CHAPTER – 5

A Comparison of Figure of Merit for Some Common Thermocouples in the High Temperature Range

5.1. Introduction

Thermoelectricity is a well known phenomenon to generate thermo-emf based on the temperature gradient of junctions of a thermocouple with the use of classical as well as advanced thermoelectric materials. The technology is becoming famous due to a large number of applications of thermoelectric devices, which are able to generate considerable energy and are also advantageous due to their pollution free nature, no moving parts and no complex designs. Waste heat is available not only in the domestic areas like in kitchens but also in the industries i.e. Generators, Electric Motors, Computers and in the Furnaces also. A thermo-generator making use of efficient and cost effective thermocouples is always sought to recover waste heat by converting it into useful thermo-electric power. The prospective use of low cost and easily available classical thermoelectric materials in a thermo-generator is the basic approach of present research work with an aim to investigate the thermo-emf generation. With this aim, thermocouples are experimentally investigated and figure of merit (FOM) so obtained in the high temperature range is compared with its theoretical values in order to authenticate the present experimental and theoretical results.

The aim of the investigations is to evaluate the suitability of classical thermocouples for their possible use in waste heat recovery. High figure of merit (FOM) along with low cost and easy availability are always considered important parameters of a thermocouple towards its suitability as a thermo-element in a thermo-generator. This
research work presents experimental results in comparison to theoretical values of FOM for two classical thermocouples in the high temperature range from 40-330°C. The generation of thermo-emf as a function of temperature gradient is measured for all thermocouples to calculate their FOM. Then, the theoretical and experimental results of FOM are compared and found to be at a significant variation due to difference in compositions and other experimental conditions, however, showing the identical behavior.

Different classical thermo-electrical materials have also been investigated by many researchers due to their low cost and easy availability. Presently, we have also selected the classical thermoelectric materials (Iron, Nichrome and Constantan) for investigations making their two thermocouples: Fe-Constantan and Constantan-Nichrome. These thermocouples were investigated for the generation of thermo emf in a high temperature range from 40 to 330°C, as waste heat is generally available in this temperature range. The figure of merit for these thermocouples was calculated from the experimental data which was then compared with their theoretically calculated values to strengthen the authenticity of present experimental investigations. The standard equations (Rowe D.M. 1995; Tritt M. T. 2001) of thermoelectricity are used for the calculations. The elemental characterization by XRF of presently used (market available) thermoelectric materials is also carried out for possible quality comparison and repeatability of experimental results.

5.2. Methodology

The figure of merit, a dimensionless quantity given by $ZT = \frac{\alpha^2 \sigma T}{\lambda}$, is one of the most important terms to describe the performance of the thermoelectric materials. Parameters $\alpha, \sigma, \lambda$ and $T$ are the Seebeck constant, electrical conductivity, thermal conductivity of the thermoelectric material and the temperature difference of the two junctions of the
thermocouple respectively. It is clear from the relation that to enhance the figure of merit, thermal conductivity should be minimum and the electrical conductivity should be maximum to the possible. Researchers working in the industrial application of thermoelectricity are oriented to improve the figure of merit of thermo-electric materials. In the present work, experimental values of figure of merit are compared with their theoretical values for selected thermocouples in order to ascertain their quality, suitability and repeatability.

5.3. Theoretical Calculations

The figure of merit of all the thermocouples is calculated from the relation (Tritt, M.T., 2001):

\[
Z = \frac{(\alpha_a - \alpha_b)^2}{[(\rho_a \lambda_a)^{1/2} + (\rho_b \lambda_b)^{1/2}]^2}
\] (5.1)

Here, \(\alpha_a\) and \(\alpha_b\) are the Seebeck constants (in V/K) and \(\rho_a\) & \(\rho_b\) are the resistivity (specific resistances) (in \(\Omega\) m) of both the materials of a thermocouple. Similarly, \(\lambda_a\) and \(\lambda_b\) are the thermal conductivities (in Wm\(^{-1}\)K\(^{-1}\)) of both the thermoelectric materials. To calculate figure of merit from equation 1, theoretical values of all the physical parameters are used as of the pure materials. These values used to calculate the Seebeck constant \(\alpha_{ab}\) of a thermocouple are given in Table 5.1. Calculated values of Seebeck Constant \(\alpha_{ab}\) and \(Z\) for different thermocouples are given in Table 5.2.
Table 5.1 Theoretical Parameters of the Thermoelectric Materials

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Parameter</th>
<th>Iron</th>
<th>Constantan</th>
<th>Nichrome</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Thermal Conductivity $\lambda$ (Wm$^{-1}$K$^{-1}$)</td>
<td>80.4</td>
<td>19.5</td>
<td>11.3</td>
</tr>
<tr>
<td>2.</td>
<td>Electrical Conductivity $\sigma$ (S m$^{-1}$)</td>
<td>1.041x10$^7$</td>
<td>2x10$^7$</td>
<td>6.67x10$^5$</td>
</tr>
<tr>
<td>3.</td>
<td>Seeback constant, $\alpha$ (µV/°C)</td>
<td>19</td>
<td>-35</td>
<td>25</td>
</tr>
</tbody>
</table>

Table 5.2 Theoretical values of Seebeck Constant ($\alpha_{ab}$) and $Z$ for different Thermocouples

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Parameter</th>
<th>Fe-Constantan</th>
<th>Constantan-Nichrome</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Seebeck Constant $\alpha_{ab}$ (V/°C)</td>
<td>5.4x10$^{-5}$</td>
<td>6x10$^{-5}$</td>
</tr>
<tr>
<td>2.</td>
<td>$Z$ (°C$^{-1}$)</td>
<td>1.22x10$^{-5}$</td>
<td>2.95x10$^{-5}$</td>
</tr>
</tbody>
</table>

5.4. Experimental Calculations

The equation of thermoelectricity to explain the generation of thermo emf, is generally represented in text books as: $E = \alpha T \pm \beta T^2/2$, where $\alpha$ and $\beta$ are the Seebeck constants in µV/°C and µV/°C$^2$ respectively and $T$ is the temperature difference ($T=T_1+T_2/2$). Thermo-power, the rate of change of magnitude of thermo-emf w.r.t. the temperature gradient, is given as: $\frac{dE}{dT} = \alpha + \beta T$. Finally, the equation of thermo-emf generation is generally taken as $\frac{dE}{dT} = \alpha$ because $\beta$ is very small as compared to $\alpha$ and for the two thermoelectric materials making a thermocouple, $\alpha$ is replaced by $\alpha_{ab}$ and becomes as:
\[
\left( \frac{dE}{dT} \right)^2 = (a_{ab})^2 \tag{5.2}
\]

Thus, the figure of merit is given by:

\[
ZT = \frac{(a_{ab})^2 T}{\rho \lambda} \tag{5.3}
\]

Taking \( \rho = \frac{R \alpha}{l} \) & \( \frac{\lambda \alpha}{l} = K \), the ZT can be written as:

\[
ZT = \frac{\left( \frac{dE}{dT} \right)^2 T}{RK} \tag{5.4}
\]

where, \( \rho \), \( \lambda \), \( \alpha \) and \( l \) are the resistivity, thermal conductivity, area of cross-section and length of the thermoelectric material respectively. As the final resistance of the thermocouple is a series combination of individual resistances, so \( R \) (of thermocouple) is calculated as:

\[
R = R_1 + R_2 \tag{5.5}
\]

Taking the value of \( K \) as:

\[
K = \frac{K_1 + K_2}{2} \tag{5.6}
\]

The physical parameters of thermocouple wires and thermo-emf generation are measured by using a standard digital multimeter (make HP 34401A) with an accuracy up to six decimal places. Temperature of thermocouple junctions is measured with the help of a mercury thermometer with an accuracy of 0.5\(^0\)C. The measured physical parameters of different wires used to make thermocouples are given in Table 5.3.
Table 5.3 Experimentally measured Parameters of Selected Thermoelectric Materials

<table>
<thead>
<tr>
<th>S. No.</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>1.112x10⁻⁶</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 (Ω⁻¹m⁻¹)</td>
<td>1.67x10⁻⁹</td>
<td>7.143x10⁻⁹</td>
<td>8.33x10⁻⁸</td>
<td>2.933x10⁻⁸</td>
</tr>
</tbody>
</table>

Table 5.4 Experimental values of Seebeck Constant ($\alpha_{ab}$) and Z for Different Thermocouples

<table>
<thead>
<tr>
<th>Sr. No</th>
<th>Parameter</th>
<th>Fe-Constantan</th>
<th>Constantan-Nichrome</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>$\frac{d\alpha}{dT} = \alpha_{ab}$ (V°C⁻¹)</td>
<td>1.955x10⁻⁵</td>
<td>1.074x10⁻⁵</td>
</tr>
<tr>
<td>2.</td>
<td>$Z = \frac{(dE/dT)^2}{RK}$ (°C⁻¹)</td>
<td>310x10⁻⁸</td>
<td>153.3x10⁻⁸</td>
</tr>
</tbody>
</table>

5.5. Results and Discussion

The comparison of theoretical and experimental calculations of figure of merit for the selected thermocouples show that there is not a perfect matching between the theoretical and experimental values for any of the thermocouple. There is a much difference between the theoretical and experimental performances. This indicates that with increase in temperature the thermal and electrical conductivities vary in such a way that the experimental figure of merit (ZT) is low than the theoretical values in the entire temperature range. Mismatching in theoretical and experimental results in case of selected thermocouples might have arises due to the differences in:
i) Composition of materials considered for theoretical calculations with those experimentally available

ii) Theoretical and experimental values of thermal conductivities of thermoelectric materials

iii) The selected thermo electric materials (Fe, Constantan, Nichrome) are the market available materials and hence their experimental performances are different than the theoretical results which are for the bulk & pure materials.

iv) The research work justify the behavior of thermocouples i.e. linear variations of ZT w.r.t. the temperature gradients in both the theoretical and experimental observations.

v) The gap between theoretical and experimental curves increases with increase in temperature gradient which can be due to increase in thermal conductivity along with that of the energy conversion characteristics.

vi) Only the same theoretical value of thermal conductivity is used in both the experimental and theoretical studies, but the ZT verses temperature gradient curves show that variation in thermal conductivity increases with the temperature gradient (ZT varies inversely to the thermal conductivity of a thermoelectric material). This leads to the continuous increasing gap between the theoretical and experimental ZT values.
Figure 5.1 Experimental and theoretical comparison of the figure of merit of Fe-Constantan thermocouple
Figure 5.2 Experimental and theoretical comparison of the figure of merit of Constantan-Nichrome thermocouple

5.6. Conclusions

This research part concludes that:

- Fe-Constantan emerges as a better thermocouple supported by the experimental theoretical studies. Thus, indicating the reliability of market available materials of this thermocouple in comparison of the other selected thermocouples.

- Mismatching of theoretical and experimental values of figure of merit for Constantan-Nichrome thermocouple arises mainly due to the difference in the Nichrome composition. Theoretical composition of pure Nichrome was taken as nickel (80%) + chromium (20%) whereas elemental characterization indicates the main presence is of iron element. The presence of copper also brings uncertainty in the theoretical and experimental values of thermocouples with copper as a part of it. This may be assigned to some type of inaccuracy in the values of its physical properties.