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Optimization of Thermo electric cooler by using Genetic Algorithm

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The use of thermoelectric coolers played indispensable role significantly in recent years. Thermoelectric cooler has potential application in numerous fields such as TEC contain no moving parts, able to operate in any orientation, having compact size, and excellent cooling alternative to vapor compression cooler systems which are sensitive to mechanical vibration. There are two basic attributes which decide the effectiveness of TEC: coefficient of performance (COP) and cooling capacity or rate of refrigeration (ROR). In the present work optimization of performance parameters of thermoelectric cooler (TEC) are conducted on single stage thermoelectric cooler. Based on TEC parameters and three different values of thermal resistance of hot side heat exchanger, set of solutions for TEC are derived for optimal values of rate of refrigeration and coefficient of performance at fixed values of input current of TEC, electrical resistance at junctions where Cold side temperature and ambient temperature are fixed. Here Genetic algorithm has been used for optimization. The result shows the significant enhancement achieved based on optimized values of length and cross- sectional area of TE elements. Further, a Pareto-optimal front using NSGA-II is employed for various set of values of optimal rate of refrigeration and optimal coefficient of performance by simultaneous optimization of both the objectives.

Keywords: Thermoelectric cooler, optimization, cooling capacity, coefficient of performance, Genetic Algorithm.

I. INTRODUCTION

There are several Technological advancements in many fields of engineering which have given multi options to provide ease for human comfort and ecological clean alternatives. In recent advancements, the electronic industry has developed rapidly. An electronic device sizes are shrunk and their performance capacity raised but there chip-level power density has continued to rise greatly which highly affect the devices degrading their quality of performance. Thermal management is a major issue in system performance of such electronic devices. Such as laser diodes, semiconductor optical devices, infrared detectors where TEC is employed to control their thermal and electrical stability. Thermoelectric cooler most suitable and acceptable where environmental concerns such as global warming, ozone depletion and a lack of energy efficiency are necessary to consider and to investigate alternative cooling technologies to the refrigeration that uses refrigerants [1].

The pairs of thermoelectric cooler are made of two semiconductor elements, frequently made of bismuth telluride highly doped to create an excess (**n**-type) or a deficiency of electrons (**p**-type). The heat absorbed at the cold junction is transferred to the hot junction at a rate proportional to the current passing through the circuit and the number of semiconductors pairs. In practice, pairs are combined into a module which they are electrically connected in series and thermally in parallel.

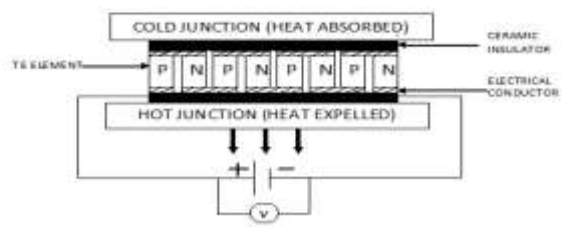

Fig 1: Schematic diagram of single stage thermoelectric cooler where TE elements connected electrically in series and thermally in parallel

Since TEC system is employed in electronic equipment, it must be constructed and operated with utmost precision. The basic performance attributes of TEC are the cooling capacity and coefficient of performance (COP) of the system. According to Wu and co-workers [2] indicated that the thermal performance of the hot- side heat exchanger strongly affected the COP and the cooling capacity. Their result indicates that the thermal performance of the hot side heat exchanger strongly affected the COP and the cooling capacity. Under poor design conditions, the hot side heat exchanger may reduce the range of the operating current. The main goal of this paper is to design such thermoelectric cooler which optimizes the performance characteristics and geometrical parameters.

There are many such studies which have been conducted in order to maintain a bridge between thermal resistance and performance characteristics of TEC. Yamanashi et al. [1, 2] and Chen [3] studied the optimum design of a multistage TEC system with a maximum COP [1]. Several other research works have been carried out to examine the optimization of TECs, and they also proposed algorithms to optimize the internal structure of systems to maximize either COP or ROR. The scaling law [8] is used to investigate the effects of the geometrical parameters (size of leg of TEC) on performance, and reveals that the maximum cooling capacity increases with the decrease of the leg length. Otherwise, the electrical contact resistance [9] and the thermal contact resistance [10] strongly affect the performance of the TEC. Since thermoelectric devices are very sensitive to boundary as well as operating conditions; choice of suitable materials, geometry, and operating conditions play a vital role in creating the optimum thermoelectric technology for a specific requirement. Thus, it is important to study these devices to extract their maximum performance.

Recently GA is gripped a lot and used extensively as optimization tool. It is a computerized search and optimization technique that is based on the evolutionary principles of natural genetics and natural selection [11, 12], extensively applied to solve various complex problems of TEC. This present work involves optimization of rate of refrigeration and coefficient of performance of thermoelectric cooler. Where, length of thermoelectric elements cross-sectional area of thermoelectric element and Number of legs of TE elements used as a variable parameter. Since optimizing the geometric dimension of the TEC will increase cooling capacity, while simultaneously considering its minimum COP. This study proposed a method of optimizing the dimension of TECs using genetic algorithm (GAs) to the maximum cooling capacity and coefficient of performance simultaneously at the particular value of thermal resistance.

II. MATHEMATICAL MODEL

The COP is a measure of performance of TEC like for other thermoelectric devices. COP is the amount of heat extracted per unit time divided by amount of supplied electrical power [1]. The following assumptions are made to simplify the calculations:

1. The heat absorption and heat rejection occurs only at the junctions.
2. The leakage of heat from the thermo couple to the surroundings is neglected.
3. p – type and n – type thermoelectric elements have identical properties, except that the polarities of their Seebeck coefficient are geometrically opposite.
4. The Thomson effect is neglected.

Under steady state conditions, we may write the following energy balance equations for single stage system:

$$Q_c = N\left[I\alpha T_C - K(T_h - T_c) - 0.5I^2R\right] \quad (1)$$

$$Q_h = N\left[I\alpha T_h - K(T_h - T_c) + 0.5I^2R\right] \quad (2)$$

Where Q_c (watt) is the rate of refrigeration (ROR) or heat extracted per unit time from the cold junction , Q_h(watt) is the heat rejected per unit time from the hot junction , I (ampere) is the input current of the TEC . α (volts / Kelvin) is the seebeck coefficient, T_c(Kelvin) is the cold side temperature, T_h (Kelvin) is the hot side temperature , K (watt/ Kelvin) is the thermal conductance of thermoelectric elements , R (ohm) is the electrical resistance (conductors + contact resistance at junctions) of thermoelectric elements and N is the number of thermoelectric elements .

These equations may be expressed as :

$$Q_c = N\left[I\alpha T_c - \frac{KA(T_h - T_c)}{L} - \frac{1}{2}I^2\left(\frac{\rho L}{A} + \frac{2r_c}{A}\right)\right] \quad (3)$$

$$Q_h = N\left[I\alpha T_h - \frac{KA(T_h - T_c)}{L} + \frac{1}{2}I^2\left(\frac{\rho L}{A} + \frac{2r_c}{A}\right)\right] \quad (4)$$

Where K (watt / meter- Kelvin) is the thermal conductivity , A (square meter) is the area of thermoelectric elements , L (meter) is the length of thermoelectric elements , ρ is the electrically resistivity (ohm – meter) and r_c (ohm- square meter) is the electrical contact resistance at junctions.

The above thermoelectric material properties are determined by

$$\alpha = (\alpha)_p - (\alpha)_n \quad (5)$$

$$\rho = (\rho)_p - (\rho)_n \quad (6)$$

$$r_c = (r_c)_p - (r_c)_n \quad (7)$$

$$K = (K)_p - (K)_n \quad (8)$$

Where the subscripts p and n indicate the properties of p – type and n – type semiconductors. Input electrical power (P) is

$$P = Q_h - Q_c \quad (9)$$

Or

$$P = N\left[I\alpha(T_h - T_c) + I^2\left(\frac{\rho L}{A} + \frac{2r_c}{A}\right)\right] \quad (10)$$

The input electrical power may also be calculated as

P = No. of TE elements × Input voltage × Applied current
= N [(Seebeck Voltage + Voltage due to resistance) × applied current

$$= N\left[I\alpha\left(T_h - T_c\right) + I^2\left(\frac{\rho L}{A} + \frac{2r_c}{A}\right)\right] \tag{11}$$

COP of the thermoelectric cooler is

$$COP = \frac{Q_c}{P} \tag{12}$$

or

$$COP = \frac{N\left[I\alpha T_c - \frac{KA\left(T_h - T_c\right)}{L} - \frac{1}{2}I^2\left(\frac{\rho L}{A} + \frac{2r_c}{A}\right)\right]}{N\left[I\alpha\left(T_h - T_c\right) + I^2\left(\frac{\rho L}{A} + \frac{2r_c}{A}\right)\right]} \tag{13}$$

When the hot side heat exchanger has a thermal resistance of the R $_{th}$ the temperature consistence between the hot side of the Tec and of the base of heat exchanger should be maintained as

$$T_h = Q_h R_{th} + T_{avg} \tag{14}$$

The material properties are considered to be dependent on the average temperature, T_{avg} given by, $T_{avg} = \left(T_h + T_c\right)/2$ and can be obtained by applying experimental formula of MELCOR , USA [9].

$$\alpha = (22224 + 930.6\, T_{avg} - 0.9905 T_{ave}^{\,2)}\ x\ 10^{-9}$$
$$\rho = (5112 + 163.4\, T_{avg} + 0.6279\, T_{ave}^{2})\ x\ 10^{-10}$$
$$K = (62605 - 277.7\, T_{avg} + 0.4131\, T_{ave}^{2})\ x\ 10^{-4} \tag{15}$$

III. OPTIMIZATION: GENETIC ALGORITHM: SINGLE STAGE TEC

This work utilizes genetic algorithm (GA) to treat the optimization of TEC keeping rate of refrigeration (ROR) and coefficient of Performance (COP) as objective function. Length of elements, cross- sectional area of elements and number of elements are the variable. Based on three different values of thermal resistance of the hot side heat exchanger (R_{th}) optimization of ROR and COP of thermoelectric cooler has been concluded.

IV. IMPLEMENTATION OF GENETIC ALGORITHM

The TEC system should be designed as compact as possible because the space in an electronic equipment is limited. If we know the thermal resistance of the hot side exchanger and the confined volume space where TEC system is to be placed then the optimization of performance parameters become little bit easy.

The problem of the optimization of the thermoelectric cooler is formulated as the following objective optimization problem:

Max ROR/COP (Objective Function)

Subject to
$L_{min} < L < L_{max}$
$A_{min} < A < A_{max}$
$N_{min} < N < N_{max}$

where, L is the length of TE elements , the area of TE elements and N number of Thermo electric Element. The cold side temperature (T_c) of the TEC is the set as 295 Kelvin for this work. Ambient Temperature (T_a) is taken as 298.15 Kelvin (standard Ambient temperature and pressure).

The following values set for all the cases have been taken from chang's work

Input current of the TEC , I = 1 ampere

Electrical contact resistance at junctions , r_c = 1 x 10^{-8} Ωm^2

Cross sectional area of TEC devices , S = 25 mm^2

The minimum limit for length of the thermoelectric elements (L_{min}) is taken as 0.1 mm and maximum limit for length of thermoelectric elements(L_{max}) taken as 1.0 mm . The minimum limit for area of the thermoelectric elements (A_{min}) is taken as 0.3 mm^2 and maximum limit for the area of the thermoelectric elements (A_{max}) is taken as 0.6 mm^2. For the implementation of GA, the population size and the maximum number of generation for evolution must be determined. Also, crossover rate and mutation rate are to be chosen for constructing a new set of solutions.

The initial settings used are as mention below. The cross over operator and mutation operator are applied some probabilities.

Population size	: 30
No. of generations	: 1000
Real Variables	: 3
Lower and upper Bound of Length	: 0.1 mm to 1.0 mm
Lower and Upper Bound Area	: 0.3 mm^2 to 0.6 mm^2
Lower and upper bound of Number of elements	: 1-83
Probability of cross over	: 0.8
Probability of mutation	: 0.33
Distribution index for cross over	: 10
Distribution index for mutation	: 50
Random seed number for 1 run	: 0.1234

In present work, we used real coded GA (RGA), since the value of decision variables (length, area of elements and number of thermo Electric Elements) that are expressed as genes of chromosomes are selected as real number with in upper limit and lower limit . The selected value of decision variables is used as a input value and gives the objective function to calculate the value of fitness. Fitness value (rate of refrigeration in this case) of each solution is checked. Solution from population is taken and used to form a new population (same size). This is motivated by a hope that a new population will perform that its predecessors. Every new population is called next generation. Solutions chosen to from new solutions (offspring) are selected based on their fitness- the more suitable they are, the better their chances of being reproduced. This process is repeated till predestined number of population (number of generation) is reached which is 1000 is presented study. Five runs were held for this optimization procedure. Maximum value of rate of refrigeration (ROR) at any generation number is considered as the best fitness at that generation number. The optimization of rate of refrigeration is done for three different values of thermal resistance of hot side heat exchanger (R_{th}). These values of R_{th} are 0.1 ^{0}C/ W, 0.3 ^{0}C/ W, 0.5 ^{0}C/W.

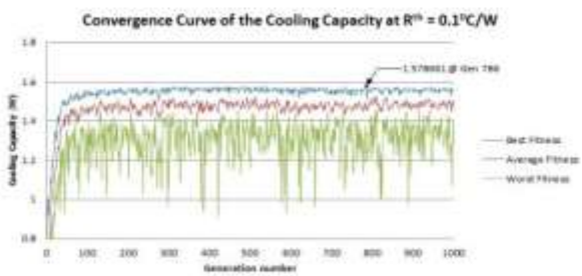

Figure 2 : Rate of refrigeration (W) at R_{th} = 0.1 ^{0}C/W

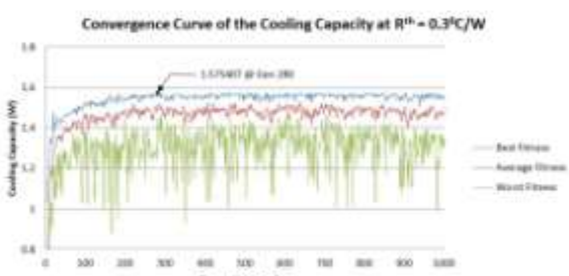

Figure 3 : Rate of refrigeration (W) at R_{th} = 0.3 ^{0}C/W

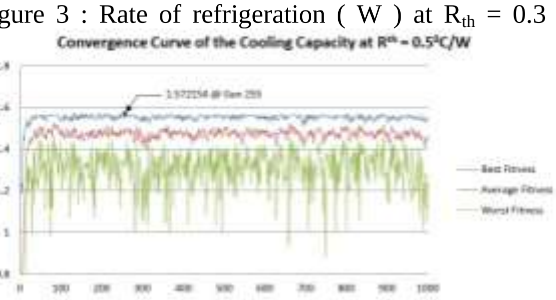

Figure 4 : Rate of refrigeration (W) at R_{th} = 0.5 ^{0}C/W

Table – 1 Optimum parameters for maximum ROR

R_{th} (^{0}C/W)	L (mm)	A (mm^2)	N	Optimized ROR (Watt)	T_h (kelvin)	COP
0.1	0.227173	0.36228	69	1.578660	298.168224	0.364861
0.3	0.226813	0.362308	69	1.575407	298.185267	0.364229
0.5	0.226843	0.357131	70	1.572154	298.202584	0.353192

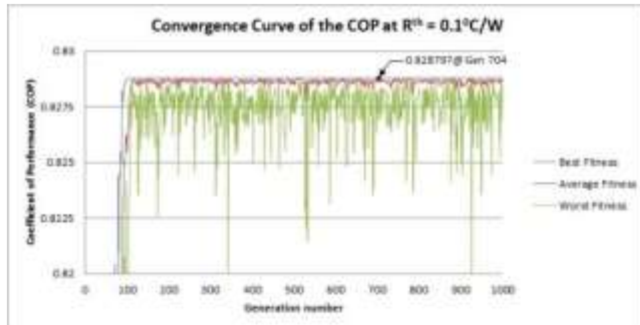

Figure 5 : Coefficient of performance at R_{th} = 0.1 ^{0}C/W

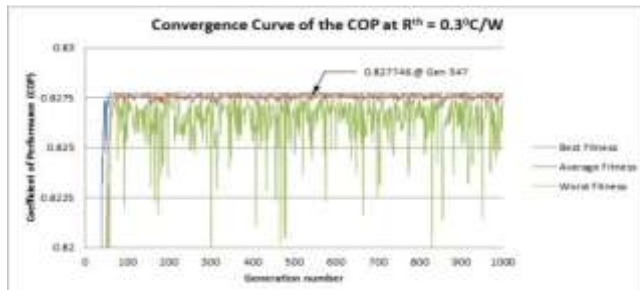

Figure 6: Coefficient of performance at R_{th} = 0.3^{0}C/W

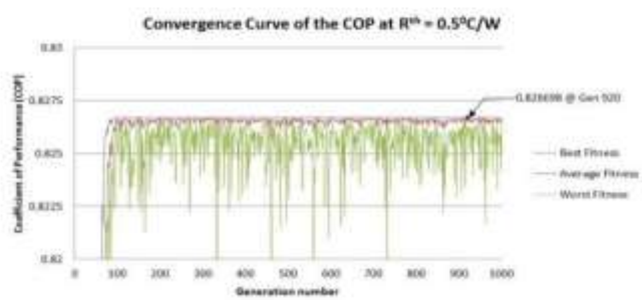

Figure 7: Coefficient of performance at R_{th} = 0.5^{0}C/W

Table No. 2 Optimum parameters for Maximum COP

R_{th}(^{0}C/W)	L (mm)	A (mm^2)	N	ROR (Watt)	T_h (Kelvin)	Optimized COP
0.1	0.361528	0.600000	26	1.008131	298.167082	0.828797
0.3	0.362357	0.600000	26	1.008063	298.181859	0.827746
0.5	0.363186	0.600000	26	1.007956	298.196634	0.826698

On comparing the results obtain during optimization of rate of refrigeration and coefficient of performance separately that only the specific performance parameter is optimized but the other one is in the range of average fitness or worst fitness. Under these circumstances, the next step is to do multi- objective optimization of COP and ROR so we can get solutions that are optimal with respect to the both objective. Thus in multi- objective optimization approach the pareto- optimal technique is employed.

Max ROR
Max COP
Subject to
$L_{min} < L < L_{max}$
$A_{min} < A < A_{min}$
$N_{min} < N < N_{max}$

Non-dominated sorting genetic algorithm-II has been used for multi-objective optimization. Genetic algorithm settings are described below:

Population size : 30 (for value of R_{th} 0.1 and 0.3, 0.5)
No. of generation : 1000
No. of objectives : 2
Number of real variables : 3
Lower limit of real variables- I : 0.1
Upper Limit of real variable- I : 1.0
Lower Limit of real variable – II : 0.3
Upper Limit of real variable –II : 0.6
Lower limit of real variable – III : 1
Upper limit of real variable –III : 83
Probability of crossover of real variable : 0.8
Probability of Mutation of real variable : 0.33
Distribution index for cross over : 10
Distribution index for mutation : 20

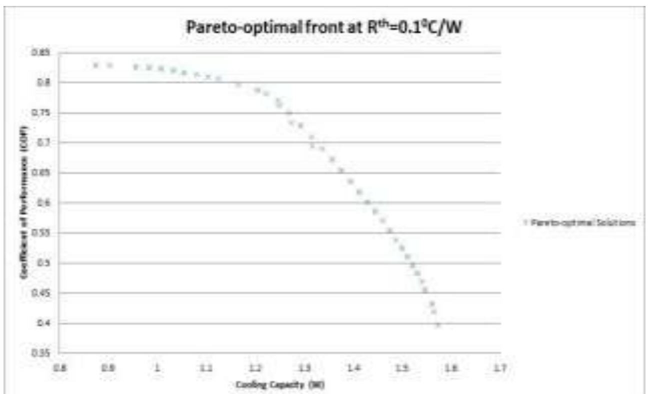

Figure 8: Pareto-Optimal Front at R_h= 0.1^0C/W

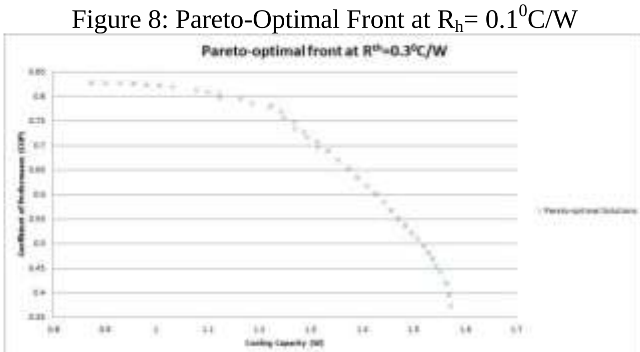

Figure 9: Pareto-Optimal Front at R_h= 0.3^0C/W

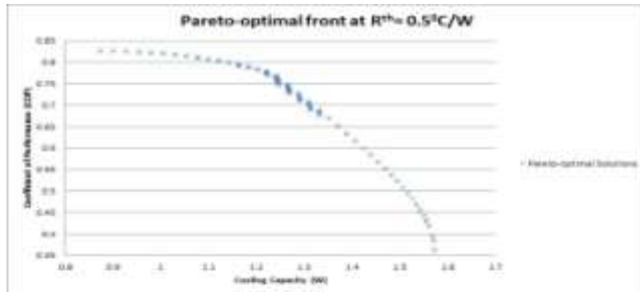

Figure 10: Pareto-Optimal Front at R_h= 0.5^0C/W

Table No. 3 Optimum parametric value of ROR and COP on different R_{th}

Thermal Resistance R_{th} ^{0}C/W	Length of TE(mm)	Area of TE(mm^2)	Number of TE (N)	ROR (optimum)	COP (optimum)
0.1	0.384565	0.390624	41	1.254461	0.796653
0.3	0.384769	0.390625	41	1.243803	0.7865911
0.5	0.386331	0.390625	41	1.242577	0.779662

V. CONCLUSIONS

Optimizing cooling capacity at different value of thermal resistance at 0.1 ^{0}C/W, 0.3 ^{0}C/W, 0.5 ^{0}C/W respectively:

1. Optimum values of ROR achieved are 1.578660 watts, 1.575407 watts, 1.572154 watts at 0.1 ^{0}C/W, 0.3 ^{0}C/W, 0.5 ^{0}C/W values of thermal resistance respectively.
2. The Area of TE is 0.36228, 0.362308, 0.357131 mm^2 respectively which in the permitted range of area of TE elements was 0.3- 0.6 mm^2.
3. The Length of TE is 0.227173, 0.226813, and 0.226843 while optimizing cooling capacity which lies in the permissible range of 0.1- 1.0 mm.
4. The Number of TE cooler (N), at 0.1^0C/W , 0.3^0C/W the optimized value of ROR is 69 but for 0.5^0C/W thermal Resistance the value of number of Thermo electric elements is 70.
5. The corresponding value of COP during optimizing cooling capacity, the Values of coefficient of performance are not optimum for different value of R_{th} 0.1 ^{0}C/W, 0.3 ^{0}C/W, 0.5 ^{0}C/W is 0.364861, 0.364229, 0.353192.

Optimizing coefficient of performance at different value of thermal resistance at 0.1 ^{0} C/W, 0.3 ^{0} C/W, 0.5 ^{0} C/W respectively:

6. Optimum values of COP achieved are 0.828797, 0.827746 and 0.826698 at 0.1 ^{0}C/W, 0.3 ^{0}C/W, 0.5 ^{0}C/W values of thermal resistance respectively.
7. The value of Area of TE is 0.600000, 0.600000, 0.600000 mm^2 respectively which in the permitted range of area of TE elements which is 0.3- 0.6 mm^2 .
8. The value of Length of TE element slightly different from each other i.e. 0.361528, 0.362357,

0.363186 at 0.1 ^{0} C/W, 0.3 ^{0} C/W, 0.5 ^{0} C/W values of thermal resistance respectively.

9. The Number of TE cooler (N) , at 0.1^{0}C/W , 0.3^{0}C/W the optimized value of COP is 26.
10. The corresponding value of ROR during optimizing coefficient of performance, the Values of ROR are not optimum for different value of R_{th} 0.1 ^{0} C/W, 0.3 ^{0} C/W, 0.5 ^{0} C/W is 1.008131, 1.008063, 1.007956.

Multi- objective optimization of both COP and ROR by using pareto- optimal Front:

11. Optimum values of COP achieved are 0.796653, 0.7865911,and 0.779662 at 0.1 ^{0} C/W, 0.3 ^{0} C/W, 0.5 ^{0} C/W values of thermal resistance respectively.
12. Optimum values of ROR are 1.254461, 1.243803 and 1.242577 at 0.1 ^{0} C/W, 0.3 ^{0} C/W, 0.5 ^{0} C/W values of thermal resistance respectively.
13. The Area of TE is 0.390624, 0.390625 , 0.390625 mm^2 respectively which in the permitted range of area of TE elements which is 0.3- 0.6 mm^2 .
14. The Length of TE element 0.384565, 0.384769 and 0.386331 at 0.1 ^{0} C/W, 0.3 ^{0} C/W, 0.5 ^{0} C/W values of thermal resistance respectively.
15. The Number of TE cooler (N) , at 0.1^{0}C/W , 0.3^{0}C/W while optimizing both COP and ROR is 41.

Since the method of GA is applied for optimizing the dimensions of TEC system. When the thermal resistance of the hot side heat exchanger is known, then the element length, element area, and the number of elements can be optimized where both cooling capacity and coefficient of performance can be optimized simultaneously. For designing of TEC, a designer may choose any of the above solution according to importance of the parameters. He can select the parameters as per design criteria from the pareto-optimal solutions which give optimized values with both the objectives.

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