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

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

Jaspal Singh [α] & S.S. Verma [σ]

Abstract - Figure of merit along with low cost and easy availability are considered the important parameters of a thermoelectric material for its suitability and efficiency. This paper reports figure of merit for some common thermocouples as a function of thermal and electrical conductivity of thermoelectric materials in the high temperature range. The five different thermocouples are studied in normal mode (without any applied electric or magnetic field) for the generation of thermo emf and then the figure of merit is calculated. Finally, theoretical and experimental results are compared in the temperature range from 300-630 K.

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I. Introduction

Thermoelectricity is a well known phenomenon to generate thermo emf by the thermoelectric materials. This phenomenon is based on the temperature gradient of the junctions a thermocouple. This technology is becoming famous due to a large number of thermocouple devices, which are able to generate energy in the considerable means and are also advantageous due to their pollution free nature, no moving parts and no complex designs. Applications range from house warmer systems to the advanced solar cell technologies [1-2].

Present days are the days of energy crises due to a much consumption of energy in all the fields with low efficient devices. Thermoelectricity can play a meaningful role to contribute towards energy crisis all along with renewable energy sources. This technique can easily generate the thermo emf in the considerable means with the advent of common thermocouples. The common thermoelectric materials like Cu, Fe, Al and Nichrome are very advantageous due to their low cost and easy availability [3-4].

The figure of merit is one of the most important term to describe the performance of the thermoelectric materials. This is the dimensionless quantity given by ZT $= \frac{\alpha^2 \sigma T}{\lambda}$ here α, σ and λ are the Seebeck constant, electrical conductivity and thermal conductivity of the thermoelectric material respectively. The temperature difference of the two junctions of the thermocouple is given by T. This has been observed that more is the figure of merit of a thermo electric material more is its efficiency and vice-versa. This is also clear from the relation that to enhance the figure of merit, the thermal conductivity should be minimum and the electrical conductivity should be maximum to the possible. Numbers of researchers working in the area of thermoelectric are oriented to improve figure of merit [5-7].

Normal mode of our study is the investigation of thermo emf generation under the conditions, i.e. without outside application of electric or magnetic fields [8-9]. We selected five thermocouples Cu-Fe, Fe-Nichrome, Constantan-Nichrome, Fe-constantan and Cu-Nichrome for present investigations on the basis of their less cost and easy availability. These thermocouples are investigated for the generation of thermo emf in wide temperature range from the room temp (300K) to 630K. The figure of merit for the thermocouples is calculated from the experimental data which is then compared with the calculated theoretical values. The standard equations of thermoelectricity are used for the calculations of present theoretical values.

II. Methodology

Present research findings represent to theoretical and experimental comparison of the figure of merit of some common thermocouples.

a) Theoretical Calculations

The figure of merit of all the thermocouples is calculated from the relation [10]:

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

Here α_a and α_b are the Seebeck constants (in V / °C) and and ρ_a & ρ_b are the resistivity's (specific resistances) (in Ω m) of both the materials of a thermocouple. Similarly, $\lambda_a$and λ_b are the thermal conductivities (in W $m^{-1}K^{-1}$) of both the thermoelectric materials. To calculate the figure of merit, we have used the theoretical values of all the physical properties of

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equation (1) for pure materials [10]. The X-ray diffraction peaks for elemental analysis of all four materials given in Figure 1 (a, b, c & d) show the presence of only major component of the main material and thus materials are taken near to be pure.

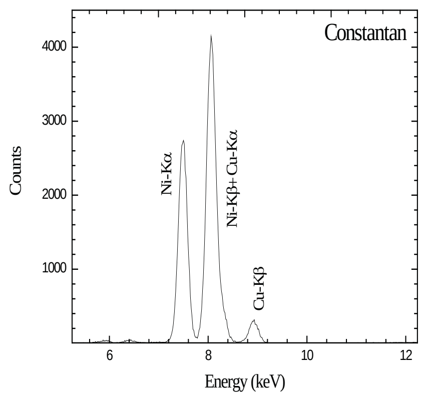

Figure 1(a) : Constantan Wire

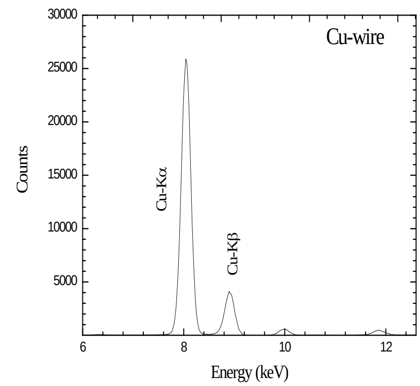

Figure 1(b) : Copper Wire

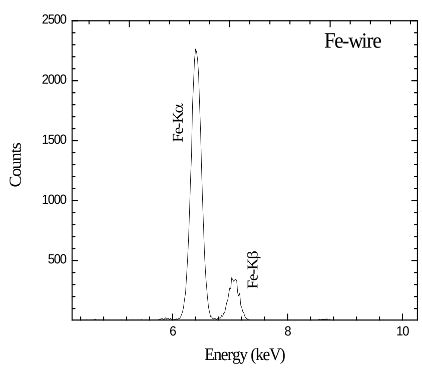

Figure 1(c) : Iron Wire

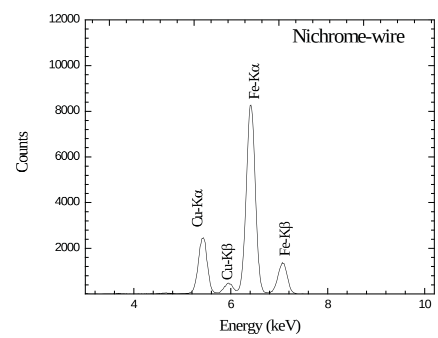

Figure 1(d) : Nichrome Wire

Figure 1 : (a, b, c & d): X-ray characterization graphs for different wires used presently to make the thermocouples

The values of all theoretical parameters take and thus calculated are given below in Tables 1 and 2:

Table 1 : Theoretical Parameters of the thermoelectric materials

Sr. No.	Parameter	Copper	Iron	Constantan	Nichrome
1.	Thermal Conductivity λ ($Wm^{-1}K^{-1}$)	401	80.4	19.5	11.3
2.	Seebeck Constant α (μV/ ^{0}C)	6.5	19	-35	25
3.	Resistivity ρ (Ohm-m)	1.678×10^{-8}	9.6×10^{-8}	5×10^{-7}	1.5×10^{-6}
4.	Electrical Conductivity σ ($S\ m^{-1}$)	5.96×10^{7}	1.041×10^{7}	2×10^{7}	6.67×10^{5}

Table 2 : Theoretical Values of Seebeck Constant (α) and Figure of Merit (Z) for different thermocouples

Sr. No.	Parameter	Cu-Fe	Fe-Nichrome	Cu-Nichrome	Fe-Constantan	Constantan-Nichrome
1.	Seebeck Constant α (V/ ^{0}C)	1.3×10^{-5}	6×10^{-6}	1.9×10^{-5}	5.4×10^{-5}	6×10^{-5}
2.	Figure of merit , Z ($^{0}C^{-1}$)	1.2×10^{-8}	1.3×10^{-7}	3.2×10^{-8}	1.22×10^{-5}	2.95×10^{-5}

b) Experimental Calculations

We use the following mathematical equations to calculate the Figure of merit from the experimental parameters of the thermoelectric materials. The basic thermoelectric equation is:

$$E = \alpha t + \frac{1}{2}\beta t^2 \quad (2)$$

Here E is the thermo emf in mV and α, β are the Seebeck constants. The thermo power i.e. the rate of change of thermo emf w.r.t. time is given by: $\frac{dE}{dT} = \alpha + \beta t$ from (2) but β is very small so $\frac{dE}{dT} = \alpha$ and for the two thermoelectric materials (a thermocouple) α can be replaced by α_{ab} and by squaring we can write:

$$\left(\frac{dE}{dT}\right)^2 = (\alpha_{ab})^2 \quad (3)$$

Thus, the figure of merit is given by:

$$ZT = \frac{(\alpha_{ab})^2 T}{\rho\lambda} \quad (4)$$

We know that:

$$\rho = \frac{Ra}{l} \quad (5)$$

Here a and l are the area of crossection and length of the thermoelectric material respectively. Then from (3), (4) and (5), the figure of merit is given as:

$$ZT = \frac{\left(\frac{dE}{dT}\right)^2 T}{R\left(\frac{\lambda a}{l}\right)} \quad (6)$$

Putting $\frac{\lambda a}{l} = K$ then ZT becomes as [10]:

$$ZT = \frac{\left(\frac{dE}{dT}\right)^2 T}{RK} \quad (7)$$

As the final resistance of the thermocouple is a parallel combination of individual resistances, so R (of thermocouple) can be calculated as:

$$R = \frac{R_1 R_2}{R_1 + R_2} \quad (8)$$

Taking the value of K as:

$$K = \frac{K_1 + K_2}{2} \quad (9)$$

By using the values of K (Thermal Conductivity) and R (resistance) from equations (8) and (9) we calculate the figure of merit of equation (7). This is to note here that the value of $\frac{dE}{dT}$ is extracted from the slope of graph between thermo emf (E) and the temperature gradient (T) for the individual thermocouples. The equation for a linear fit of a graph is, $y = A + Bx$ and then the slope is $\frac{dy}{dx} = B$ but our graphs are between thermo emf (E) and the temperature difference (T) so $\frac{dE}{dT} = B$ (a constant numerical value i.e. Seebeck Constant α). Hence we can take $\frac{dE}{dT} = \alpha$

Table 3 : Experimental Calculations of Seebeck Constant (α) and Figure of Merit (Z) for different thermocouples

Sr. No.	Parameter	Cu-Fe	Fe-Nichrome	Cu-Nichrome	Fe-Constantan	Constantan-Nichrome
1.	$\frac{dE}{dT} = \alpha$ (v/°C)	4.2×10^{-7}	1.32×10^{-6}	1.25×10^{-6}	1.955×10^{-5}	1.074×10^{-5}
2.	$Z = (dE/dT)^2 / RK$ (°C^{-1})	1.7×10^{-10}	3.8×10^{-8}	1.3×10^{-9}	1.233×10^{-5}	8.5×10^{-6}

Table 4 : Experimental parameters of thermoelectric materials

Sr. No.	Parameter	Copper	Iron	Constantan	Nichrome
1.	Resistance (Ohm)	0.1918	0.7062	0.5174	1.6874
2.	Area of Cross-Section (m^2)	1.51×10^{-6}	9.5×10^{-7}	1.112×10^{-6}	9.7×10^{-7}
3.	Length (m)	48×10^{-2}	48×10^{-2}	48×10^{-2}	48×10^{-2}
4.	Resistivity ρ (Ohm-m)	6×10^{-6}	1.4×10^{-6}	1.2×10^{-6}	3.41×10^{-6}
5.	Electrical Conductivity σ (S m^{-1})	1.67×10^{6}	7.143×10^{5}	8.33×10^{5}	2.933×10^{5}

III. Experimental Setup

The four thermoelectric materials i.e., Cu, Fe, Constantan and Nichrome were used to fabricate five thermocouples of each wire of 48cm length. The basics of the experimental set up used in present studies stand same as in our earlier research [11] though with suitable modifications. A hot and cold temperature arrangement for thermocouple junctions was made with a wooden stand. An electric furnace was used to heat the junction and fresh water from tap with an arrangement was used to maintain the room temperature of the cold junction. The HP 34401 digital multi-meter was used to measure the thermo emf and resistance of the wires [11].

IV. Results and Discussion

Experimentally measured thermo emf as a function of temperature difference between hot and cold junctions for all five thermocouples is shown in Figure 2. Going through the performance comparison of different thermocouples from Figure 2, it is clear that for similar experimental conditions Fe-constantan thermocouple gives the maximum thermo emf generation where as Cu-Fe gives the least values. Thermo emf generation for Fe-constantan thermocouple increases to the highest temperature difference upto 3000C giving values to the range of 7mV.

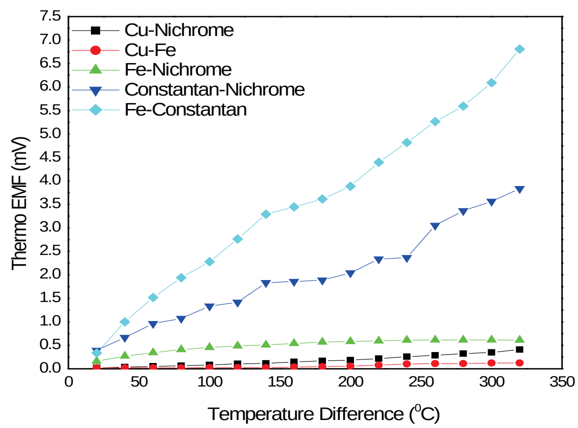

Figure 2 : Thermo emf generation with temperature difference of thermocouple junctions

From the above discussed theoretical and experimental calculations for Z, we obtained the theoretical and experimental values of dimensionless parameter ZT i.e. the figure of merit for all five thermocouples as a function of temperature difference, T in Kelvin of thermocouple junctions. A comparison of theoretical and experimentally calculated values of ZT with the temperature difference, T for each of the thermocouple was done and is shown in Figure 3 (a, b, c, d & e).

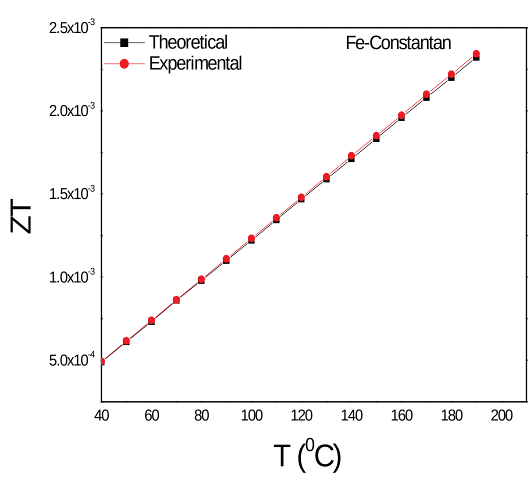

Figure 3(a) : Comparison for Fe-Constantan

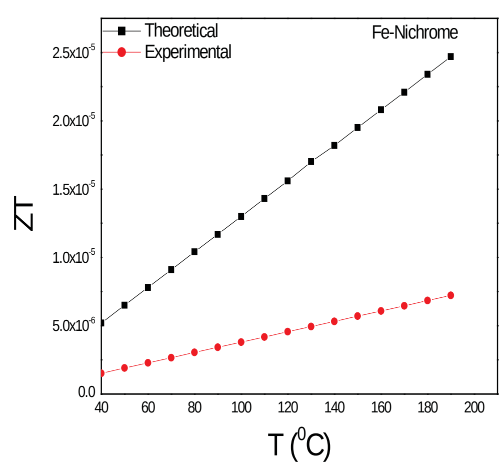

Figure 3(b) : Comparison for Fe-Nichrome

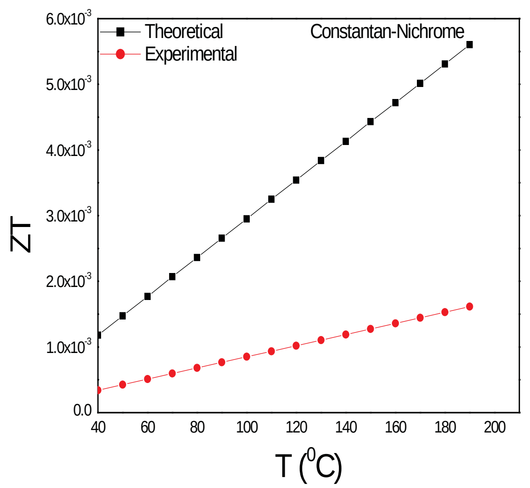

Figure 3(c) : Comparison for Constantan-Nichrome

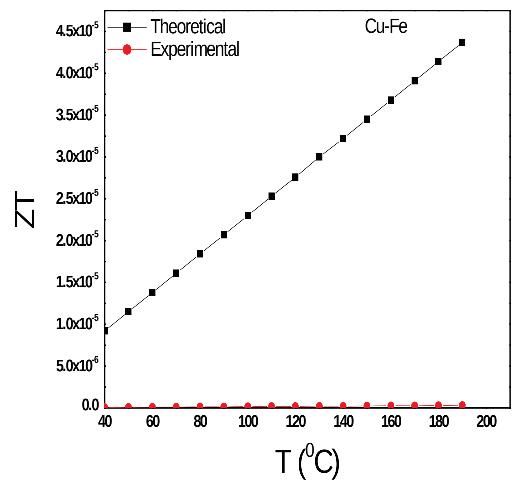

Figure 3(d) : Comparison for Copper-Iron

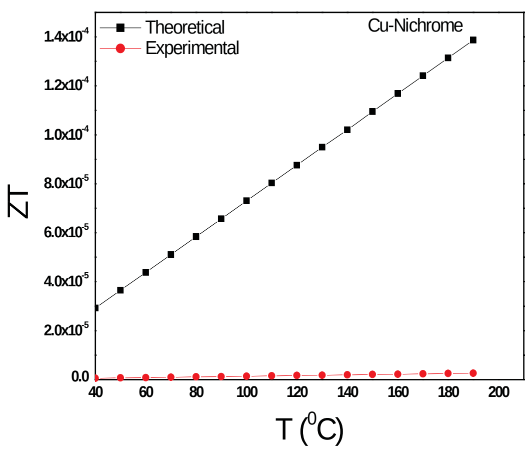

Figure 3(e) : Comparison for Copper-Nichrome

The comparison shows that there is a perfect matching between the theoretical and experimental values of figure of merit for the Fe-Constantan thermocouple, which not only confirms the accuracy of present measurements but also indicate the worthiness of this thermocouple for better performance in its uses in thermoelectrics. Theoretical vs experimental comparison also comes better for Fe-Nichrome and Constantan-Nichrome thermocouples but there was a significant difference between the values for other two i.e., Cu-Fe and Cu-Nichrome thermouples. The wide difference between theoretical and experimental values may be assigned to low levels of thermoemf generation in these thermocouples due their strong dependence on physical & chemical properties and operating parameters of thermocouple materials. Comparison of results directly indicates the superiority of Fe-Constantan thermocouple over other four thermocouples for their use in thermoelectrics.

V. Conclusions

This paper concludes that:

- Fe-Constantan shows a better thermocouple combination to match for their experimental and in the theoretical values of thermo emf generation.
- Poor matching of theoretical with experimental findings for thermocouples of Fe-Nichrome and Constantan-Nichrome indicates the uncertainty in the experimental behavior of Nichrome, significant contribution from its components or high inaccuracy in the values of its physical properties.
- More gaps between matching of theoretical and experiment values of thermo emf for Copper-Nichrome and Copper-Iron thermocouples again show the uncertainty in the experimental behavior of Nichrome, significant contribution from its components or high inaccuracy in the values of its physical properties.
- Influence of thermoelectric nature or properties of different thermocouple materials hence, indicates towards their performance in their thermoelectric applications.

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