effect on the Seebeck voltage developed by the thermocouple circuit. The copper wires are at room temperature (uniform temperature) and hence the law of intermediate materials asserts that the circuit is equivalent to one in which the copper wire is absent! In fact the temperature variations along the wires are as indicted in Fig. 13. The reason for the use of copper lead wires is to cut down on the cost of expensive thermocouple wires. Sometimes compensating lead wires are made use of. These are made of the same material as the thermocouple wires but not of the same high quality. They may also be made of cheaper alloys that have thermoelectric properties closely following the thermoelectric properties of the thermocouple wires themselves.

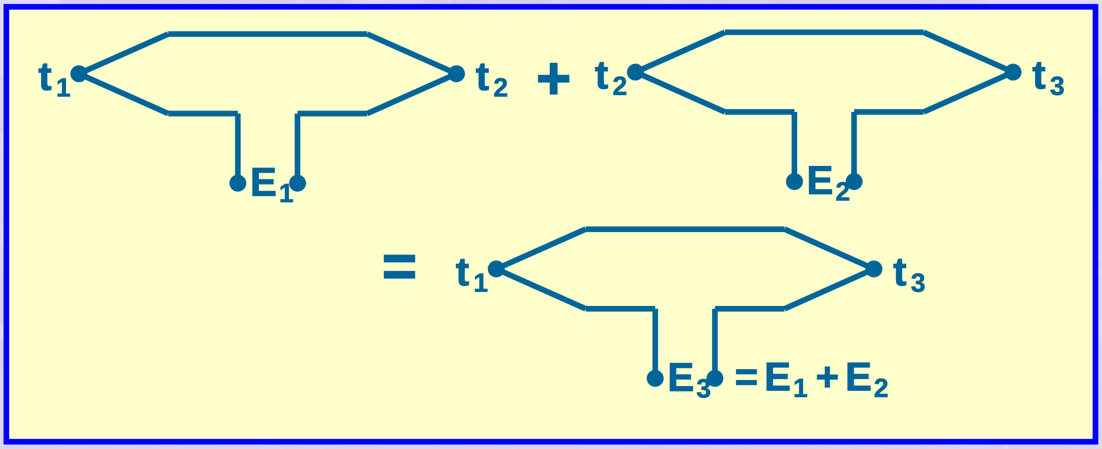


Figure 12 Explanation of the law of intermediate temperatures

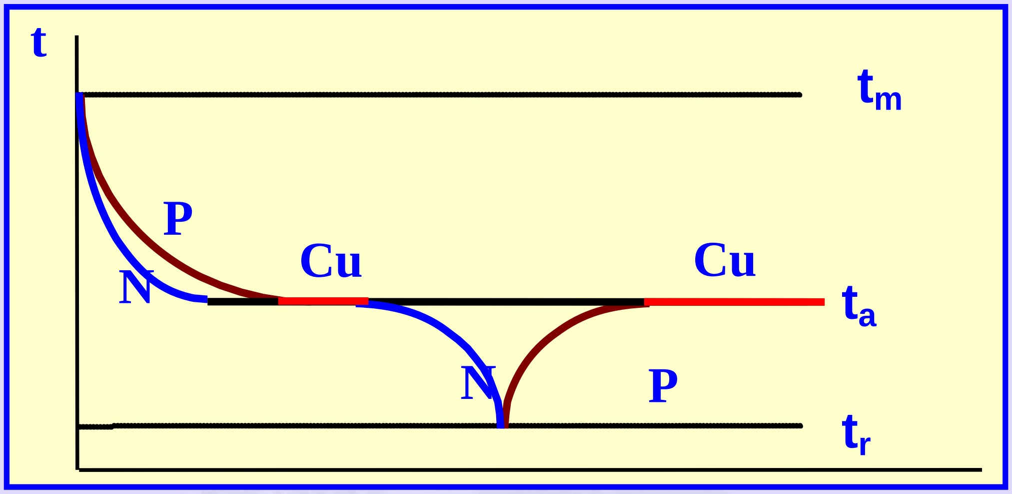


Figure 13 Temperature variations along the wires

Ice point reference

The measurement of temperature by the use of a thermocouple requires a reference junction maintained at the ice point. This is achieved in the laboratory by the use of an arrangement shown schematically in Fig. 14. Crushed ice water (as long as there is both ice and water the temperature remains fixed at the ice point) is placed in a well insulated enclosure with a lid. A test tube containing a conducting liquid is buried in the crushed ice water mixture as shown in the figure. The reference junction is placed in the test tube, immersed in the conducting liquid, s indicated. This arrangement maintains the reference junction within a few tenths of a degree of the ice point.

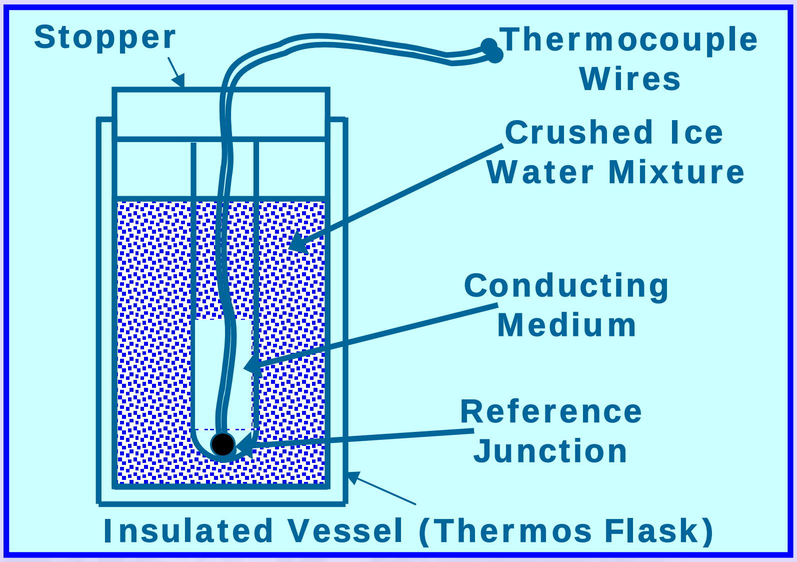


Figure 14 Ice point reference junction

It is seldom that individual ice point references are maintained while using several thermocouples for measuring temperatures at different points in an apparatus. The laws of thermoelectricity come to our help in designing a suitable arrangement with selector switch and a single ice point reference junction as shown in Fig. 15.

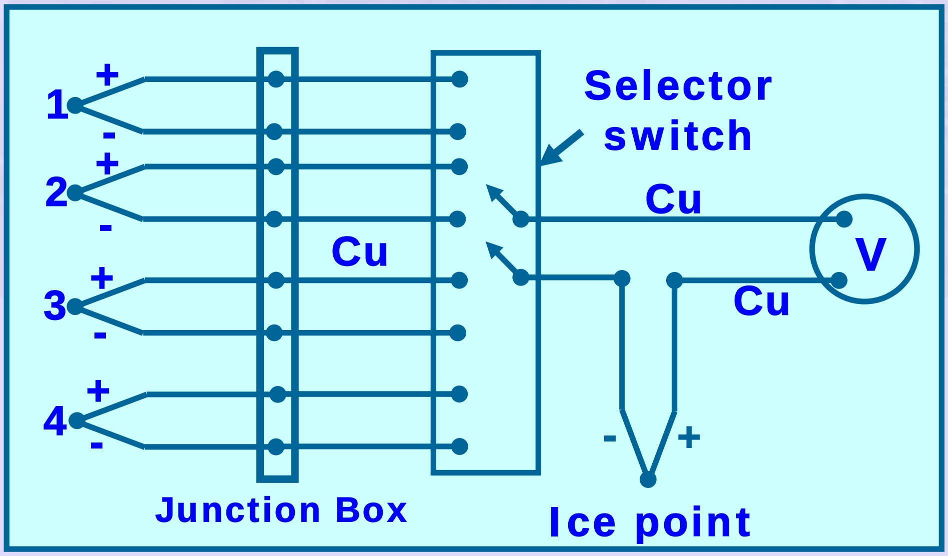


Figure 15 Many measuring junctions with a single reference junction

The switch is generally a rotary switch with gold plated contacts. Switches are available with a capacity of 8, 16 or 32 thermocouple connections. The switch is a double pole single throw type that will connect each thermocouple pair to complete the circuit with the voltmeter and the cold junction.

Use of thermocouple tables

Practical aspects of thermoelectric thermometry

Even though, in principle, one can use any two dissimilar materials as candidates for constructing thermocouples thermometry demands that there be standardization so that one may use with very little effort. Also no single thermoelectric thermometer can cover the wide range of temperatures met with in practice. The materials chosen must be available easily from manufacturers with guaranteed quality. In view of these only a few combinations of materials are made use of in day to day laboratory practice.

The common thermocouple materials are shown in Table 4. The entries in the table are such that all the materials that are below the one under consideration are negative with respect to it. This means that the thermoelectric power increases as the row count between two materials increases. The Seebeck voltages of materials are measured with respect to **Platinum 67** (the platinum standard used by the National Institute of Standards and Technology – NIST - USA) as the standard second element. The columns correspond to the usable temperature ranges for the materials. Several of the materials are alloys and they are sold under trade mark. Law of intermediate materials is invoked to combine the thermoelectric data of two materials that are individually measured with Platinum 67 as the reference material.

Table 4 Common thermocouple materials

100 ℃	*500 ℃*	*900 ℃*
Antimony	Chromel	Chromel
Chromel	Nichrome	Nichrome
Iron	Copper	Silver
Nichrome	Silver	Gold
Copper	Gold	Iron
Silver	Iron	$Pt_{90}Rh_{10}$
$Pt_{87}Rh_{13}$	$Pt_{90}Rh_{10}$	Pt
Pt	Pt	Cobalt
Palladium	Cobalt	Alumel
Cobalt	Palladium	Nickel
Alumel	Alumel	Palladium
Nickel	Nickel	Constantan
Constantan	Constantan	
Copel	Copel	
Bismuth		

Presumably Seebeck was experimenting with Antimony and Bismuth when he discovered thermoelectricity. It appears that he had hit upon materials with the largest thermoelectric power! If the candidate thermocouple material is positive with respect to Platinum 67 the Seebeck voltage will be positive across the candidate – Platinum 67 terminals. In general, if a candidate material is positive with respect to a second material the Seebeck voltage will be positive across the candidate and the second material terminals.

Table 5 Standard thermocouple types

Type	+ / - Wires	+/- Color
B	Pt94%Rh6% / Pt	Grey / Red
E	Chromel / Constantan	Purple / Red
J	Iron / Constantan	White / Red
K	Chromel / Alumel	Yellow / Red
R	Pt87%Rh13% / Pt	Black / Red
S	Pt90%Rh10% / Pt	Black / Red
T	Copper / Constantan	Blue / Red

Table 6 Typical thermocouple reference table

From: http://www.temperatures.com/tctables.html

	ITS90 Table for Type K thermocouples										
C	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
	Thermoelectric voltage in mV										
0	0	0.039	0.079	0.119	0.158	0.198	0.238	0.277	0.317	0.357	0.397
10	0.397	0.437	0.477	0.517	0.557	0.597	0.637	0.677	0.718	0.758	0.798
20	0.798	0.838	0.879	0.919	0.96	1	1.041	1.081	1.122	1.163	1.203
30	1.203	1.244	1.285	1.326	1.366	1.407	1.448	1.489	1.53	1.571	1.612
40	1.612	1.653	1.694	1.735	1.776	1.817	1.858	1.899	1.941	1.982	2.023
50	2.023	2.064	2.106	2.147	2.188	2.23	2.271	2.312	2.354	2.395	2.436
60	2.436	2.478	2.519	2.561	2.602	2.644	2.685	2.727	2.768	2.81	2.851
70	2.851	2.893	2.934	2.976	3.017	3.059	3.1	3.142	3.184	3.225	3.267
80	3.267	3.308	3.35	3.391	3.433	3.474	3.516	3.557	3.599	3.64	3.682
90	3.682	3.723	3.765	3.806	3.848	3.889	3.931	3.972	4.013	4.055	4.096
100	4.096	4.138	4.179	4.22	4.262	4.303	4.344	4.385	4.427	4.468	4.509
110	4.509	4.55	4.591	4.633	4.674	4.715	4.756	4.797	4.838	4.879	4.92
120	4.92	4.961	5.002	5.043	5.084	5.124	5.165	5.206	5.247	5.288	5.328
130	5.328	5.369	5.41	5.45	5.491	5.532	5.572	5.613	5.653	5.694	5.735
140	5.735	5.775	5.815	5.856	5.896	5.937	5.977	6.017	6.058	6.098	6.138

Not all combinations of materials given in Table 4 are used in practice. A small number of them (Table 5) are used and are available from reputed manufacturers. Also the thermoelectric data are available in the form of tables for each of these. As an example Table 6 shows an excerpt of the table appropriate for K type (Chromel is the positive element and Alumel is the negative element) thermocouple. The table assumes that the reference junction is maintained at the ice point.

Some interesting things may be noted by examining the table. The Seebeck coefficient for K type thermocouple is approximately 40 μV/°C. If we use a voltmeter that can resolve 0.01 mV or 10 μV the temperature resolution is about 0.25°C! Even this is in not achieved in practice. Voltmeters capable of such high resolution are expensive and hence it is not possible to achieve sub degree resolution levels in ordinary laboratory practice. The accuracy limits that are possible to achieve are given in Table 7 for various thermocouple pairs.

Table 7 Accuracy and range values of some thermocouple sensors

Thermocouple	Full range °C	Accuracy °C or %	Range °C ISA* standard limits
Chromel Alumel, K Type	-185 to 1371	±2°C ±0.75%	-18 to 277 277 to 1371
Iron – Constantan, J Type	-190 to 760	±2°C ±0.75%	-18 to 277 277 to 760
Copper – Constantan, T Type	-190 to 400	±2% ±0.8°C ±0.75%	-190 to –60 -60 to 93 93 to 370
$Pt_{90}Rh_{10}$-Pt, S Type	0 to 1760	±2.8°C ±0.5%	0 to 538 538 to 1482
W – $W_{74}Rh_{26}$ $W_{95}Rh_5$-$W_{74}Rh_{26}$	0 to 2870	±4.5°C ±1%	0 to 427 427 to 2870

*ISA stands for Instrument Society of America

Note that Tungsten - Tungsten Rhenium thermocouples (special but expensive thermocouples) are useful for the measurement of very high temperatures normally inaccessible to other thermocouples. However the accuracy limits are not as good as for the other thermocouples

The useful ranges of thermocouples are determined, (a) by the thermoelectric behavior and (b) by the physical properties of the wire materials, as the temperature is changed. At elevated temperatures the integrity of the thermocouple wire materials as well as the junction is important. The materials of the wires are also prone to thermal fatigue when the junctions are subjected to thermal cycling during use. In view of the fact that the materials near the junctions experience these thermal cycles it is possible to discard a small length close to the junction and remake a junction for subsequent use. Materials also age during use and may have to be discarded if the thermoelectric properties change excessively during use.

To round of this discussion we present (Fig. 16) the thermoelectric output of a K type thermocouple over the range of its usefulness. We notice that over an extended range the output is non-linear. Note that this pair of materials is far apart in Table 1. Hence the thermoelectric power is very large and next only to J type (Iron – Constantan) thermocouple. The sensitivity also compares favorably with T type (Copper – Constantan) thermocouple. Even though these three types have high sensitivity the ranges are different. K type has the widest range among these three types. Both K type and T type thermocouples are commonly used in laboratory and industrial applications. Iron is prone to corrosion and hence is of limited use.

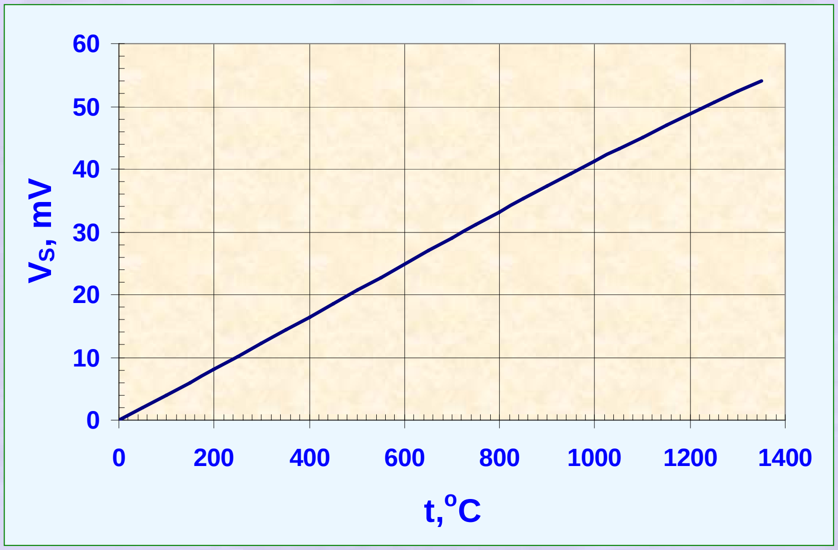


Figure 16 Seebeck volts – temperature relationship for K type thermocouple

Insulation systems

Thermocouples are made with wires of various diameters according to requirement. The P and N wires are expected to not contact each other (electrically) excepting at the junctions. Hence it is necessary to cover the wire with an electrical insulator. It is normal for the P and N wires to be individually covered with insulation, the two wires laid parallel to each other and covered with an outer sheath encasing both the wires. The insulation material is chosen with the temperature range in mind. A list of insulation materials along with the useful range of temperatures is given in Table 8.

Table 8 Thermocouple insulation systems

Insulation	Temperature limits ^oC
Nylon	-40 to 160
PVC	-40 to 105
Enamel	Up to 107
Cotton over enamel	Up to 107
Silicone rubber over Fiberglass	-40 to 232
Teflon and Fiberglass	-120 to 250
Asbestos	-78 to 650
Tempered Fiberglass	Up to 650
Refrasil®	Up to 1083

Sometimes the thermocouple is protected from mechanical damage by a protective tube. The protective tube material is again chosen based on the temperature range and the ruggedness desired.

Table 9 Ceramic protecting tube materials

Material	Composition	Max. Temp.^oC
Quatrtz	Fused Silica	1260
Siliramic®	Silica-Alumina	1650
Durax®	Silicon Carbide	1650
Refrax®	Silicon Nitride Bonded Silicon Carbide	1735
Alumina	99% Pure	1870

Some of the materials shown in tables 8 and 9 are proprietary in nature and are identified by the trade name. Some times the protective tube material may be made of metal like stainless steel. Since metals are good conductors of electricity the insulation of the individual wires must be adequate to avoid any electrical contact with the protective metal tube.

Thermocouple junctions

Thermocouple junctions may be formed by various means. The most common method is to weld or fuse the two materials to form a junction. Welding is commonly made by twisting the two wires for a short length, passing a high current through the junction by discharging a capacitor charged to a high voltage. The momentary high current will heat the junction (due to contact resistance) to a high temperature at which the two metals fuse together to form a nice bead. The entire process may be accomplished in an inert atmosphere to avoid any oxidation of the wires. The junctions may be various types as shown schematically in Figs. 17 and 18.

Figure 17 Types of Thermocouple junctions

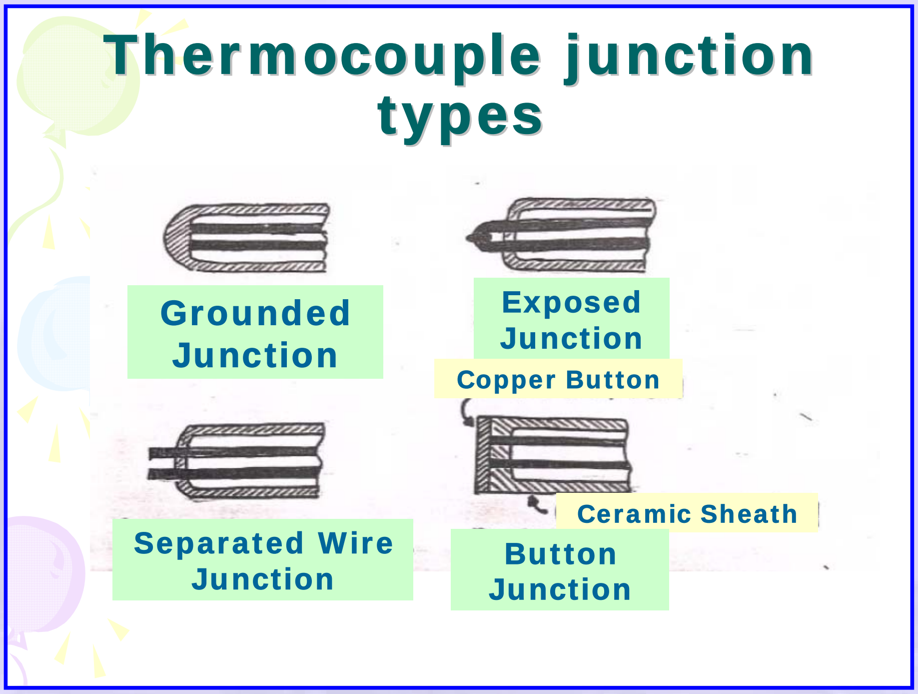
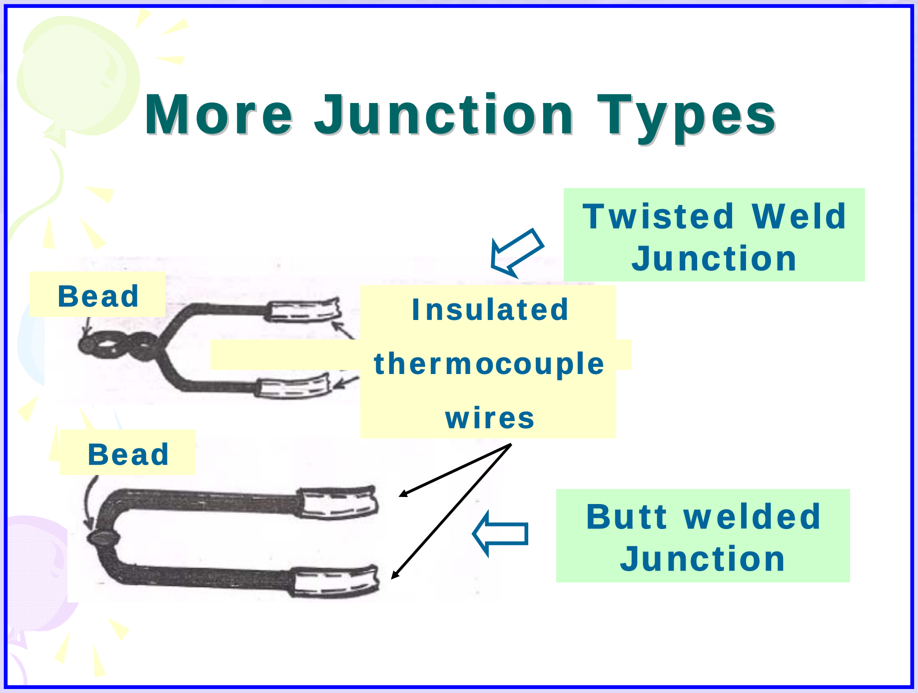


Figure18 More Junction Types



Grounded junction: Such a junction is used (Fig. 17) if one wants avoid direct contact between the thermocouple bead and the process fluid. The protective tube provides a barrier between the junction and the process fluid. This type of arrangement increases the response time of the thermocouple when measuring temperature transients.

Exposed junction: This arrangement (Fig. 17) is acceptable if the process space does not adversely affect the thermocouple materials. This type of arrangement decreases the response time of the thermocouple when measuring temperature transients.

Separated wire junction: The two wires are allowed to float within the process space as shown in Fig. 17. The process fluid (molten metal in metallurgical applications) provides the electrical connection between the P and N wires.

Button junction: The P and N wires are attached to a copper (high conductivity material) button such that the thermal contact between the process fluid (may be gas like air) and the junction is enhanced. This is beneficial from the response time point of view as well as from the thermometric error point of view (as we shall see later).

Junctions may be made by twisting the P and N wires together. Twisting action itself cold works the two materials to form good contact. In addition the two wires may also be welded as shown in Fig. 18. The junction may also be formed by butt welding the two wires as shown in Fig. 18.

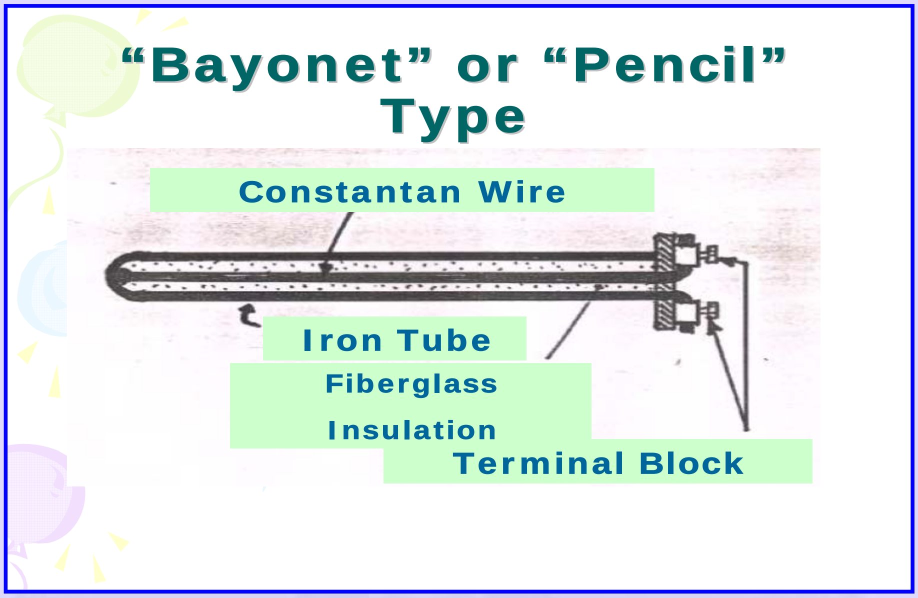


Figure 19 Bayonet or pencil type of thermocouple probe

Sometimes a thermocouple probe is constructed in the form of a bayonet or pencil as indicated in Fig. 19. The figure shows a J type thermocouple probe with the protective tube of Iron (P type material) and a wire of constantan (N type material) attached to the bottom of the tube with fiberglass insulation between the two. The connections to the external circuit are made through terminal blocks.

Thermocouples in series and parallel

Differential thermocouple:

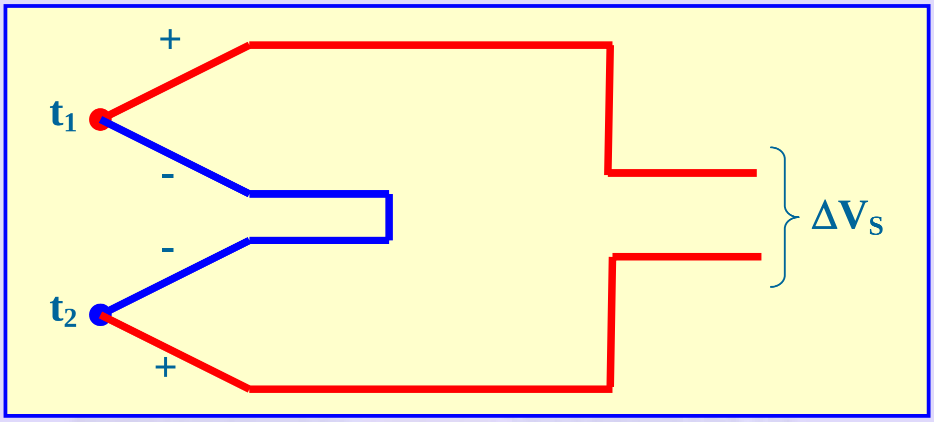


Figure 20 Differential thermocouple for the direct measurement of temperature difference

Thermocouples may be used in other ways than the ones described earlier. The temperature difference between two locations in a process may be obtained by measuring the two temperatures individually using two separate thermocouples and then taking the difference. The errors involved in each such measurement will propagate and give an overall error that may be unacceptable in practice. A way out of this is to use the differential thermocouple (this is just the basic thermocouple circuit with the hot and cold junctions at different temperatures!) and measure the temperature difference directly once ΔV_S is measured. In applications where the temperature difference to be measured is small, we obtain the temperature difference directly as $\Delta t = \frac{\Delta V_S}{\alpha_S}$ where a constant value of α_S appropriate to the chosen thermocouple pair may be used. It is even possible to amplify the output using a high gain low noise amplifier to improve the measurement process.

The differential thermocouple arrangement may also be used as a calibration arrangement. If $t_1 = t_2$, the differential thermocouple should give zero voltage output, if the two thermocouples are of the same type and behave alike. If we choose one of the thermocouples to be a standard calibrated one, the other the thermocouple is one to be calibrated, and both are of the same type it is easy to arrange both the junctions to be subjected to the same temperature. The non-zero output, if any, gives the error of one thermocouple against the other. The temperature itself may be measured independently using a standard thermocouple so that we can have a calibration chart giving the thermocouple error as a function of temperature.

The amplification may also be accomplished by using several junctions in series as shown in Fig. 21. This arrangement is referred as a thermopile and produces an output that is n times the value with a single differential thermocouple where n is the total number of hot or cold junctions. In the example shown the thermopile is being used as a radiation flux sensor. The shading ring prevents illumination of the cold junctions and thus produces a number of differential thermocouples in series.

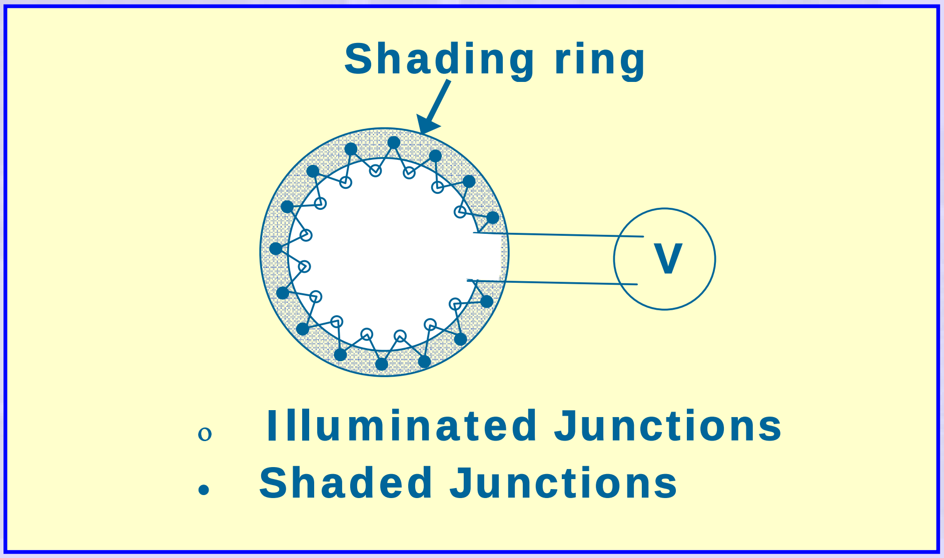


Figure 21 Several differential thermocouples in series forming a thermopile

Thermocouples in parallel:

In practice we may require the average temperature in a region where the temperature may vary. One way of doing this would be to measure all the temperatures individually with separate thermocouples and then take the mean. However, it is possible to measure the mean value directly using several thermocouples connected in parallel as shown in Fig. 22. The thermoelectric output corresponding to the junctions are as indicated in the figure and these correspond to the respective measuring junction temperatures. Assuming that all the thermocouples are identical, the output voltage is given by

$$V_0 = \frac{V_1 + V_2 + V_3}{3} \quad (1)$$

Thus the inferred temperature is the mean of the measuring junction temperatures. The accurate averaging of the Seebeck voltages relies on each thermocouple's wire resistances being equal. If this is difficult to achieve one may use equal but large (large compared to the resistance of the thermocouple wires) "swamping" resistance in each circuit to alleviate the problem. This is indicated in Fig. 23.

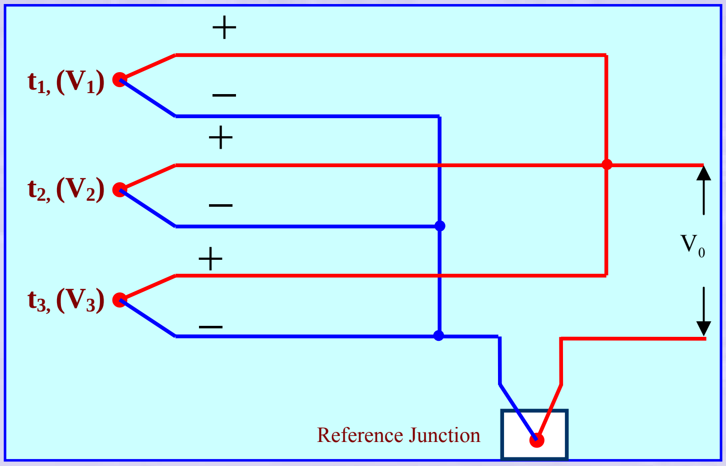


Figure 22 Thermocouples connected in parallel

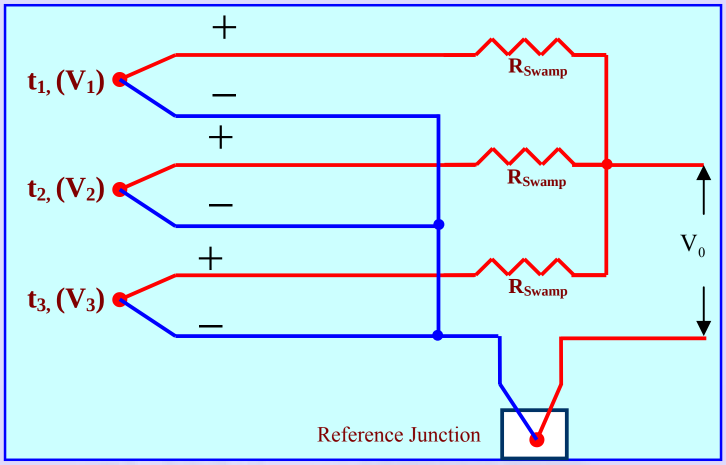
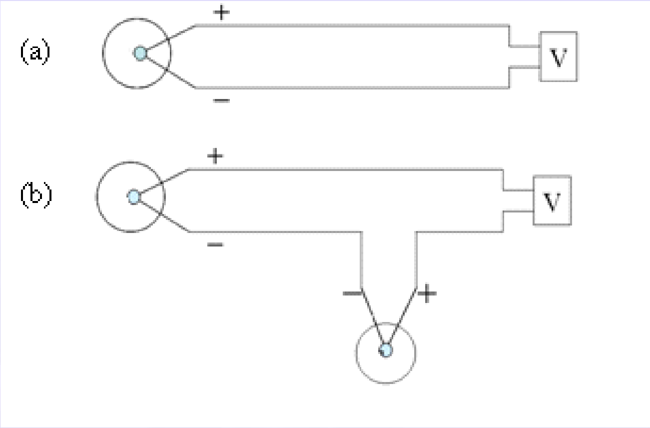


Figure 23 Thermocouples connected in parallel and with “Swamp” resistances

Example 4

➢ *A K type thermocouple is used as shown in Fig. (a) without a reference junction. The terminals of the voltmeter are at room temperature of 30°C while the measuring junction is at 100°C. What is the voltmeter*



reading? What would have been the reading had it been connected as shown in Fig. (b)?

- *Circuit as in (a):*

  The conditions are $t_m = 100°C,\ t_{ref} = 30°C$

  From the K type thermocouple table we read off the following:

  $$(\text{Seebeck volts with } t_m = 100°C, t_{ref} = 0°C) = 4.095\,\text{mV}$$

  $$(\text{Seebeck volts with } t_m = 30°C, t_{ref} = 0°C) = 1.203\ \text{mV}$$

  Hence the voltmeter reading is (using the law of successive temperatures)

  $$\begin{aligned} V &= (\text{Seebeck volts with } t_m = 100°C, t_{ref} = 0°C) \\ &\quad - (\text{Seebeck volts with } t_m = 30°C, t_{ref} = 0°C) \\ &= 4.095 - 1.203 = 2.892\,\text{mV} \end{aligned}$$

- *Circuit as in (b):*

  The conditions are $t_m = 100°C,\ t_{ref} = 0°C$

  From the K type thermocouple table we read off the following:

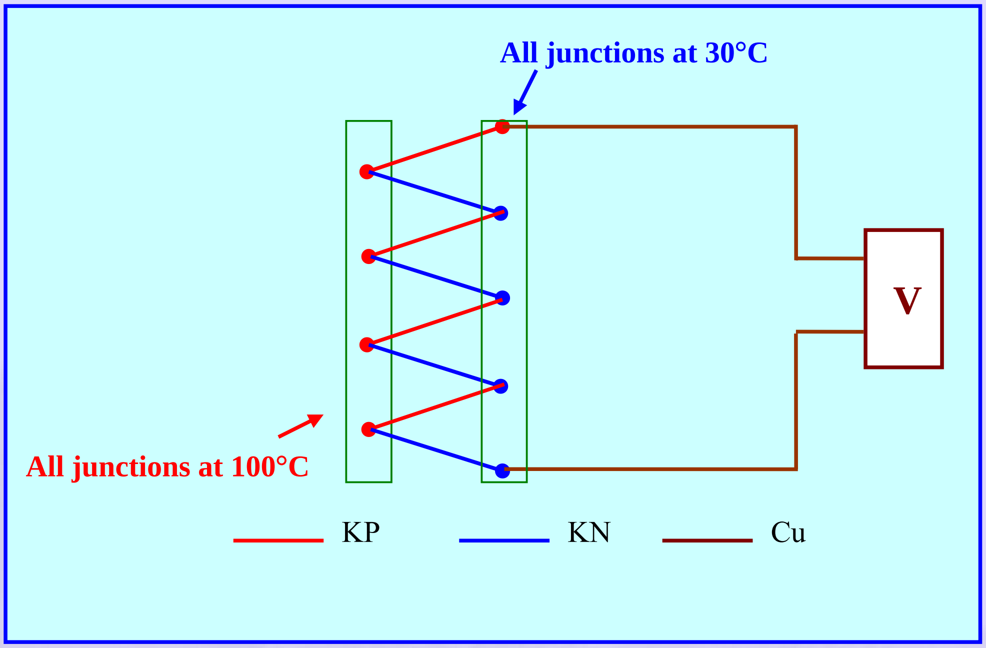
  $$(\text{Seebeck volts with } t_m = 100°C, t_{ref} = 0°C) = 4.095\,\text{mV}$$

  Hence the voltmeter reading is

$$V = (\text{Seebeck volts with } t_m = 100°C, t_{ref} = 0°C)$$
$$= 4.095 \text{ mV}$$

Example 5

➢ *Consider the thermopile arrangement shown in the figure. What will be the output voltage?*



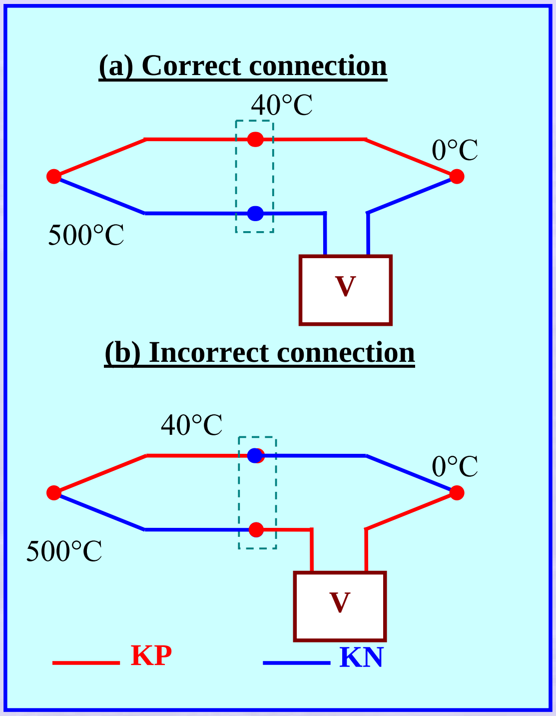
o *Three materials are used in the circuit. KP and KN at the measuring temperature of 100°C form four junctions. There are three cold junctions between KN and KP at 30°C. There is one junction each between KP – Cu and KN – Cu. Since these two junctions are at the same temperature, the law of intermediate temperatures says that these two junctions are equivalent to a single junction between KN and KP at 30°C. Thus effectively there are four cold junctions.*

o *Thus the voltage indicated will be four times that due to a measuring junction at 100°C and a reference junction at 30°C. By the law of intermediate temperatures, we thus have:*

$$
\begin{aligned}
V &= 4\times\left[\text{Seebeck between }100^\circ\text{C and }30^\circ\text{C}\right]\\
&= 4\times\begin{bmatrix}\left(\text{Seebeck between }100^\circ\text{C and }0^\circ\text{C}\right)\\ -\left(\text{Seebeck between }30^\circ\text{C and }0^\circ\text{C}\right)\end{bmatrix}\\
&= 4\times\left(4.095-1.203\right)=4\times 2.892=11.568\text{ mV}
\end{aligned}
$$

Example 6

- *The extension wires of K type thermocouple were interchanged by oversight. The actual temperatures were:*
- *Measuring junction* $t_m = 500°C$; *Reference junction* $t_{ref} = 0°C$;
- *Junction between thermocouple wires and extension wires* $t_j = 40°C$.
- *What is the consequence of this error?*



- *Figures indicate the correct and incorrect arrangements for this measurement. The temperatures are also marked in the figures.*
- *Correct arrangement:*
- *In this case the junctions between the thermocouple and lead wires do not play any role! The voltmeter reading will be (using K type thermocouple tables)*

$$V = \text{Seebeck voltage of K type thermocouple at } 500°C$$
$$= 20.640 \text{ mV}$$

- *(b) Incorrect arrangement:*
-

- *In this case there are effectively four junctions. The net voltage indicated is given by*

$$V = V_{500°C} - V_{40°C} + V_{0°C} - V_{40°C}$$

- *The notation used is*

$V_{t°C}$ = Seebeck voltage with measuring junction at t°C and reference junction at 0°C

- *Using K type thermocouple tables we get*

$$V = 20.640 - 1.611 + 0 - 1.611 = 17.418 \text{ mV}$$

- *If one were to convert this to a temperature based on the assumption that the measuring junction and reference junction are correctly connected, the temperature would be (using K type thermocouple tables)* $t = 424.2°C$. *Thus the consequence of the mistake is that the temperature is underestimated by 74.8°C.*