4.1. Thermo-EMF Generation Characteristics of Classical Thermocouples

The classical thermocouples, Iron-Constantan, Constantan-Nichrome, Copper-Iron, Copper-Nichrome, Iron-Nichrome (easily available and cheap thermoelectric materials) are studied for the generation of thermo emf in the temperature range of 330°C. There are three modes of investigation on thermo emf generation, first is the normal mode (free from any applied parameter), second is for the applied magnetic field of different magnitudes in the parallel and perpendicular orientations and the third one is the mode of applied electric field that is also in the parallel and perpendicular orientations. The mechanical stress is also applied (by putting mechanical load from 100 gm to 500 gm) to investigate its effects on the phonon interactions which in fact affect the thermal conductivity and hence the thermoelectric properties.

The thermo emf generation is represented by the graphical data in the entire temperature range. This can be easily verified that how the generation characteristics are being affected by the applied electric and magnetic fields. To evaluate the energy conversion characteristics, the maximum thermo emf values (corresponding to the maximum temperature gradient) of normal mode are compared with all the other modes. The physical parameters of all the classical thermoelectric materials are measured for the investigation of their thermoelectric behavior.
Table 4.1 Experimental Parameters of the Selected Thermoelectric Materials

<table>
<thead>
<tr>
<th>Nr.</th>
<th>Parameter</th>
<th>Copper</th>
<th>Iron</th>
<th>Constantan</th>
<th>Nichrome</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Resistance (Ohm)</td>
<td>0.1918</td>
<td>0.7062</td>
<td>0.5174</td>
<td>1.6874</td>
</tr>
<tr>
<td>2.</td>
<td>Area of Cross-Section (m²)</td>
<td>1.51x10⁻⁶</td>
<td>9.5x10⁻⁷</td>
<td>1.12x10⁻⁶</td>
<td>9.7x10⁻⁷</td>
</tr>
<tr>
<td>3.</td>
<td>Length (m)</td>
<td>48x10⁻²</td>
<td>48x10⁻²</td>
<td>48x10⁻²</td>
<td>48x10⁻²</td>
</tr>
<tr>
<td>4.</td>
<td>Resistivity ρ (Ohm·m)</td>
<td>6x10⁻⁶</td>
<td>1.4x10⁻⁶</td>
<td>1.2x10⁻⁶</td>
<td>3.41x10⁻⁶</td>
</tr>
<tr>
<td>5.</td>
<td>Electrical Conductivity σ (Sm⁻¹)</td>
<td>1.67x10⁶</td>
<td>7.143x10⁵</td>
<td>8.33x10³</td>
<td>2.933x10³</td>
</tr>
</tbody>
</table>

4.1.1 Generation of Thermo EMF for Classical Thermocouples in the Normal Mode

The order of thermocouples for the generation of thermo emf in the normal mode is Iron-Constantan > Constantan-Nichrome > Copper-Iron > Copper-Nichrome > Iron-Nichrome. This can be viewed from Figure 4.1.1 that the maximum generation of thermo emf is for the thermocouple Fe-Constantan, that is 1.7 mV at the maximum temperature gradient of 330°C where as the other thermocouples limited only to 0.9 mV (Constantan-Nichrome), 0.2 mV (Copper-Iron) and 0.1 mV (Iron-Nichrome). The rest of two thermocouples, Fe-Nichrome and Copper-Nichrome almost generate very small and same thermo emf along the entire temperature range.
Figure 4.1.1 Generation of thermo emf by the classical thermocouples in the normal mode

4.1.2. Generation of Thermo EMF under the Effect of Magnetic Field

This is discussed for all the five classical thermocouples under the three different magnitudes of applied magnetic field (260 gauss, 360 gauss, and 460 gauss) in the temperature range of 330°C. This effect is analyzed in the different orientations (parallel and perpendicular) and finally compared with the performance of their normal mode thermo emf generation.
Parallel Magnetic Field

The parallel magnetic field is applied by an electromagnet; the Figure 4.1.2 shows the variation of applied magnetic field along the length of the thermocouple.

Figure 4.1.2 Variation of strength of magnetic field with the length of Classical thermocouple in parallel orientation

Magnetic Field 260 gauss

The magnitudes of thermo emf generation for all the classical thermocouples are different under the effect of applied magnetic field than that of the normal mode in the same temperature range. The best thermo generator element in this mode (Parallel Magnetic Field of 260 gauss) is Constantan-Nichrome whereas in the normal mode it is
Iron-Constantan thermocouple. The exact order of thermo emf generation is Constantan-Nichrome > Fe-Nichrome > Copper-Fe > Fe-Nichrome > Copper-Nichrome. The maximum thermo emf is 2.3 mV that is generated for the Constantan-Nichrome thermocouple at the temperature gradient of 330°C whereas it generates only 0.9 mV at the same temperature gradient in the normal mode. The thermo emf generations for the other thermocouples also enhanced to several orders as compared with their normal mode performance (Figure 4.1.3).

![Thermo emf generation by the classical thermocouples in the parallel magnetic field of strength 260 gauss](image)

Figure 4.1.3 Thermo emf generation by the classical thermocouples in the parallel magnetic field of strength 260 gauss
Magnetic Field 360 gauss

When the magnitude of magnetic field is increased to 360 gauss for the same orientation (parallel orientation), the thermo emf generation for all the thermocouples again differ than the normal mode and also than the magnetic field of 260 gauss. The maximum thermo emf is 4.3 mV for the Fe-Constantan thermocouple for the maximum temperature gradient. The minimum thermo emf is about same (0.1 mV) for all the five thermocouples. The exact order towards maximum thermo emf generation is Fe-Constantan > Constantan-Nichrome > Cu-Fe > Cu-Nichrome and Fe-Nichrome in the entire temperature range (Figure 4.1.4).

Figure 4.1.4 Variation of thermo emf by the classical thermocouples in the parallel magnetic field mode of strength 360 gauss
Magnetic Field 460 gauss

In the parallel mode of 460 gauss magnetic field the Fe-Constantan thermocouple approaches only to 2.7 mV thermo emf at the maximum temperature gradient of 330°C where as it was 4.3 mV for the parallel magnetic field of 360 guass. The other thermocouples generate almost same magnitude of thermo emf as in the parallel mode of 360 guass in the entire temperature range. This means the effect of magnetic field is more distinct in case of Fe-Constantan thermocouple only (Figure 4.1.5).

![Graph showing generation of thermo emf by the classical thermocouples in the parallel magnetic field mode of applied strength 460 gauss](image)

Figure 4.1.5 Generation of thermo emf by the classical thermocouples in the parallel magnetic field mode of applied strength 460 gauss

Above figures make a comparison of thermo emf generation characteristics for all the considered classical thermocouples in the normal mode with the parallel magnetic
field mode. This can be easily observed that the Fe-Constantan can be regarded as the best energy generator element not only in the normal mode but also in the parallel magnetic field mode. However, there is the enhancement in thermo emf values corresponding to all the thermocouples in the entire temperature range. The effect of applied parallel magnetic field can be compared from the Table 4.1.1.

Table: 4.1.1 Comparison of Maximum Thermo EMF for Classical Thermocouples in the Normal Mode and Parallel Magnetic Field Mode

<table>
<thead>
<tr>
<th>Sr.</th>
<th>Thermocouple</th>
<th>Thermo EMF in Normal Mode</th>
<th>Thermo EMF in Parallel Magnetic Field</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>260 gauss</td>
</tr>
<tr>
<td>1.</td>
<td>Fe-Constantan</td>
<td>1.8 mV</td>
<td>1.3 mV</td>
</tr>
<tr>
<td>2.</td>
<td>Constantan-Nichrome</td>
<td>1 mV</td>
<td>2.3 mV</td>
</tr>
<tr>
<td>3.</td>
<td>Fe-Cu</td>
<td>0.2 mV</td>
<td>0.8 mV</td>
</tr>
<tr>
<td>4.</td>
<td>Cu-Nichrome</td>
<td>0.1 mV</td>
<td>0.3 mV</td>
</tr>
<tr>
<td>5.</td>
<td>Fe-Nichrome</td>
<td>0.1 mV</td>
<td>0.3 mV</td>
</tr>
</tbody>
</table>

**Perpendicular Magnetic Field**

Similar to that of the parallel magnetic field mode, the same strengths of magnetic field (260 gauss, 360 gauss, and 460 gauss) are employed in the perpendicular orientation. Figure 4.1.6 shows the variation of magnetic field along the length of the thermocouple.
Figure 4.1.6 Variation of strength of magnetic field with the length of classical thermocouple in perpendicular orientation

**Magnetic Field 260 gauss**

In this mode of perpendicular magnetic field there is only Nichrome-Constantan thermocouple for which the generation of thermo emf approaches to 3.4 mV for the maximum temperature gradient of $330^\circ$C. The generation of the maximum thermo emf is 0.7 mV, 0.4 mV, 0.3 mV and 0.3 mV for the Fe-Constantan, Copper-Iron, Fe-Nichrome and Copper-Nichrome thermocouples respectively for the temperature gradient of $330^\circ$C (Figure 4.1.7).
Figure 4.1.7 Classical thermocouples in the perpendicular magnetic field of strength 260 gauss in the generation of thermo emf

Magnetic Field 360 gauss

In the perpendicular mode magnetic field of 360 gauss, the maximum thermo emf magnitude is of about 3.7 mV for the Nichrome-Constantan thermocouple. The thermo emf generation for all the other thermocouples is 3.2 mV, 0.3 mV, 0.2 mV and 0.1 mV for Fe-Constantan, Fe-Nichrome, Cu-Nichrome and Cu-Fe thermocouples, respectively at the maximum temperature gradient of 330°C (Figure 4.1.8).
Figure 4.1.8 Generation of thermo emf by the classical thermocouples in the perpendicular magnetic field mode of strength 360 gauss

**Magnetic Field 460 gauss**

Figure 4.1.9 shows the results for the maximum applied magnetic field (460 gauss) in the perpendicular orientation in which the Copper-Iron thermocouple can be considered as the best thermo generator element that generates about 9.8 mV thermo emf at the temperature difference of 150°C with a parabolic behavior. The other thermocouples approaches only to 8.8 mV (Cu-Nichrome), 3 mV (Nichrome-Constantan), 0.3 mV (Fe-Constantan) and 0.2 mV (Fe-Nichrome) corresponding to the maximum temperature gradient of 330°C.
Figure 4.1.9 Variation of thermo emf for the classical thermocouples in the perpendicular magnetic field mode of applied strength 460 gauss

Further, the comparison of thermo emf generation in the normal mode and under the perpendicular magnetic field mode shows that (Table 4.1.2) the Constantan-Nichrome thermocouple is the best energy generator element, where as in the parallel magnetic field the Fe-Constantan has appeared as the best thermo element. However, there are the variations in thermo emf magnitudes among all the thermocouples than the normal mode as well as the parallel magnetic field mode.
Table 4.1.2 Comparison of Maximum Thermo EMF for the Classical Thermocouples in the Normal Mode and Perpendicular Magnetic Field

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Thermocouple</th>
<th>Thermo EMF in Normal Mode</th>
<th>Thermo EMF in Perpendicular Magnetic Field</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>260 gauss</td>
</tr>
<tr>
<td>1.</td>
<td>Fe-Constantan</td>
<td>1.8 mV</td>
<td>0.6 mV</td>
</tr>
<tr>
<td>2.</td>
<td>Constantan-Nichrome</td>
<td>1 mV</td>
<td>3.4 mV</td>
</tr>
<tr>
<td>3.</td>
<td>Fe-Cu</td>
<td>0.2 mV</td>
<td>0.6 mV</td>
</tr>
<tr>
<td>4.</td>
<td>Cu-Nichrome</td>
<td>0.1 mV</td>
<td>0.2 mV</td>
</tr>
<tr>
<td>5.</td>
<td>Fe-Nichrome</td>
<td>0.1 mV</td>
<td>0.3 mV</td>
</tr>
</tbody>
</table>

4.1.3. Generation of Thermo EMF under the Effect of Electric Field

Similar to that of the applied magnetic field, all the thermocouples are investigated for the generation of thermo emf in the temperature range of 330°C under the effect of applied electric field. The electric field is applied by the potential difference of 4V, 8V and 12V both in the parallel and perpendicular orientations and the corresponding electric field strength is given in Table 4.1.3.

Table 4.1.3 Strength of Applied Electric Field in Parallel and Perpendicular Modes for Common Thermoelectric Materials

<table>
<thead>
<tr>
<th>Parallel Electric Field (Vm⁻¹)</th>
<th>Perpendicular Electric Field (Vm⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 V</td>
<td>8 V</td>
</tr>
<tr>
<td>8.33</td>
<td>16.67</td>
</tr>
<tr>
<td>16.67</td>
<td>25</td>
</tr>
<tr>
<td>16.67</td>
<td>33.33</td>
</tr>
<tr>
<td>50</td>
<td>12 V</td>
</tr>
</tbody>
</table>
Parallel Electric Field Equivalent of 4 V

This is the mode of applied electric field of magnitude 8.33 Vm\(^{-1}\) and the exact order of thermo emf generation is: Fe-Constantan > Nichrome-Constantan > Fe-Cu > Fe-Nichrome > Cu-Nichrome. The best thermocouple again found to be Fe-Constantan for which the generation of thermo emf is maximum than all the others in the entire temperature range. For this thermocouple (Fe-Constantan) the maximum thermo emf is 8.3 mV where as the second rank thermocouple (Nichrome-Constantan) limits only to 5 mV thermo emf at the same temperature gradient of 330\(^0\)C. However, the Nichrome-Constantan thermocouple shows a sudden decrease in thermo emf magnitude from 20\(^0\)C to 100\(^0\)C temperature gradient, but again increases with increase in temperature of the hot junction.

Figure 4.1.10 Various classical thermocouples in the generation of thermo emf in the influence of the parallel electric field for a potential difference 4 V
Parallel Electric Field Equivalent of 8 V

The equivalent applied electric filed corresponding to applied potential difference of 8 V is 16.67 Vm\(^{-1}\). With the increase in strength of applied electric field from 4 V to 8 V, the Fe-Constantan thermocouple again generates maximum thermo emf (about 8.3 mV) at the maximum temperature gradient. The other thermocouples almost lie in the same range of thermo emf generation as with the 4 V potential difference parallel electric field.

![Figure 4.1.11 Thermo emf generation for the classical thermocouples in the parallel electric field of potential difference 8 V](image-url)

Figure 4.1.11 Thermo emf generation for the classical thermocouples in the parallel electric field of potential difference 8 V
Parallel Electric Field Equivalent of 12 V

This is the case of applied electric field of 25 Vm\(^{-1}\) in the parallel orientation. The two thermocouples, Nichrome-Constantan and Fe-Constantan show a sudden change in the magnitude of thermo emf generation with the increase in strength of electric field from 8 V to 12 V for the same parallel orientation. This is 9 mV and 5 mV for the thermocouples Fe-Constantan and Nichrome-Constantan respectively at the maximum temperature gradient. However, all the other thermocouples are limited only to 0.1 - 0.3 mV for the same temperature. Hence, it is clear that only two thermo couples, Fe-Constantan and Nichrome-Constantan can be considered as the better thermo generator elements compared to all other combinations within same range of temperature and orientations.

Figure 4.1.12 Performance of classical thermocouples in the generation of thermo emf for the parallel electric field of potential difference 12 V
A comparison of thermo emf generation in the normal mode and parallel electric field mode show that thermo emf enhancements for the first two thermocouples i.e., Fe-Constantan and Constantan-Nichrome, are notable as compared to not only their normal mode thermo emf magnitudes but also to that of their magnetic field (both parallel and perpendicular) performances.

Table 4.1.4 Comparison of Maximum Thermo EMF for the Classical Thermocouples in the Normal Mode and Parallel Electric Field

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Thermocouple</th>
<th>Thermo EMF in Normal Mode</th>
<th>Thermo EMF in Parallel Electric Field</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Fe-Constantan</td>
<td>1.8 mV</td>
<td>8.3 mV 8.3 mV 8.4 mV</td>
</tr>
<tr>
<td>2.</td>
<td>Constantan-Nichrome</td>
<td>1 mV</td>
<td>5.2 mV 5.2 mV 5 mV</td>
</tr>
<tr>
<td>3.</td>
<td>Fe-Cu</td>
<td>0.2 mV</td>
<td>0.7 mV 0.1 0.5 mV</td>
</tr>
<tr>
<td>4.</td>
<td>Cu-Nichrome</td>
<td>0.1 mV</td>
<td>0.2 mV 0.3 mV 0.3 mV</td>
</tr>
<tr>
<td>5.</td>
<td>Fe-Nichrome</td>
<td>0.1 mV</td>
<td>0.5 mV 0.5 mV 0.1 mV</td>
</tr>
</tbody>
</table>

**Perpendicular Electric Field of 4 V**

Here the applied electric field is 16.67 Vm\(^{-1}\). The two thermocouples, Constantan-Nichrome and Fe-Constantan almost repeat the same behavior to generate maximum thermo emf than the other combinations. The maximum thermo emf for Fe-Constantan thermocouple is 2.5 mV and for Constantan-Nichrome it is 2.4 mV at the maximum temperature gradient of 330\(^0\)C. The other thermocouples are again limited only within 0.2 mV corresponding to the maximum temperature gradients (Figure 4.1.13).
Figure 4.1.13 Thermo emf generation by the classical thermocouples in the perpendicular electric field mode of potential difference 4 V

**Perpendicular Electric Field of 8 V**

This is the mode of applied electric field 33.33 V m\(^{-1}\) in the perpendicular orientation. The thermo emf magnitude is increased only for the two thermocouples in comparison to perpendicular 4 V orientations. If the maximum thermo emf value is considered at the maximum temperature gradient then it is 3.7 mV and 2.7 mV for the Fe-Constantan and Constantan-Nichrome thermocouples respectively that is an indication for the enhancement in thermo emf values with the increase in applied electric field strength (Figure 4.1.14).
Figure 4.1.14 Classical thermocouples showing the generation of thermo emf for the perpendicular electric field of potential difference 8 V

**Perpendicular Electric Field of 12 V**

The applied electric filed is 50 V m\(^{-1}\) and this increase in strength of applied electric field in the perpendicular orientation results with an increase of thermo emf only for Fe-Constantan thermocouple in the entire temperature range. It approaches to 4.3 mV emf value in this mode at the maximum temperature difference where as it is only 3.7 mV for 8 V (parallel orientation) and 2.7 mV for 4 V (parallel orientation) corresponding to the same temperature gradient. Whereas, all the other thermocouples including Constantan-Nichrome result to the same manner of thermo emf generation as for as the previous electric field magnitudes for the same orientation (Figure 4.1.15).
Comparison for the Generation of Thermo EMF in the Normal Mode and under the Effect of Perpendicular Electric Field

The effect of perpendicular electric field on the thermo emf generation characteristics for all thermocouples can be easily observed from the Table 4.1.5 and found that it is not so much beneficial (in the sense of enhanced thermo emf) as compared to the parallel electric field. However, the first two thermocouples Fe-Constantan and Constantan-Nichrome are again the better elements than all the rest.
Table 4.1.5 Comparison of Maximum Thermo EMF for the Classical Thermocouples in the Normal Mode and Perpendicular Electric Field

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Thermocouple</th>
<th>Thermo EMF in Normal Mode</th>
<th>Thermo EMF in Perpendicular Electric Field</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>4 V</td>
</tr>
<tr>
<td>1.</td>
<td>Fe-Constantan</td>
<td>1.8 mV</td>
<td>2.5 mV</td>
</tr>
<tr>
<td>2.</td>
<td>Constantan-Nichrome</td>
<td>1 mV</td>
<td>2.4 mV</td>
</tr>
<tr>
<td>3.</td>
<td>Fe-Cu</td>
<td>0.2 mV</td>
<td>0.1 mV</td>
</tr>
<tr>
<td>4.</td>
<td>Cu-Nichrome</td>
<td>0.1 mV</td>
<td>0.2 mV</td>
</tr>
<tr>
<td>5.</td>
<td>Fe-Nichrome</td>
<td>0.1 mV</td>
<td>0.1 mV</td>
</tr>
</tbody>
</table>

4.1.4. Generation of Thermo EMF under the Effect of Mechanical Stress

The mechanical stress considered as an important operating parameter to influence thermo-emf generation is applied on each arm of the thermocouple in a range of 100 gm to the 500 gm mechanical load within the same temperature range of 330°C. The applied mechanical load results to exert the stress as given in the Table 4.1.6.

Table 4.1.6 Strength of Applied Stress on the Classical Thermoelectric Wires

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Applied load (gm)</th>
<th>Stress ($10^5$ Nm(^{-2}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Iron</td>
</tr>
<tr>
<td>1.</td>
<td>100</td>
<td>10.32</td>
</tr>
<tr>
<td>2.</td>
<td>200</td>
<td>20.64</td>
</tr>
<tr>
<td>3.</td>
<td>300</td>
<td>30.96</td>
</tr>
<tr>
<td>4.</td>
<td>400</td>
<td>41.28</td>
</tr>
<tr>
<td>5.</td>
<td>500</td>
<td>51.6</td>
</tr>
</tbody>
</table>
100 gm Load

The generation of thermo emf for Fe-Constantan and Constantan-Nichrome thermocouples is entirely different than their performances in the other modes (Normal Mode, Electric Field and Magnetic Field). The Fe-Constantan limits only to 1 mV whereas the Constantan-Nichrome thermocouple approaches to 4.2 mV thermo emf. It can also be observed that all the other thermocouples lie within .04 mV values.

![Thermo emf generation for classical thermocouples in the mechanical stress mode corresponding to the load of 100 gm](image)

Figure 4.1.16 Thermo emf generation for the classical thermocouples in the mechanical stress mode corresponding to the load of 100 gm

200 gm Load

The exact order for generation of thermo emf values corresponding to the considered thermocouples is Constantan-Nichrome > Fe-Constantan > Cu-Nichrome > Fe-
Nichrome > Copper-Fe. The discussion can be carried out for the Constantan-Nichrome thermocouple which responds linearly to the temperature gradient of 170°C and then it is linear from 170°C to 250°C temperature gradient. The similar light variations can also be observed for its next emf-temperature variations.

![Graph of thermo emf with mechanical stress mode](image)

Figure 4.1.17 Generation of thermo emf with the mechanical stress mode of load 200 gm

**300 gm Load**

The increasing applied stress results to enhance the thermo emf only for Fe-Constantan because it approaches to 3.3 mV thermo emf at the temperature gradient of 330°C whereas, it is only 1.3 mV at the same temperature gradient for the mechanical stress of 200 gm but all the other thermocouples lie within the same magnitudes.
Figure 4.1.18 Thermo emf generation for the classical thermocouples in the mechanical stress mode of load 300 gm

400 gm Load

For an applied load of 400 gm, the exact order of thermo emf generation is Constantan-Nichrome > Fe-Constantan > Cu-Nichrome > Fe-Nichrome > Copper-Fe and the maximum thermo emf values at the maximum temperature gradient is 5.2 mV, 3 mV, 0.4 mV, 0.2 mV and 0.1 mV respectively. This can also be noticed that the thermo emf-temperature variations are non linear for the first two thermocouples (Figure 4.1.19).
Figure 4.1.19 Generation of thermo emf for the classical thermocouples in the mechanical stress mode of load 400 gm

500 gm Load

This is the maximum stress applied in the present investigations and the Fe-Constantan thermocouple approaches to 4.2 mV thermo emf from 2.8 mV (400 gm) at the same temperature gradient. On the other hand the Constantan-Nichrome falls to 3.6 mV from 5.2 mV (400 gm) for the temperature gradient of 330°C temperature. The effect concludes that only Fe-Constantan and Constantan-Nichrome thermocouples can be considered as the energy generation elements.
Comparison of Thermo EMF Generation in the Normal Mode and under the Effect of Stress

As the effect of load at its lower range has no significant effect on the thermo emf generation for almost all the selected thermocouples, therefore, the effect of higher applied stress (i.e., 300 gm, 400 gm, and 500 gm) is only compared with the normal mode thermo emf magnitudes. Even the thermo emf magnitudes are enhanced for all the thermocouples except than the Fe-Cu thermocouple than their normal mode performances. But the thermo emf values are too less corresponding to Fe-Constantan and Constantan-Nichrome thermocouples than that of their magnetic field and electric field performances.
Table: 4.1.7 Comparison of Maximum Thermo EMF for Classical Thermocouples in the Normal Mode and Stress Mode

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Thermocouple</th>
<th>Thermo EMF in Normal Mode</th>
<th>Thermo EMF in Stress Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>300 gm</td>
</tr>
<tr>
<td>1.</td>
<td>Fe-Constantan</td>
<td>1.8 mV</td>
<td>3.4 mV</td>
</tr>
<tr>
<td>2.</td>
<td>Constantan-Nichrome</td>
<td>1 mV</td>
<td>3.6 mV</td>
</tr>
<tr>
<td>3.</td>
<td>Fe-Cu</td>
<td>0.2 mV</td>
<td>0.1 mV</td>
</tr>
<tr>
<td>4.</td>
<td>Cu-Nichrome</td>
<td>0.1 mV</td>
<td>0.4 mV</td>
</tr>
<tr>
<td>5.</td>
<td>Fe-Nichrome</td>
<td>0.1 mV</td>
<td>0.2 mV</td>
</tr>
</tbody>
</table>

The thermo emf generation characteristic is affected for all the classical thermocouples under the applied electric and magnetic fields. However, the thermo emf magnitude for some thermocouples not vary to a large extent than their normal mode performances but as an overview for some thermocouples, the applied field magnitudes and orientations enhance the thermo emf to a considerable extent. This effect is also verified by Rowe D.M. (1995), according to which the Lorentz force acting on an electron in a magnetic field is usually greater than the force exerted by usually attainable electric field within the conductors. Hence, the applied electric and magnetic field exert an extra force and a new resistance called magneto-resistance comes into play and this magneto-resistance depends on the relative orientation of the field and current.

The thermo emf generation for the classical thermocouples in the normal mode and then their variations in under the effect of applied electric field can be verified by taking into account the electric field effect (EFE) carried out by Sandomirsky V. et al. on the Seebeck coefficient which finally affect the thermo emf generation and the other
properties of thermoelectric materials. This EFE concludes that the applied strength of electric field affects the electrical conductivities of both the charge carriers (electrons and holes) and hence the thermo power generation and thermo emf of the material.

Similarly, the thermo emf generation characteristics are investigated for the applied stress corresponding to the mechanical load of 100 gm to 500 gm on each of the thermoelectric wire. This is observed that the effect is considerable for higher stresses (300 gm, 400 gm, and 500 gm). The thermo emf magnitude for these higher stress values are more than that of normal mode outputs for all the thermocouples. This can be due to the strain produced in thermoelectric wires thus disturbing the phonon interactions which dominate the electronic thermal conductivity characters, thus affecting the overall performance of thermoelectric properties.

4.2. Thermo-EMF Generation Characteristics of RTD Thermocouples

The resistance temperature detective (RTD) materials generally used to measure the temperature in the high temperature regions, operates on the principle that the electrical resistance of the material changes with change in its temperature. We studied their thermo emf variations with the temperature gradient that affect the resistive and conductive properties of the RTD material. We select five standard RTD combinations (Type B, Type E, Type S, Type K, and Type R) which are the integral parts of temperature sensing systems especially in the industries and manufacturing areas due to their high accuracy and very fast response time. The EDS (Elemental Diffraction Studies) of all the RTD materials are carried out for standardization (as discussed in the introduction part under the selection of materials) that is in a good agreement with the available literature. Their thermo emf generation are carried out in the normal mode and then compared with the results under the applied magnetic field and electric field of various magnitudes both in the parallel and perpendicular
orientations. Similar to the investigations on the classical thermocouples, a thermo emf generation for the mechanical stress of 100 gm mechanical load is also being studied in case of RTDs to eliminate its affect. The physical parameters (given in Table 4.2.1) of all the five RTD thermocouples are measured to explore their resistive and conductive characteristics.

Table 4.2.1 Experimental Parameters of RTD Thermoelectric Materials for 100gm

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Material</th>
<th>Length ($\times 10^{-2}$ m)</th>
<th>Area of Cross Section $\times 10^{-7}$ m$^2$</th>
<th>$R(\Omega)$ $\times 10^{-8}$ m</th>
<th>Resistivity $\times 10^8$ $\Omega$ m</th>
<th>Electrical Conductivity $\times 10^6$ $\Omega^{-1}$ m$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Type S</td>
<td>Pt</td>
<td>80</td>
<td>3.2</td>
<td>0.175</td>
<td>7</td>
<td>14.3</td>
</tr>
<tr>
<td></td>
<td>Rh-Pt</td>
<td>80</td>
<td>3.02</td>
<td>0.179</td>
<td>7</td>
<td>14.3</td>
</tr>
<tr>
<td>2 Type K</td>
<td>Chromel</td>
<td>80</td>
<td>3</td>
<td>0.288</td>
<td>10.8</td>
<td>9.3</td>
</tr>
<tr>
<td></td>
<td>Alumel</td>
<td>80</td>
<td>3</td>
<td>0.220</td>
<td>8.3</td>
<td>12</td>
</tr>
<tr>
<td>3 Type E</td>
<td>Chromel</td>
<td>80</td>
<td>1.02</td>
<td>0.501</td>
<td>6.4</td>
<td>15.6</td>
</tr>
<tr>
<td></td>
<td>Constantan</td>
<td>80</td>
<td>1.02</td>
<td>0.512</td>
<td>7</td>
<td>14.3</td>
</tr>
<tr>
<td>4 Type R</td>
<td>Pt</td>
<td>80</td>
<td>3</td>
<td>0.350</td>
<td>13</td>
<td>7.7</td>
</tr>
<tr>
<td></td>
<td>Rh-Pt</td>
<td>80</td>
<td>3</td>
<td>0.421</td>
<td>15</td>
<td>6.7</td>
</tr>
<tr>
<td>5 Type B</td>
<td>Pt</td>
<td>80</td>
<td>3.42</td>
<td>0.224</td>
<td>9.6</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Rh-Pt</td>
<td>80</td>
<td>3.42</td>
<td>0.240</td>
<td>10.3</td>
<td>9.7</td>
</tr>
</tbody>
</table>

**4.2.1. Thermo EMF Generation in the Normal Mode**

In this mode the thermocouples can be easily classified for the generation of thermo emf and thermocouple of type E is found to be on the best side among the all because it generates maximum thermo emf for the entire temperature range. Its maximum thermo emf at the maximum temperature gradient of 315°C is 11 mV; whereas for the minimum temperature gradient of 15°C it is about 2 mV. This can be expected corresponding to the performance of Fe and Ni which are the ferromagnetic materials
along with the paramagnetic materials (Al, Cr) whose dominance can be analyzed from the elemental diffraction spectroscopy peaks of type E thermocouple in the material. The second class thermocouple is the Type K thermocouple, for which the maximum and minimum thermo emf generation are 6 mV and 0.4 mV for the maximum and minimum temperature gradients respectively. This can be viewed as the limited Seebeck response of non-magnetic materials. All the other thermocouples (of types B and R) have low emf generation at all temperatures. Their maximum thermo emf magnitudes are only in the range of 0.5 mV corresponding to the maximum temperature gradients of 315°C. This means the response of non magnetic materials (Pt, Rh, C and O) to temperature gradient is least as compared to the magnetic materials. The type S thermocouple is an alloy with the contents of ferromagnetic and paramagnetic materials (Ni, Cr and Al) which also shows the weak response for emf generations.
4.2.2. Effect of Magnetic Field

All the five RTD thermocouples (Type B, type E, type S, type K, type R) are studied for the thermo emf generation in temperature range of 315°C under the applied magnetic and electric fields to observe their energy conversion characteristics along with the temperature-emf alterations by the external parameters.

Parallel Magnetic Field

The parallel magnetic field is applied by the two poles electromagnet for which the applied strength of magnetic field along the length of the thermocouple is shown in Figure 4.2.2
Figure 4.2.2 Variation of magnetic field in parallel orientation along the length of RTD thermocouples

**Magnetic Field of 260 gauss**

For type E the thermo emf for the minimum ($15^0\text{C}$) and maximum ($315^0\text{C}$) temperature gradient are 1 mV and 11 mV respectively. But all the other thermocouples limited only in the range of 0.1 mV to 0.5 mV for the maximum temperature gradient which is an alteration than that of the normal mode results. Therefore, only thermocouple of type E can be considered as a long range temperature sensor.

Figure 4.2.3 Generation of thermo emf for the RTD thermocouples under the effect of parallel magnetic field of strength 260 gauss
Magnetic Field of 360 gauss

From the Figure 4.2.4 it is clear that for the type E thermocouple, thermo emf approaches to 13 mV for the maximum temperature gradient but for all the other RTD thermocouples it reaches only to 0.4 mV for the same temperature range.

![Thermo EMF generation for RTD thermocouples under the effect of parallel magnetic field of strength 360 gauss](image)

Figure 4.2.4 Thermo emf generation for the RTD thermocouples under the effect of parallel magnetic field of strength 360 gauss
Magnetic Field 460 gauss

In this case the thermocouple of type E generates the maximum thermo emf of 15 mV at the maximum temperature gradient of 315°C whereas; other comparison can be carried out from the Figure 4.2.5

Figure 4.2.5 RTD thermocouples in the generation of thermo emf under the effect of parallel magnetic field of strength 460 gauss
Comparison of Thermo EMF Generation by RTD Materials in the Normal Mode and under the Effect of Parallel Magnetic Field

Thermo emf variation for all the RTD thermocouples in comparison to the normal mode implies to consider the effect of magnetic field. Only the type E thermocouple can be considered as a good energy convertor thermocouple in the magnetic field mode due to the enhanced emf values than the normal mode.

Table: 4.2.2 Comparison of Maximum Thermo EMF for RTD Thermocouples in Normal Mode and Parallel Magnetic Field

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Thermocouple</th>
<th>Thermo EMF in Normal Mode</th>
<th>Thermo EMF in Parallel Magnetic Field</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>260 gauss</td>
</tr>
<tr>
<td>1.</td>
<td>Type K</td>
<td>7 mV</td>
<td>0.4 mV</td>
</tr>
<tr>
<td>2.</td>
<td>Type E</td>
<td>11 mV</td>
<td>11.8 mV</td>
</tr>
<tr>
<td>3.</td>
<td>Type R</td>
<td>0.7 mV</td>
<td>0.3 mV</td>
</tr>
<tr>
<td>4.</td>
<td>Type B</td>
<td>0.6 mV</td>
<td>0.5 mV</td>
</tr>
<tr>
<td>5.</td>
<td>Type S</td>
<td>0.8 mV</td>
<td>0.6 mV</td>
</tr>
</tbody>
</table>

Effect of Perpendicular Magnetic Field

Similar to that of the parallel magnetic field, the perpendicular magnetic field of three different magnitudes 260 gauss, 360 gauss and 460 gauss is applied on each of the RTD thermocouple. The Figure 4.2.6 illustrates that the magnetic field is maximum at the centre of the thermocouple than its end points.
Figure 4.2.6 Variation of applied magnetic field in perpendicular orientation along the length of the RTD thermocouples

Magnetic Field of 260 gauss

For the maximum temperature gradient of 315°C thermocouples of type E, K, R, S and B generate the thermo emf about of 8 mV, 1 mV, 0.4 mV, 0.2 mV and 0.1 mV respectively. However, the thermo emf generation for the minimum temperature gradient (15°C) can be studied from Figure 4.2.7
Figure 4.2.7 Thermo emf generation by RTD thermocouples under the effect of perpendicular magnetic field of strength 260 gauss

**Magnetic Field of 360 gauss**

Thermo emf for the type E thermocouple enhances to 11.4 mV for the maximum temperature gradient but for this temperature all other thermocouples are limited only in the range of 0.2 mV to 1 mV as shown in Figure 4.2.8
Figure 4.2.8 Performance of RTD thermocouples for the generation of thermo emf under the effect of perpendicular magnetic field of strength 360 gauss

**Magnetic Field of 460 gauss**

From the Figure 4.2.9 the order of thermo emf magnitude corresponding to the maximum temperature difference is: Type E > Type K > Type S > Type R > Type B with the maximum values of 13.2 mV, 2 mV, 1 mV, 0.5 mV and 0.3 mV respectively.
Comparison of Thermo EMF Generation by RTD Materials in the Normal Mode and for the Perpendicular Magnetic Field

The thermo emf magnitude for all the RTD thermocouples is different in the perpendicular magnetic field than that in the normal mode and the parallel magnetic field mode. Again, the only type E thermocouple can be treated as the energy generator element under the applied perpendicular magnetic field also.
Table: 4.2.3 Comparison of Maximum Thermo EMF for RTD Thermocouples in Normal Mode and Perpendicular Magnetic Field

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Thermocouple</th>
<th>Thermo EMF in Normal Mode</th>
<th>Thermo EMF in Perpendicular Magnetic Field</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>260 gauss</td>
</tr>
<tr>
<td>1.</td>
<td>Type K</td>
<td>7 mV</td>
<td>0.4 mV</td>
</tr>
<tr>
<td>2.</td>
<td>Type E</td>
<td>11 mV</td>
<td>11.8 mV</td>
</tr>
<tr>
<td>3.</td>
<td>Type R</td>
<td>0.7 mV</td>
<td>0.4 mV</td>
</tr>
<tr>
<td>4.</td>
<td>Type B</td>
<td>0.6 mV</td>
<td>0.6 mV</td>
</tr>
<tr>
<td>5.</td>
<td>Type S</td>
<td>0.8 mV</td>
<td>0.8 mV</td>
</tr>
</tbody>
</table>

4.2.3. Effect of Applied Electric Field

Similar to that of the applied magnetic field, all the RTD thermocouples are investigated for the generation of thermo emf under the applied electric field in both parallel and perpendicular orientations. These investigations are carried out in the temperature range of 588 K where as the electric field is applied by maintaining the potential differences of parallel plates to 4 V, 8 V and 12 V.

Table 4.2.3 Strength of Applied Electric Field in Parallel and Perpendicular Modes for RTD Thermoelectric Materials

<table>
<thead>
<tr>
<th>Strength of Applied Electric Field (Vm⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parallel Electric Field</td>
</tr>
<tr>
<td>4 V</td>
</tr>
<tr>
<td>10.7</td>
</tr>
</tbody>
</table>
**Parallel Electric Field (4 V)**

This is the case of applied electric field of magnitude $10.7 \text{ Vm}^{-1}$. In this mode the performance order of thermocouples is Type E > Type K > Type R > Type S and B. The magnitude of maximum thermo emf for the first three thermocouples (E, K and R) is about $11 \text{ mV}$, $3.6 \text{ mV}$ and $1 \text{ mV}$ respectively; whereas for type S and B it limits only to $0.5 \text{ mV}$ at the maximum temperature gradient of $315^\circ\text{C}$. The behavior of type E thermocouple is not linear with the temperature variations as compared to all other thermocouples.

![Graph showing thermo EMF vs temperature difference for different thermocouples under 4 V electric field.](image)

**Figure 4.2.10** The RTD thermocouples in generation of thermo emf under the effect of parallel electric field of potential difference 4 V
Parallel Electric Field (8 V)

The corresponding electric field is of the magnitude of 21.3 Vm$^{-1}$. The performance order is same as of the 4 V but the emf magnitude decreases. The first rank thermocouple of type E generates only 6 mV maximum thermo emf at the maximum temperature gradient; whereas type K and R limits only to 4.2 mV and 0.8 mV respectively at the same temperature difference (i.e. 315$^\circ$C). But the last rank thermocouples (type S and B) generate only 0.6 mV thermo emf as the maximum value.

Figure 4.2.11 Thermo emf generation for the RTD thermocouples under the effect of parallel electric field of potential difference 8 V
Parallel Electric Field (12 V)

At this potential difference the electric field applied is 32 Vm$^{-1}$ and the exact order of the performance of thermocouples is Type E > Type K > Type R > Type S > Type B with a maximum thermo emf generation of 8 mV, 3 mV, 0.5 mV, 0.4 mV and 0.2 mV respectively for the maximum temperature gradient of 315°C. The behavior of all the thermocouples except of type E is linear.

Figure 4.2.12 Generation of thermo emf for the RTD thermocouples under the effect of parallel electric field of potential difference 12 V
Comparison of Thermo EMF Generation by RTD Materials in the Normal mode and for Parallel Electric Field

This is clear from the given Table 4.2.4 that only type R-RTD thermocouple generates more thermo emf than that of its normal mode performances. But all the rest thermocouples generate too less thermo emf as compared to their normal mode values. Hence, for the precise measurements of temperature these all should be taken into account.

Table: 4.2.4 Comparison of Maximum Thermo EMF for the RTD Thermocouples in Normal Mode and Parallel Electric Field

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Thermocouple</th>
<th>Thermo EMF in Normal Mode</th>
<th>Thermo EMF in Parallel Electric Field</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>4 V</td>
</tr>
<tr>
<td>1.</td>
<td>Type K</td>
<td>7 mV</td>
<td>4 mV</td>
</tr>
<tr>
<td>2.</td>
<td>Type E</td>
<td>11 mV</td>
<td>11 mV</td>
</tr>
<tr>
<td>3.</td>
<td>Type R</td>
<td>0.7 mV</td>
<td>1 mV</td>
</tr>
<tr>
<td>4.</td>
<td>Type B</td>
<td>0.6 mV</td>
<td>0.2 mV</td>
</tr>
<tr>
<td>5.</td>
<td>Type S</td>
<td>0.8 mV</td>
<td>0.3 mV</td>
</tr>
</tbody>
</table>

Perpendicular Electric Field

Similar to that of the applied parallel electric field, all the RTD thermocouples are also investigated for the generation of thermo emf under the perpendicular applied electric field in the temperature range of 315°C where as the perpendicular electric field is applied by maintaining the potential differences of parallel plates to 4 V, 8 V and 12 V.
**Electric Field (4 V)**

For the 4 V applied potential difference, the strength of electric field is 22.2 Vm$^{-1}$. The order of performance for maximum thermo emf generation is Type E > Type K > Type R > Type S and B. For the thermocouple of type E, maximum thermo emf is 5.7 mV only, where as it is 11 mV in the parallel mode of 4 V applied potential difference. Similarly, for the type K and R it reduces to 1 mV and 0.2 mV respectively corresponding to the maximum temperature gradient. As of the previous mode, the S and B type thermocouples again show same generation of thermo emf (of 0.1 mV); which is less than all of the parallel modes. The type E thermocouple having large variations in the entire temperature range but all the others show a linear behavior.

![Figure 4.2.13 Performance of RTD thermocouples for generation of thermo emf under the effect of perpendicular electric field of potential difference 4 V](image)
**Electric Field (8 V)**

For 8 V applied potential difference the magnitude of electric field is $44.4 \text{ Vm}^{-1}$. The order of thermo emf generation is same as of the previous mode. The first three ranked thermocouples of Type E, K and R generate 8.4 mV, 1.1 mV and 0.2 mV as the maximum thermo emf at the maximum temperature gradient respectively, which is enhanced for type E than its value in the 4 V with perpendicular mode. The other thermocouples of type S and B again limit to maximum emf of 0.1 mV. However, the variations in thermo emf generation are less in this mode as compared to all of the previous modes.

![Thermo emf generation for the RTD thermocouples under the effect of perpendicular electric field of potential difference 8 V](image)

Figure 4.2.14 Thermo emf generation for the RTD thermocouples under the effect of perpendicular electric field of potential difference 8 V
**Electric Field (12 V)**

For 12 V, the applied electric field is 66.7 Vm⁻¹ and the order of thermo emf generation is slightly different from all the other modes, that is Type E > Type K > Type S > Type R and B. At the maximum temperature gradient of 315°C the maximum thermo emf is 5 mV, 1.4 mV, 0.2 mV and 0.1 mV for the above order respectively. All the other corresponding results can be compared from the graphical data of Figure 4.2.15.

![Figure 4.2.15 Generation of thermo emf for the RTD thermocouples under the effect of perpendicular electric field of potential difference 12 V](image)
Comparison of Thermo EMF Generation by RTD Materials in the Normal mode and for Perpendicular Electric Field

The similar performance as of the parallel magnetic field can be viewed here. This all shows that all the RTD thermocouples can be treated as the good energy convertors only in the normal mode expect than the type E-RTD thermocouple that generates more thermo emf in some modes of magnetic field than the normal mode. But for the precise temperature measurements such variations should be taken in to consideration for all the RTD materials.

Table: 4.2.5 Comparison of Maximum Thermo EMF for RTD Thermocouples in the Normal Mode and Perpendicular Electric Field

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Thermocouple</th>
<th>Thermo EMF in Normal Mode</th>
<th>Thermo EMF in Perpendicular Electric Field</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>4 V</td>
</tr>
<tr>
<td>1.</td>
<td>Type K</td>
<td>7 mV</td>
<td>1 mV</td>
</tr>
<tr>
<td>2.</td>
<td>Type E</td>
<td>11 mV</td>
<td>5.8 mV</td>
</tr>
<tr>
<td>3.</td>
<td>Type R</td>
<td>0.7 mV</td>
<td>0.4 mV</td>
</tr>
<tr>
<td>4.</td>
<td>Type B</td>
<td>0.6 mV</td>
<td>0.2 mV</td>
</tr>
<tr>
<td>5.</td>
<td>Type S</td>
<td>0.8 mV</td>
<td>0.2 mV</td>
</tr>
</tbody>
</table>

4.2.4. Generation of the Thermo EMF under the Effect of Applied Stress

Due to the noticeable effect of stress on the generation of thermo emf, the mechanical stress is also applied on each of the RTD thermocouples. The Table 4.2.6 shows the stresses exert on each wire of the thermocouple due to mechanical load of 100 gm on each arm of the RTD thermocouples.
Table 4.2.6 Strength of Applied Stress on the RTD Thermocouples

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Thermoelectric Material</th>
<th>Stress (×10⁶ Nm⁻²) for 100 gm load</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Type S</td>
<td>Platinum</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rhodium-Platinum</td>
</tr>
<tr>
<td>2.</td>
<td>Type K</td>
<td>Chromel</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Alumel</td>
</tr>
<tr>
<td>3.</td>
<td>Type E</td>
<td>Chromel</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Constantan</td>
</tr>
<tr>
<td>4.</td>
<td>Type R</td>
<td>Platinum</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rhodium-Platinum</td>
</tr>
<tr>
<td>5.</td>
<td>Type B</td>
<td>Platinum</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rhodium-Platinum</td>
</tr>
</tbody>
</table>

**Stress of 100 gm load**

Type E and Type K thermocouples can be considered as the better energy generator elements than that to all other three types of RTD materials. The up-down variations of thermo emf-temperature relations for the type E-RTD put an objection for its accuracy in the orientations where the thermal/mechanical stress exists. Thermo emf generation behavior for the other combinations can also be observed in the entire temperature range by their comparisons with normal mode performances (Figure 4.2.16).
Comparison of Thermo EMF Generation by RTD Materials in the Normal mode and under the Effect of Applied Stress

Unlike the classical thermocouples (where the stress is applied from 100 gm to 500 gm load) the stress on RTD thermocouples is applied only corresponding to 100 gm mechanical load taking into consideration the softness and thin dimensions of the RTD thermocouple wires. Moreover, presence of higher value stress in the environment where RTD thermocouples are put to use is also limited. Instead of electric field and magnetic modes, no RTD thermocouple indicates the significant change in thermo emf generation as compared to the normal mode in the entire temperature range. The effect of this stress can be easily compared from the given Table 4.2.7.
Table: 4.2.7 Comparison of Thermo EMF for RTD Thermocouples in Normal Mode and Stress Mode

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Thermocouple</th>
<th>Thermo EMF in Normal Mode</th>
<th>Thermo EMF for 100 gm Stress</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Type K</td>
<td>7 mV</td>
<td>5 mV</td>
</tr>
<tr>
<td>2.</td>
<td>Type E</td>
<td>11 mV</td>
<td>6 mV</td>
</tr>
<tr>
<td>3.</td>
<td>Type R</td>
<td>0.7 mV</td>
<td>0.5 mV</td>
</tr>
<tr>
<td>4.</td>
<td>Type B</td>
<td>0.6 mV</td>
<td>0.2 mV</td>
</tr>
<tr>
<td>5.</td>
<td>Type S</td>
<td>0.8 mV</td>
<td>0.3 mV</td>
</tr>
</tbody>
</table>

All the RTD thermocouples are investigated for the generation of thermo emf in the temperature range of 315°C and this is observed that the electric and magnetic field affect the generation of thermo emf for type E thermocouple to a considerable extent as compared to other RTD thermocouples. The Boltzmann equation (modified equation for Lorentz force) introduced by Rowe D.M. (1995) explains the dominance of presence of extra force rather than the internal electric field of conductor. It also explained that the magnetic field has the effect of changing the direction of motion of electrons. The thermo emf generation under the applied electric field is in a good accord of electric field effect (EFE) carried out by Sandomirsky V. et al. according to which the applied electric field affect the Fermi energy levels of thermoelectric materials and also the thermo power generation by affecting the charge carrier concentrations and their corresponding electrical conductivities. Similarly, the lowest stress corresponding to 100 gm mechanical load may cause the phonon drags and reduce the thermal conductivity that results in the generation of thermo emf.
4.3. Generation of Thermo EMF for the Semiconducting Thermoelectric Pallets

The thermo emf generation for each of the pallets (Pb₃Te₃, Bi₂Te₃, Pb₂Te₃) in cylindrical dimensions are carried out in the normal mode as well as under the applied magnetic field and electric fields of different magnitudes. As thermo generator elements, these thermoelectric pallets are more efficient in the normal mode in comparison to the effect of applied electric field, however, the effect of applied magnetic field is more pronounced and the maximum thermo emf is generated for the entire temperature range corresponding to all the pallets.

Thermo emf generation for each of the pallets is enhanced for all the applied strengths of magnetic field than that of their normal mode performances. Hence, their conversion efficiency increases with the increase in strength of the applied magnetic field. This means that the energy conversion characteristics can be further explored greatly under the effect of applied magnetic field. First rank can be assigned to the pallet Pb₂Te₃ in the magnetic field mode, corresponding to which the output thermo power is improved by several orders. Even in the normal mode and electric field mode, the pallets Bi₂Te₃ and Bi₂Pb₃ show greater magnitude of thermo emf in the entire temperature range than the third pallet Pb₂Te₃. All the corresponding results are explained and compared by the graphical data.

4.3.1. Normal Mode

In this mode, Bi₂Te₃ pallet is the best thermo generation element which can be observed from Figure 4.3.1. It generates 2 mV thermo emf at the minimum temperature gradient of 15₀°C and about 5.6 mV at maximum temperature gradient of 155₀°C. The other Bi₂Pb₃ and Pb₂Te₃ pallets generate only 2 mV and 1 mV at the minimum temperature gradient (15₀°C), respectively but at the maximum temperature gradient of
155°C the thermo emf generation is 4.6 mV and 4 mV, respectively. The exact order of energy conversion performance in the entire temperature range is Bi$_2$Te$_3$ > Bi$_2$Pb$_3$ > Pb$_2$Te$_3$.

Figure 4.3.1 Performance of thermoelectric pallets in the normal mode for the generation of thermo emf

### 4.3.2. Effect of Applied Electric Field

All the three semiconducting pallets, Pb$_2$Te$_3$, Bi$_2$Te$_3$ and Bi$_2$Pb$_3$ are investigated for the generation of thermo emf in the temperature range of 155°C under the three magnitudes of electric field corresponding to the applied potential differences of 4 V, 8 V and 12 V.
Electric Field (4 V)

For the applied electric field of 20 Vm$^{-1}$(i.e. 4 V potential difference), we observed that the generation of thermo emf is almost same for the pallets of Bi$_2$Pb$_3$ and Bi$_2$Te$_3$ in the entire temperature range. The generated thermo emf is 3.9 mV, 4 mV, and 3.7 mV for pallets Bi$_2$Pb$_3$, Bi$_2$Te$_3$, and Pb$_2$Te$_3$ respectively at the maximum temperature gradient of 155$^0$C where as its magnitude is 2.2 mV, 2 mV and 1.2 mV respectively at the minimum temperature gradient of 15$^0$C. Hence, there is the decrease in thermo emf magnitudes for all pallets over the entire temperature range in comparison to their normal mode performances.

Figure 4.3.2 Thermo emf generation for thermoelectric pallets under the effect of electric field of potential difference 4 V
**Electric Field (8 V)**

However, at the applied electric field of 40 V m$^{-1}$ (i.e., 8 V potential difference), the magnitude of generated thermo emf is about 4.8 mV for the pallets of Bi$_2$Pb$_3$ and Bi$_2$Te$_3$ but only 3.2 mV for Pb$_2$Te$_3$ at maximum temperature gradient (155$^\circ$C) as shown in Figure 4.3.3. On the other hand, the minimum thermo emf at the minimum temperature gradient of 15$^\circ$C is 2.3 mV, 1.2 mV and 2.9 mV for the three pallets Bi$_2$Pb$_3$, Pb$_2$Te$_3$ and Bi$_2$Te$_3$ respectively. The order of performance towards the energy conversion efficiency is, Bi$_2$Te$_3$ > Bi$_2$Pb$_3$ > Pb$_2$Te$_3$ in the entire temperature range.

![Figure 4.3.3 Thermoelectric pallets in the generation of thermo emf under the effect of electric field of potential difference 8 V](image-url)
Electric Field (12 V)

At the electric field of 60 Vm⁻¹ (i.e., 12 V potential difference), although the pallets of Bi₂Pb₃ and Bi₂Te₃ generate the same magnitude of thermo emf (about 5.3 mV) at the maximum temperature gradient, but the pallet of Bi₂Pb₃ exhibits a higher value over the entire range of temperature. Hence, Bi₂Pb₃ is proposed to be a better material for the generation of thermo emf which can be analyzed from Figure 4.3.4. The pallet of Pb₂Te₃ generates only 4 mV and 1.4 mV thermo emf corresponding to 155°C and 15°C temperature gradients, respectively. The resultant order of energy conversion characteristics is Bi₂Te₃ > Bi₂Pb₃ > Pb₂Te₃.

Figure 4.3.4 Generation of thermo emf by the thermoelectric pallets under the effect of electric field of potential difference 12 V
Comparison for the Generation of Thermo EMF for the three Thermoelectric Pallets in the Normal Mode and for the Effect of Applied Electric Field

The effect of applied electric field (any magnitude) from outside cannot be taken as the predominant parameter to influence the enhanced thermo emf generation. This only advocates their importance in the normal mode as compared to their performance under the applied electric field.

Table: 4.3.1 Comparison of Maximum Thermo EMF for the Thermoelectric Pallets in the Normal and Electric Field Mode

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Pallets</th>
<th>Thermo EMF in Normal Mode</th>
<th>Thermo EMF in Electric Field</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>4 V</td>
</tr>
<tr>
<td>1</td>
<td>Bi₂Te₃</td>
<td>5.7 mV</td>
<td>4.1 mV</td>
</tr>
<tr>
<td>2</td>
<td>Bi₂Pb₃</td>
<td>5 mV</td>
<td>3.9 mV</td>
</tr>
<tr>
<td>3</td>
<td>Pb₂Te₃</td>
<td>4.2 mV</td>
<td>3.8 mV</td>
</tr>
</tbody>
</table>

4.3.3. Effect of Applied Magnetic Field

Similar to that of the electric field, all the pallets are also investigated for the generation of thermo emf under of the applied magnetic field at three different magnitudes.

Magnetic Field (260 gauss)

Under the influence of 260 gauss applied magnetic field, the order of thermo emf generation is Pb₂Te₃ > Bi₂Te₃ > Bi₂Pb₃. The generation for the first rank pallet Pb₂Te₃ approaches to 5 mV and 6 mV at the minimum (15⁰C) and maximum (155⁰C) temperature gradients, respectively. Similarly for the other pallets Bi₂Te₃ and Bi₂Pb₃ the thermo emf generation is 2.8 mV and 2.6 mV respectively at the minimum temperature
gradient but at the maximum temperature gradient these are 4.6 mV and 4.5 mV respectively. The thermo emf generation for the entire temperature range is approximately linear which can be observed from the Figure 4.3.5.

Figure 4.3.5 Thermo emf generation of thermoelectric pallets under the magnetic field of strength 260 gauss

Magnetic Field (360 gauss)

The Figure 4.3.6 represents the order of thermo emf generation in this mode of magnetic field in the sequence Pb_2Te_3 > Bi_2Pb_3 > Bi_2Te_3. For the best pallet Pb_2Te_3 thermo emf values are 5.6 mV and 7.4 mV at the minimum and maximum temperature gradients respectively. The minimum and maximum thermo emf values at the corresponding temperature gradients are 2.5 mV, 5.2 mV and 2.6 mV, 4.2 mV for the
2\textsuperscript{nd} and 3\textsuperscript{rd} ranked pallets Bi\textsubscript{2}Pb\textsubscript{3} and Bi\textsubscript{2}Te\textsubscript{3} respectively. The other aspects can be compared from the Figure 4.3.6 at the various temperatures.

![Figure 4.3.6 Thermo emf generation for thermoelectric pallets under the magnetic field of strength 360 gauss](image)

**Magnetic Field (460 gauss)**

For the applied magnetic field of 460 gauss, the order of thermo emf generation is Pb\textsubscript{2}Te\textsubscript{3} > Bi\textsubscript{2}Te\textsubscript{3} > Bi\textsubscript{2}Pb\textsubscript{3}. The minimum thermo emf values are 5.2 mV, 2.6 mV and 2.5 mV for the above three ordered pallets respectively corresponding to the minimum temperature gradient but at the maximum temperature gradient these thermo emf values are 7 mV, 5.5 mV and 4.7 mV, respectively which can be verified from the Figure 4.3.7.
Comparison of Thermo EMF Generation for the Thermoelectric Pallets in the Normal Mode and under the Applied Magnetic Field

From the above investigations related to the effect of applied magnetic field on the three cylindrical pallets selected in the present study, only Pb₂Te₃ pallet can be considered as the better thermo generator element under the effect of any magnitude of applied magnetic field as compared to other two pallets.
Table: 4.3.2 Comparison of Maximum Thermo EMF for the Thermoelectric Semiconducting Pallets in the Normal and Magnetic Field Mode

<table>
<thead>
<tr>
<th>Sr.No.</th>
<th>Pallets</th>
<th>Thermo EMF in Normal Mode</th>
<th>Thermo EMF in Magnetic Field</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>260 gauss</td>
</tr>
<tr>
<td>1.</td>
<td>Bi$_2$Te$_3$</td>
<td>5.7 mV</td>
<td>4.8 mV</td>
</tr>
<tr>
<td>2.</td>
<td>Bi$_2$Pb$_3$</td>
<td>5 mV</td>
<td>4.5 mV</td>
</tr>
<tr>
<td>3.</td>
<td>Pb$_2$Te$_3$</td>
<td>4.2 mV</td>
<td>6.4 mV</td>
</tr>
</tbody>
</table>

It is to be mention that the thermo emf generation results for the selected thermoelectric pallets obtained in the present research work are in a good agreement as explained by Bulusu A. et al. (2008). It is to mention that both Bi$_2$Te$_3$ and Pb$_2$Te$_3$ pallets are the good thermo generator elements in the temperature range of 300-700 K. Further, to support the obtained results for Lead Telluride semiconductor pallets, it is known that Lead Telluride belongs to the lead chalcogenides systems similar to the materials like PbS and PbSe and also have a rock-salt structure with a FCC unit cell. These are the polar semiconductors with a mixed ionic-covalent bond which leads to ionic charging and quasi-state bonding resulting in the increase in their electrical conductivity. Bulusu A. et al. (2008) have also reported about the higher Seebeck coefficient of Lead Telluride than that of the Bismuth Telluride, which could have resulted in the better thermo emf generation characteristics of this pallet. Further, theoretical basis is required to explain the exact behavior for thermo emf generation of these semiconductor pallets under the influence of operating parameters so that they can be put to their best use in terms of thermoelectric modules.