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Review Article

A review on recent opportunities in MATLAB software based modelling for thermoelectric applications

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ABSTRACT

The thermoelectric application is one of most popular energy harvesting application from waste heat. The thermoelectric generators, thermoelectric coolers, and thermoelectric modular devices criterion comes in both sustainable energy as well as renewability of electrical energy from waste heat sinks. The recovery operations are optimized with the help of modeling using MATLAB software. The material science based thermoelectric applications can be modeled with the help of MATLAB simulink modeling. The numerical and algorithmic method of MATLAB modeling is for the development of hybrid thermoelectric coolers and generators (solar thermoelectric generators, radiative cooler, heat sinks). Later, the use of MATLAB software gives opportunities to develop the cost effective and high power thermoelectric generators. The emerging commercial device making is also discussed for thermoelectric generator using MATLAB optimization.

Keywords: MATLAB simulink; MATLAB algorithmic; MATLAB programming; Heat transfer; Thermoelectric cooler and heat generator

1. Introduction

Energy efficiency and power management become the backbone of the industrial revolution. The TEG, TEC and TEM were used for the power productions [26, 56, 66]. The use of renewable energy sources reduces the greenhouse gases emission and protect from cause global warming. TEG is the most important renewable technology in conversion heat to electrical energy and electric to thermal energy [63].The Seebeck and Peltier effects in TEG help to convert heat energy into electrical energy and can incorporate with a solar, all waste heat recovery, nuclear heat management in power plant [23, 26, 45, 47, 65, 66, 68].The thermoelectric conversation technology can be studied with numerous model for probability distribution, Weibul distribution, lognormal distribution, Seebeck effect, thermal coefficient, Peltier effect, PF and figure of merit [1, 2, 5, 29, 31, 41, 49, 53, 58, 68]. MATLAB is one of the powerful tools to model and optimize all the factors related to TEG, TEC and TEM. In the present work, huge areas related to TEM, TEG and TEC are covered with short reviews and also meant the important of MATLAB software role in thermoelectric applications. The emerging opportunities in TEG using MATLAB simulink, MATLAB numerical and algorithmic modeling, cost efficient model, high power gain from MATLAB TEG model and optimization of parameters for TEG using MATLAB is reviewed detailed in the below sections.

Abbreviations	**Nomenclatures**	
TEM- Thermoelectric Module	I_{sc}- Stage of Current vs. Time	P_{in} – Input Power (W, mW)
TEG- Thermoelectric Generator	I – Current (A, mA)	P_{max} – Output Power Maximum (W, mW)
TEC- Thermoelectric Cooler	V- Voltage (V, mV)	P_{pv} – Output of hybrid solar thermoelectric (W, mW)
PCM – Phase Change Material	R- Resistance (Ω, mΩ, KΩ)	P_{te} – Output Power of Thermoelectric Module (W, mW)
STEG – Solar Thermoelectric Generator	P- Power (W, mW)	P, p – P type semiconductor material
STWHG - Smart Thermoelectric Waste Heat Generator	T_H – Hot Junction Temperature (K, °C)	N, n – N type semiconductor material
MPPT- Maximum Power Point Tracking	T_C – Cold Junction Temperature (K, °C)	ΔT – Change in Temperature (K, °C)
PF- Power Factor	$T_{\infty H}$ – Temperature vs. Hot junction (K, °C)	K_{tem} – Thermoelectric Temperature (K, °C)
NSGA-II – Non Dominated Sorted Genetic Algorithm	$T_{\infty C}$ - Temperature vs. Cold junction (K, °C)	K_p – Thermal Resistance of Passive Elements (K, °C)
MOEA/D – Multi Objective Evolutionary Algorithm	I_{load} - Load current with resistance (mA/ Ω)	
MEMS – Micro-Electro-Mechanical systems	R_{int} – Internal Impendence/Resistance (Ω)	

2. Thermoelectric Application Using MATLAB-Simulink

Kane A. et al. [26]. developed a thermoelectric module (TEM) can convert heat energy into electrical power using MATLAB-simulink. They develop a TEM is compact, noiseless, and temperature independent assumption. This mathematical model functions with time and space as shown in the Fig. 1a. The Thomson effect correlates the heating or cooling in a single element; when current or temperature passes through the TEM. The electrical power can be generated by a TEM if a temperature difference is maintained between the two terminals vice versa as a heat pump is shown in Fig. 1b. The TEM is composed of 2 substrates as p and n-type thermo elements. Here, they used three materials Bi_2Te_3, Bi_2Se_3, and Sb_2Te_3 parameters for p and n- type. The TEM generator depends on various parameters as V vs. T, I vs. R, electrical resistance, Seebeck coefficient. Similarly, the dyamic changes in operating conditions and comparing the transient solutions [8, 24, 50, 56, 61, 63, 66, 69]. The resultant output shows the power and efficiency in dynamic form as like Min Chen et al. [45] characteristic curve. The assumed parameter value for the Bi_2Te_3 is shown in the Table. 1.

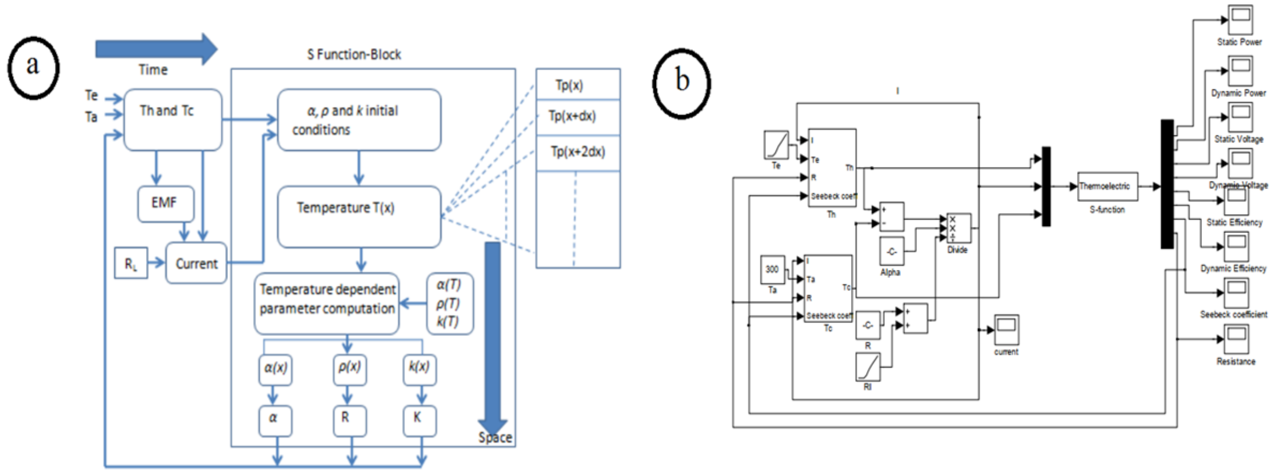

Fig.1. (a) Time and space function block [26], (b) Mathematical model using MATLAB-Simulink [26]

Table 1. Assumed parameters for TEM

Type	Seebeck Coefficient (V/K)	Electric resistivity (W/cmK)	Length of cell (cm)	Area of cell (cm^2/couple)	Heat exchange (cm)	Thermal Conductance (W/cm^2K)	Ref.(s)
p-type (Bi_2Te_3)	230E-06	1.75E-03	1	1	0.104	0.7	Ref. [26]
n-type (Bi_2Sn_3)	195E-06	1.35E-03	1	1.14	0.104	0.7	Ref. [26]
p-type (Cu alloys)	235E-06	1.83E-03	-	1	-	0.4	Ref.[68]
n-type (Al_2O_3)	X > 0.00E-06	1E+12	-	-	0.106	0.37	Ref.[49]

Tsai H. L. et al. [65] controls the carrier concentration in different materials is been optimized the thermoelectric geometry area couple. The authors used MATLAB simulink tool intend of SPICE soft-package to thermocouples will be inter-connected in series to increase the voltage and parallel for increase the thermal conductivity for TEM. They studied both thermoelectric modules (heater and cooler) for better power generation and reduction in thermal resistivity. Likewise, Mitrani. D et al. [47] compare the voltage output as $V = -R(I - I_{sc})$.

Montecucco, A. et al. [51] concentrate on both program and simulink mathematical model to construct the thermoelectric generator. Here, the basic idea of program is based on iteration method with parameters- $T_{\infty H}$, $T_{\infty C,}$ T_H and T_C for temperature and $I_{load,}$ R_{int} for electrical. The parameters for any material can be used for the TEM, TEG, and TEC. The simulations are made by user-algorithm and simulink software. The electrical characteristics for temperature 150°C is clamped at 2kN (1.2 MPa) is shown in Fig. 2a; the Fig. 2b shows power variation with time(s) is measured from P_{in}. The P_{in} value varies 50W to 150W in discrete time interval with respect to I_{load} = 0.2A to 1A. Similar to program and simulink mathematical model Manikandan S. et al. [42] process a combined system of TEG and TEC and achieved maximum power. The overall efficiency of TEG increased 16.9%; it also increases the cooler efficiency upto 36.49%. Khamil K. N. et al. [29] analysis the particular case in TEG performance; they used MATLAB/simulink to examine the performance of Peltier and Seebeck module. They provide a numerical modeling to check with the experimental data sets and also to equate the function of Seebeck and Peltier module. This model helps to identify the errors in percentile, and easy way to find voltage (V) value at any temperature range (hot to cold). The junction settings should be in the MATLAB command window to connect with the simulink. Arora R. et al. [5] designed a hybrid TEG using MATLAB simulink by heat pump model; also used DC-DC converter to get 100% duty cycle. The output power was raised from 56.18W to 75W and it was compared with MPPT for optimize the duty cycle with maximum heating capacity. Elazalik M. et al. [15] investigate the TEG operation of MPPT as experimental and modeling by MATLAB is shown in Fig.3a, they also used DC-DC converter to boost cycle and raised power upto 13.8W for the temperature range from 377K to 457K.

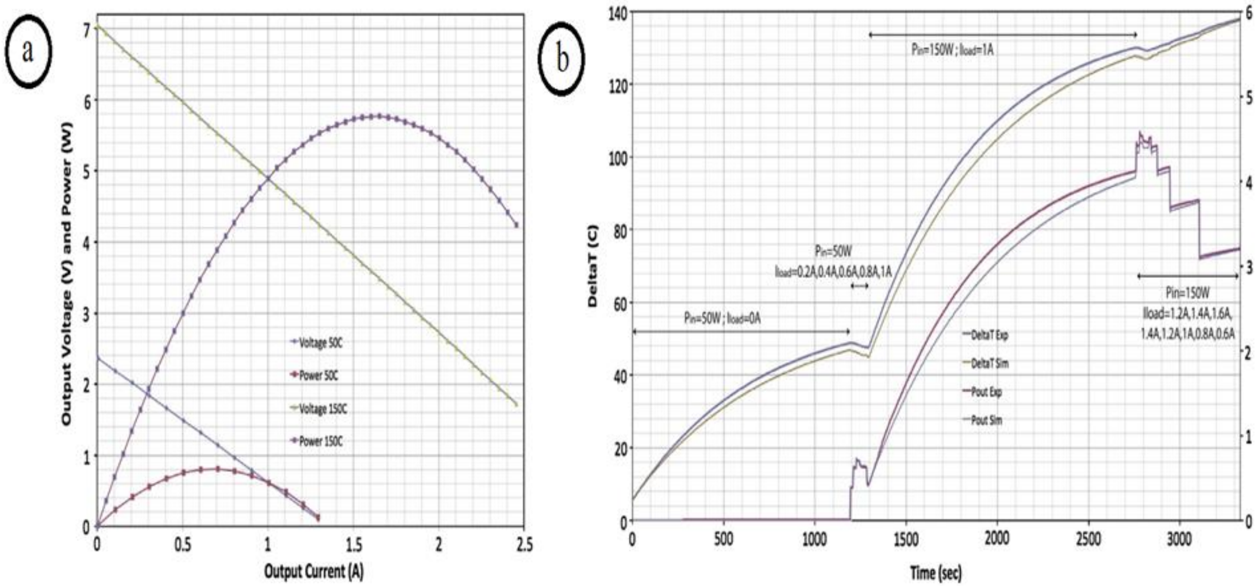

Fig.2. (a) Electrical characteristics [51], (b) output power vs. time of TEG [51]

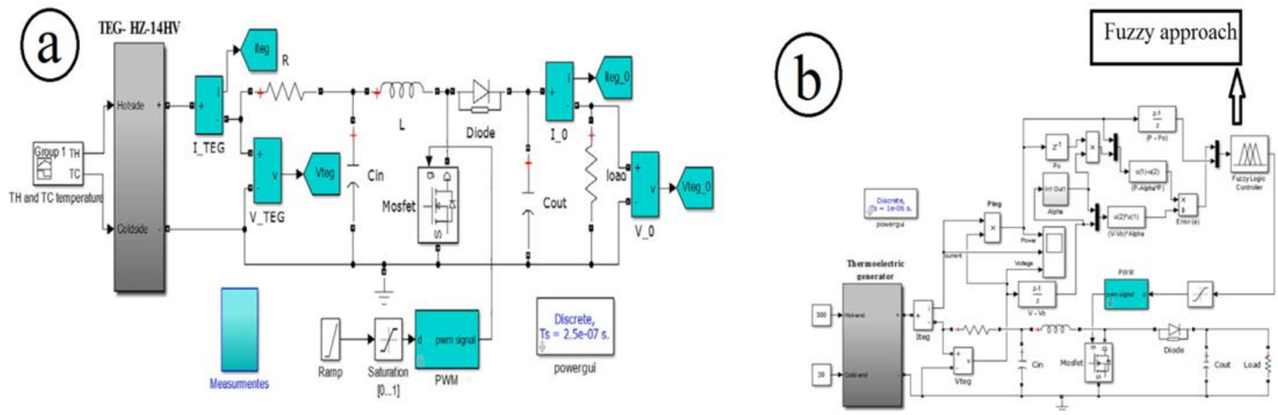

Fig.3. (a) TEG using MATLAB – simulink [15], (b) TEG by Fuzzy logic control [25]

3. Algorithmic and Numerical in Thermoelectric Device

In connection to Arora R. et al. [5] and Elazalik M. et al. [15]; the power and energy conversion efficiency was improved by Kanagaraj N. et al. [25]. The Fig. 3b shows the use of fuzzy logic control for MPPT technique for optimize the steady state output power. Here also the DC-DC boost converters were used along with variable fractional factor. The resultant shows the dynamical change in difference between temperatures of hot and cold junction; it improves the harvest energy level from normal TEG.

In numerical analysis with MATLAB, Maduabuchi C.C. et al. [41] make a hybrid 3D geometry model to perform STEG. Here, they used PCM to increase the output power and minimize the heat dissipation in the system. The STEG should be placed in ambient condition (298K) to recover more power due to cold junction. This numerical model of hybrid PCM- STEG shows 19% more efficiency than normal TEG in the hot junction. Similarly, Kim M.S. et al. [31] investigate the same phenomena of operation with light intensity power as 1.5kWm^{-2}. Foddouli A. et al. [16] investigate the hybrid system (Solar + TEG) using numerical analysis method using MATLAB. They work on both heat and electricity production from solar with the help of solar water heater and TEG. The fluid inlet and outlet operation is controlled by numerical program [13, 37, 57, 72] and the STEG also model with numerical [46, 62]; its efficiency has been increased from 1.95% to 3.95% for 27^{o}C and the power increased from 2.6W to 7.76W. The resultant showed good performance and high stability than normal TEG.

Zhan Z. et al. [70] proposed a radiative cooler model for TEG- heat sink. Here, they used aluminum heat sink bare with TEG model. Similarly, Liu J. et al. [39] also investigate TEG- radiative cooler model using MATLAB. The Fig. 4 shows silver, aluminum heat sink bare for copper based TEG-leg model. Here, the radiative cooler reduces the heat from aluminum sink and generate power upto 1.2 W/m^2. Sattar S. [58] used TEG-leg to calculate the probabilities of failures in function between P-N-P-N-P-N connections; he used MATLAB algorithmic program formed from Weibull and lognormal distribution [10, 28, 34, 71] for finding the stresses, tensile strength and compression phenomena in P-N-P-N-P-N TEG-leg connections.

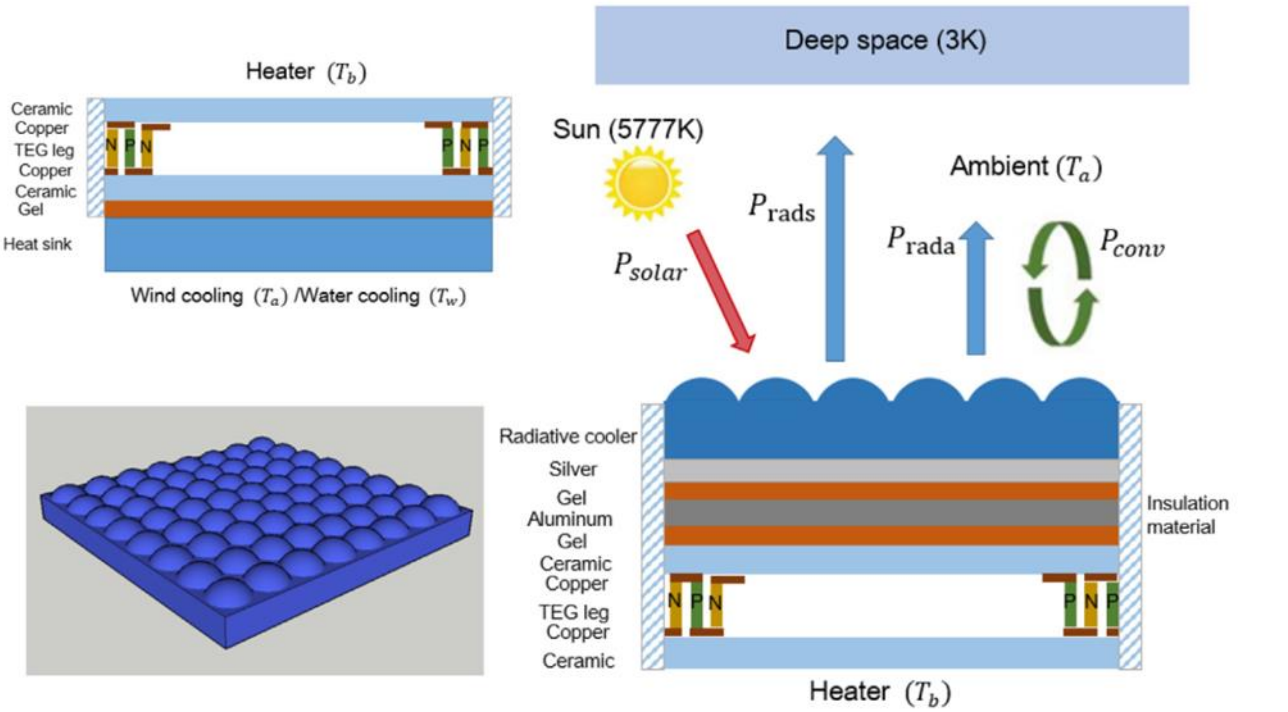

Fig.4. TEG-leg in radiative cooler application [39]

4. Cost Effective and High Power Gain in Thermoelectric Device

Omer G. et al. [53] examine the power and cost for energy consumption in industrial sector. They used MATLAB software to construct a STWH-Generator for industrial establishment; the Fig. 5 shows the step wise factors to control the STWHG. The achievement of STWH-Generator gives 152W power for 100^{o}C and reduces the cost upto \$0.133/kWh. From that, the payback coefficient is calculated from the derivation (K= G/M >1); the calculated total-cost/kWh is shown in the Table. 2. Similar to this method the main theme formula was developed by Ahiska, R. et al. [1, 2]. Thankakan R. et al. [64] analysis the thermoelectric energy harvesting modeling using algorithmic and MATLAB simulink method; here, they used single switch high gain to couple with inductor booster for the conversion of temperature to electric current. This couple effect improves the conversion ratio in high efficiency and low duty cycle. The power converter of thermoelectric ΔT operates at 95ºC to 135ºC; it increases the converter efficiency upto 91.5% at low duty cycle of 0.4.

Table 2. Total cost effective factor for $/kWh

Temperature (ºC)	Power (kW)	Average summation value of $/kWh	Ref.(s)
10	0.1	192.078	Ref. [53]
20	0.2	115.250	Ref. [53]
30	0.6	112.691	Ref. [53]
40	1.0	109.263	Ref. [53]
50	1.5	101.360	Ref. [53]
60	2.2	96.369	Ref. [53]
70	3.0	84.036	Ref. [53]
80	3.9	71.306	Ref. [53]
90	5.0	67.069	Ref. [53]
100	6.2	61.631	Ref. [53]

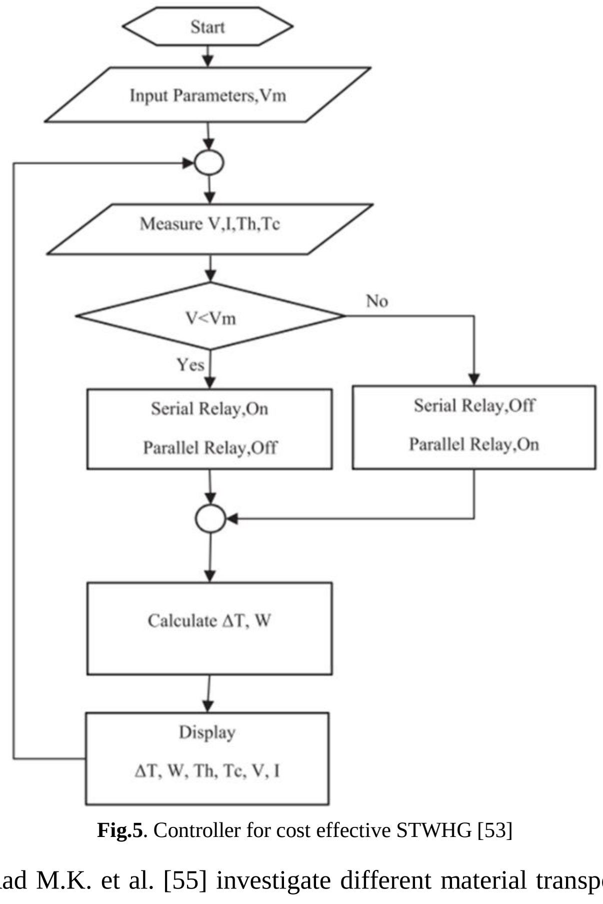

Fig.5. Controller for cost effective STWHG [53]

Rad M.K. et al. [55] investigate different material transport properties in TEGs via MATLAB mathematical model. They reduced the thermal resistance between heat sink and heat source to increase the power in TEG. They collected lot of data related to different materials (Fe, Co, Ru, Os, C, P, As and Sb) to analysis their PF. They analyzed and conclude that the high efficient transport property of PF as 3×10^{-3} to 1.4×10^{-2} W/K^{2}m. Kim C.N. et al. [30] develop a numerical model of TEG for electric constant resistance and finite thermal analysis, through this method the PF can be increased in future research.

Moh'd A.AN. et al. [48] investigate TEG as dual mode operation. They analysis TEG using MATLAB Simulink for economic feasibility and optimize TEG for suitability in Mediterranean region. They integrate solar and TEG for electricity production to reduce the production cost as well as increases the PF. Here, the model prefer heat pump for both cold and hot junction to make the temperature difference and they optimize temperature between 0ºC to 200ºC; with the help of heat pump, they increases the 4.3% of total power consumption in 1 year. The capital cost of production has reduced $138 in total power production during a year.

5. MATLAB Optimization in Thermoelectric Device

Keri A.J.F. et al. [27] used iterative method for power transmission controller in MATLAB to enhance the parametric studies on thermoelectric. Kane et al. [26] also use the iterative method for optimize the passive thermal layers using simulink space domain model. Similarly, Ferrario A. et al. [17] model the TEM using MATLAB iterative numerical algorithm to optimize the temperature losses. Here, the temperature loss between TEM leg-1 and TEM leg-2 is equivalent to K_{tem}/K_p for the materials (Bi_2Te_3, Al_2O_3, and Graphite). The loss to thermal conductance of $1/K_{tem}$ and $1/K_p$ is shown in the Table. 3 for TEM leg-1 and TEM leg-2. Soltani S. et al. [59] used non linear algebraic equation for thermal and electrical efficiency in TEG via Newton Raphson iterative method in MATLAB. From his mathematical model optimization, they obtained the electrical power of 22.714W for TEG. Similarly, Dong S. et al. [14] also used MATLAB iterative method with time dependent for STEG to optimize the thermal and electrical efficiency. They obtained 2.13×10^{-3} V/K Seebeck coefficient for single cell of STEG. The time expected manner has been calculated using P/P_{max} and P_{pv}/P_{te} relations. Arora R. et al. [6] optimize the nonlinear Thomson effect in TEG; they used multi-elements in single/2nd stage of TEG. In single stage, the parameters are optimized via MOEA/D and NSGA-II algorithms [7, 11, 12, 33, 35, 38, 44, 54]. Likewise for 2nd stage of TEG are optimized by decision making methods such as fuzzy, LINMAP and TOPSIS [9, 18, 40, 43]. The resultant outcomes are $3.3 \leq$ TEG (%) ≤ 6.1, $0.045 \leq$ entropy-TEG ≤ 0.071 and 1.48W $\leq$ power $\leq$ 3.80W for different algorithms is shown in the fig. 5(a-c), respectively. Similarly, Ge Y. et al. [19] used TOPSIS and multi-objective genetic algorithm for 3D - TEG numerical simulation. They concentrate on optimization for cold leg of TEG and obtain the maximum power as 5.523W $\leq$ power $\leq$ 56.293W for volume 432 to 3868 mm^3.

Table 3. Leg 1 and 2 of TEM using MATLAB-numerical

Loss optimization	TEM Leg-1	TEM Leg-2	Ref.(s)
$1/K_{tem}$	4.34 KW^{-1}	0.362 KW^{-1}	Ref. [17]
$1/K_p$	0.21 KW^{-1}	0.054 KW^{-1}	Ref. [17]

Janak L. et al. [22] modeled MEMS TEG using MATLAB Simulink (simscape); the special design of the model is MEMS TEG which has supercapacitors and batteries for energy storage applications. Here, the optimization was done by several architecture designs via changing the value in electronic components of MEMS TEG [3, 4, 20, 21, 32, 36, 60, 67]. This model was formed as device and it was commercially available for aircraft TEG applications by Extreme Thermal solution, Inc [3]. Similar to commercial TEG, Muthu G. et al. [52] investigate a year performance of STEG in south indian region (Location: Thiruchirappali); they found the maximum efficiency of STEGs is between April and August month and STEGs minimum efficiency at December month. From that, they tried to optimize the conversion efficiency using numerical model of parabolic dish via MATLAB to get high efficient STEG in Thiruchirappali. The future making of TEG and hybrid TEGs device can easily analysis with MATLAB to increase performance of thermoelectric applications.

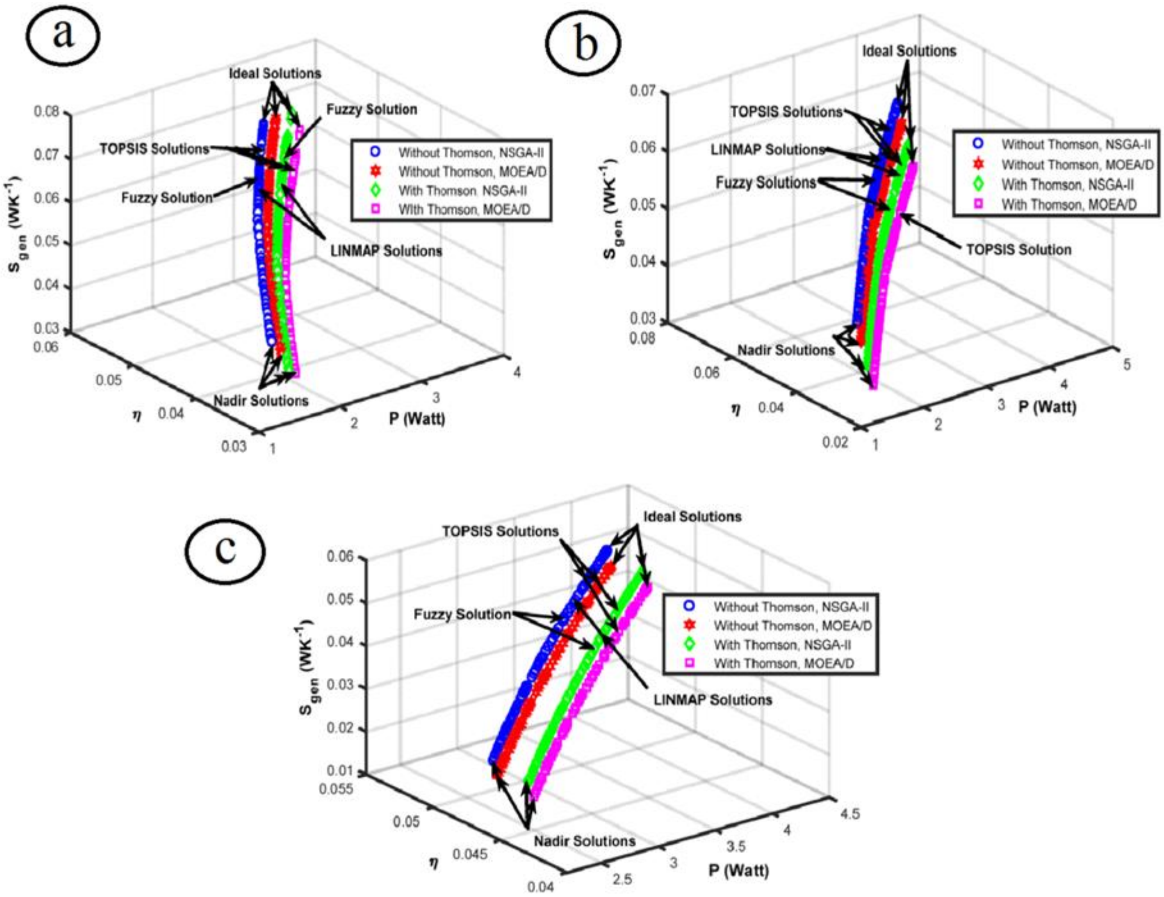

Fig.6. Different solution of (a) Thermoelectric generators [6], (b) entropy generation in TEG [6], (c) power generation in TEG [6]

6. Conclusion

The importance of TEG based probability distribution, Weibul distribution, lognormal distrubtion, Seebeck effect, PF and efficiency from TEG and STEG MATLAB modeling is discussed. The emerging opportunities like material science based MATLAB simulink, numerical and algorithm method in development of hybrid system of TEGs, cost factor models, increase the power gain low and high temperature TEGs are discussed briefly with lot of literature supports. The optimization of TEGs using MATLAB is studied for iterative method of power gain, material effects in performance and commercial appliances. The future research scope of the paper is to encourage and promote TEGs and hybrid TEGs modeling via MATLAB software. Those literatures may help researchers to minimize the cost of production in commercial TEGs with the more efficient device for fabrication.

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