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Performance Evaluation of a Thermoelectric Refrigerator

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Abstract*---The research focused on simulation of a thermoelectric refrigerator maintained at 4°C. The performance of the refrigerator was simulated using Matlab under varying operating conditions. The system consisted of the refrigeration chamber, thermoelectric modules, heat source and heat sink. Results show that the coefficient of performance (C.O.P) which is a criterion of performance of such device is a function of the temperature between the source and sink. For maximum efficiency the temperature difference is to be kept to the barest minimum.

***Index Terms*– Thermoelectric Cooler Module, Heat Source, Heat Sink, Peltier Effect, Thermoelectric Cooling Materials, Refrigeration Load, Coefficient Of Performance.**

I. INTRODUCTION

Thermoelectric refrigerator sometimes called a thermoelectric cooler module or Peltier cooler is a semi conductor based electric component that functions as a small heat pump. By applying a low voltage direct current (DC) power source to a thermoelectric cooler module, heat will be moved through the module from one side to the other [1]. One module face, therefore, will be cooled while the opposite face simultaneously is heated. Both thermoelectric refrigerators and mechanical refrigerators are governed by the same fundamental laws of thermodynamics and both refrigeration systems; although considerably different in form, function in accordance with the same principles. In a mechanical refrigeration unit, a compressor raises the pressure of a refrigerant and circulates the refrigerant through the system. In the refrigerated chamber, the refrigerant boils and in the process of changing to a vapor, the refrigerant absorbs heat causing the chamber to become cold. The heat absorbed in the chamber is moved to the condenser where it is transferred to the environment from the condensing refrigerant. In a thermoelectric cooling system, a doped semi-conductor material essentially takes the place of the refrigerant, the condenser is replaced by a finned heat sink, and the compressor is replaced by a Direct Current (DC) power source. The application of Direct Current (DC) power to the thermoelectric cooler modules causes electrons to move through the semi-conductor material [1]. At the cold end of the semi-conductor material, heat is absorbed by the electron movement, moved through the material, and expelled at the hot end. Since the hot end of the material is physically attached to a heat sink, the heat is passed from the material to the heat sink and then in turn, transferred to the environment.

II. HISTORY OF THERMOELECTRIC COOLING

The physical principles upon which modern thermoelectric coolers are based actually date back to the early 1800's, although commercial thermoelectric cooler modules were not available until almost 1960. The first important discovery relating to thermoelectricity occurred in 1821 when a German Scientist, Thomas Seebeck, found that an electric current would flow continuously in a closed circuit made up of two dissimilar metals maintained at two different temperatures. Seebeck did not actually comprehend the scientific basis for his discovery, however, and falsely assumed that flowing heat produced the same effect as flowing electric current [2]. In 1834, a French watchmaker and part time physicist, Jean Peltier, while investigating the "Seebeck Effect", found that there was an opposite phenomenon whereby thermal energy could be absorbed at one dissimilar metal junction and discharged at the other junction when an electric current flowed within the closed circuit. Twenty years later, William Thomson later Lord Kelvin issued a compressible explanation of the Seebeck and Peltier effects and described their interrelationship. At the time however, these phenomenon were still considered to be more laboratory curiosities and were without practical application [2]. In the 1930's, Russian scientists began studying some of the earlier thermoelectric work in an effort to construct power generators for use at remote locations throughout the country. This Russian interest in thermoelectricity eventually caught the attention of the rest of the world and inspired the development of practical thermoelectric modules. Today's thermoelectric refrigerators make use of modern semi-conductor technology whereby doped semi-conductor material takes the place of dissimilar metals used in early thermoelectric experiments.

III. SEEBECK EFFECT

Fig. 1 Illustrate the Seebeck Effect.

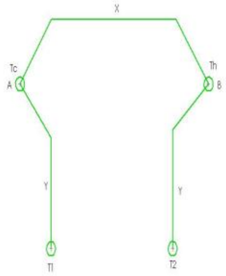

Fig. 1 Seebeck Effect

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The thermocouple conductors are two dissimilar metals denoted as X and Y materials. With heat applied to the end B of the thermocouple and the end A is cooled, a voltage will appear across terminals T_1 and T_2. This voltage is known as the Seebeck e.m.f.

IV. PELTIER EFFECT

The Peltier effect bears the name of Jean-Charles Peltier, a French physicist who in 1834 discovered the calorific effect of an electrical current at the junction of two different metals. When a Current (I) is made to flow through the circuit, heat is evolved at the upper junction (T_2) and absorbed at the lower junction (T_1). The Peltier heat absorbed by the lower junction per unit time $\dot{Q}$ is equal to

$$\dot{Q} = \pi_{AB} I \quad (1)$$

Where π_{AB} is the Peltier coefficient.
Peltier heat is reversible, when the direction of current is reversed; the Peltier heat is the same, but in opposite direction. Peltier coefficient depends on the temperature and materials of a junction. Fig. 2 Illustrates The Peltier Effect.

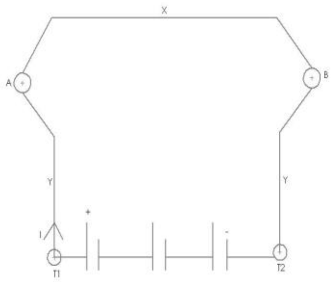

Fig. 2 Peltier Effect

If a voltage is applied to terminals T_1 and T_2, electric current (I) will flow in the circuit. As a result of the current flow, a slightly cooling effect will occur at thermocouple junction A where heat is expelled. Note that this effect will be reversed whereby a change in the direction of electric current flow will reverse the direction of heat flow.

V. THOMSON EFFECT

When an electric current is passed through a conductor having a temperature gradient over its length, heat will be either absorbed by or expelled from the conductor. Whether heat is absorbed or expelled depends upon the direction of both the electric current and temperature gradient. This phenomenon, known as Thomson effect is of interest in respect to the principles involved but plays a negligible role in the operation of practical thermoelectric models.

VI. THERMOELECTRIC COOLING MATERIALS

Although the principle of thermoelectricity dates back to the discovery of the Peltier effect, there was little practical application of the phenomenon until the middle 1950's. Prior to then, the poor thermoelectric properties of known materials made them unsuitable for use in a practical refrigerating device. According to Nolas et al [3], from the middle 1950s to the present the major thermoelectric material design approach was that introduced by A.V. Ioffe, leading to semi-conducting compounds such as Bi_2Te_3, which is currently used in thermoelectric refrigerators. In recent years there has been increased interest in the application of thermoelectric to electronic cooling, accompanied by efforts to improve their performance through the development of new bulk materials and thin film micro coolers [3]. The usefulness of thermoelectric materials for refrigeration is often characterized by the dimensionless product, ZT, of the thermoelectric figure of merit Z and temperature T. The expression for the thermoelectric figure of merit is given by:

$$Z = \frac{\alpha^2}{\rho K} \quad (2)$$

Where α is the Seebeck coefficient
ρ is the electrical resistivity
K is the thermal conductivity
Fluerial et al [4] reported that in 1991 JPL started abroad search to identify and develop advanced materials. Among the materials considered, Skutterudite and Zn_4Sb_3 based materials appeared particularly promising and several of these materials are being developed. ZT values equal to or greater than one have been obtained for these materials over different ranges of temperature varying from 375 to 975K. However, to be particularly useful for electronic cooling applications, improvements in ZT are needed over the temperature range of 300 to 325K or below. Another strategy for enhancing ZT being pursued by researchers at MIT, Harvard and UCLA focuses on reduced dimensionality as occurs in quantum wells (2D) or quantum wires.

Table I Figure of Merit for Different Materials [5]

Material	Figure of merit
Pb – Te	1.2×10^{-3}
Pb – Se	1.2×10^{-3}
$Pb_2 – Te_3$	1.2×10^{-3}
$Bi_2 – Te_3$	1.3×10^{-3}
$(BiSb)_2 – Te_3$	3.3×10^{-3}

VII. THERMOELECTRIC REFRIGERATORS

The thermoelectric refrigerator consists of the following components:

A. The Thermoelectric Module

The thermoelectric module consists of pairs of P-type and N-type semi-conductor thermo element forming thermocouple which are connected electrically in series and thermally in parallel. The modules are considered to be highly reliable components due to their solid state construction. For most application they will provide long, trouble free service. In cooling application, an electrical current is supplied to the module, heat is pumped from one side to the other, and the result is that one side of the module becomes cold and the other side hot [6].

B. Heat Sink

The heat sink usually made of aluminum, is in contact with the hot side of a thermoelectric module. When the positive and negative module leads are connected to the respective positive and negative terminals of a Direct Current (D.C) power source, heat will be rejected by the module's hot side, the heat sink expedites the removal of heat. Heat sink typically is intermediates stages in the heat removal process whereby heat flows into a heat sink and then is transferred to an external medium. Common heat sinks include free convection, forced convection and fluid cooled, depending on the size of the refrigerator.

C. Cold Side

The cold side also made of aluminum is in contact with the cold side of a thermoelectric module, when the positive and negative module leads are connected to the respective positive and negative terminals of a direct current (D.C) power source, heat will be absorbed by the module's cold side. The hot side of a thermoelectric module is normally placed in contact with the object being cold.

D. Spacer Block

The spacer block though optional in water chillers is used to ensure sufficient air gap between the heat sink and the object being cooled.

E. Power Source

Thermoelectric module is a Direct Current (D.C) device. Specified thermoelectric module performance is valid if a Direct Current (D.C) power supply is used. Actual D.C power supply has a rippled output. This D. C. component is detrimental [7]. Degradation of thermoelectric module performance due to the ripple can be approximated by [7]:

$$\frac{\Delta T'_{MAX}}{\Delta T_{MAX}} = \frac{1}{1+\frac{N^2}{2}} \qquad (3)$$

VIII. MODULE SELECTIONS

Selection of the proper thermoelectric module for a specific application requires an evaluation of the total system in which the refrigeration will be used. For most applications, it should be possible to use one of the standard module configurations while in certain cases a special design may be needed to meet stringent electrical, mechanical or other requirement. The overall cooling system is dynamic in nature and system performance is a function of several interrelated parameters. Before starting the actual thermoelectric module selection process, under listed questions must be answered. At what temperature must the cooled object be maintained? How much heat must be removed from the cold object? Is thermal response time important? What is the expected ambient temperature? What is the extraneous heat input (heat leak) into the system? How much space is available for the module and heat sink? What power is available? What is the expected approximate temperature of the heat sink during operation? Table 2 shows the average parameters for a 31 couple Bismuth telluride module at various temperatures and current.

Table II Parameters of Bismuth Telluride Module [8]

S/N	Temp. ^{0}C	∝ v/k	Rm Ω	K W/K	Rm Ω	K W/K
			9A	9A	15A	15A
1	0	0.01229	0.3440	0.1815	0.2064	0.3024
2	10	0.01257	0.3634	0.1828	0.2180	0.3047
3	20	0.01282	0.3833	0.1858	0.2300	0.3096
4	30	0.01304	0.4035	0.1905	0.2421	0.3176
5	40	0.01323	0.4239	0.1971	0.2544	0.3286

IX. DESIGNS

Every specific application where a thermoelectric cooler module or refrigerator is required is characterized by a set of operation parameters, which dictate the necessity and accurate selection of the optional thermoelectric cooler type among a wide range of single and multi-stage thermoelectric cooler modules.

These parameters are:

ΔT – Operating temperature difference

Q_C – Operating cooling capacity

I – Applied or available current

V - Terminal voltage

A. Specification of the Thermoelectric Refrigerator

The cold space of the refrigerator will be maintained at 4^0C, this also is the cold side temperature of the module. The heat sink temperature will be maintained at 40^0C to maintain the necessary temperature difference for heat transfer as the ambient temperature on a very hot day is been 30 – 35^0C. Therefore the thermodynamic force property for the Peltier device is 36^0C. The maximum current to be drawn by the module is 9A.

B. Thermoelectric Cooler Module

The thermoelectric cooler module material chosen is Bismuth telluride.

The properties of a 31 couple, 9A Bismuth Telluride module [8] are:

Seebeck coefficient ($\propto_m$) = 0.01229 V/k

Module thermal conductance (K_m) = 0.1815 W/k

Module resistance (R_m) = 0.344Ω

C. Heat Load Analysis

The quantity of heat to be removed by the module comprises: Heat conduction through the walls of the cooling chamber Infiltration due to door openings The product load

C1. Heat Conduction

The capacity of the refrigerated space is 36L. The materials of construction are:

The external wall, mild steel sheet material, the insulation, polyethane foam, the internal wall, aluminum sheet material. Heat transfer Q_{CO} per unit area is defined by

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$$Q_{CO} = \frac{T_h - T_c}{\frac{1}{h_o} + \frac{x_1}{k_1} + \frac{x_2}{k_2} + \frac{x_3}{k_3} + \frac{1}{h_i}} \quad (4)$$

C2. Infiltration due to Door Opening

The amount of heat to be removed from the refrigerated space due to infiltration or air change due to door opening is given by [5]

Q_{INF} = Infiltration rate (L/s) x Enthalpy change (J/L) (5)

From tables [5]

Infiltration rate = 3.75 L/s

Enthalpy change = 0.0708 J/L

C3. Product Load

The quantity of heat to be removed from the products inside the refrigerated space is known as the product load. The product load is estimated from the equivalent water contents of the products in the refrigerated space, since it has a higher specific heat capacity.

Therefore, product load is defined as

$$Qp = M_w \, Cp_w \, (T_{w2} - T_{w1}) \quad (6)$$

C4. Total Refrigeration Load

$$Q_T = Q_{co} + Q_{INF} + Qp \quad (7)$$

D. Cooling Capacity per Module

The quantity of heat pumped by the module is obtained from [5]:

$$Q_C = \propto_M T_C I - \frac{1}{2} I^2 R_M - K_M (T_h - T_C) \quad (8)$$

Fig. 3 shows the schematic diagram of the thermoelectric refrigerator.

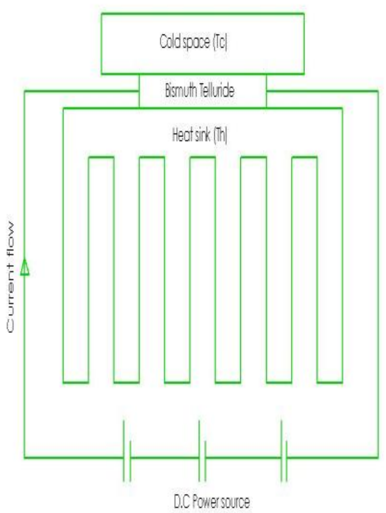

Fig. 3 Schematic of Thermoelectric Refrigerator

The minimum number of modules to be cascaded is obtained by:

$n = Q_T/Q_c$

E. Voltage Input to the Module

The input voltage to the module is obtained from [5]:

$$V_{IN} = \propto_M (T_h - T_C) + IR_M \quad (9)$$

F. Electrical Power Input

The power required is obtained from the expression [5]

$$P = \propto_M I(T_h - T_C) + I^2 R_M \quad (10)$$

G. Heat Rejected by the Module

The quantity of heat to be rejected by the module is obtained from [5]:

$$Q_R = \propto_M I(T_h - T_C) + I^2 R_M + \propto_M T_C I - \frac{1}{2} I^2 R_M - K_M (T_h - T_C) \quad (11)$$

H. Coefficient of Performance of the System

The coefficient of performance of the thermoelectric cooler is obtained from:

$$C.O.P. = Q_c/P \quad (12)$$

X. RESULTS

The modeling was carried out with the Matlab software. The overall cooling system is dynamic in nature and system performance is a function of interrelated parameters, it is necessary to state that the parameters used in the model are average values. Ideal conditions are assumed in that extraneous heat leakages are neglected.

.A C.O.P versus Current

The expression for the coefficient of performance is defined in equation 12 while equation 8 and 10 defined Q_C and P respectively. Fig. 4 is a simulation of coefficient of performance against input current at various temperature differences.

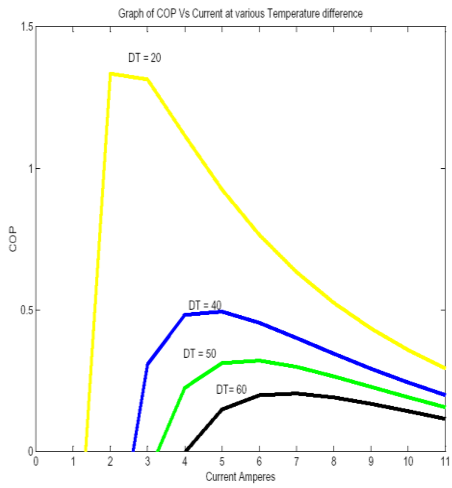

Fig. 4 Coefficient of Performance against Input Current

It can be seen from the plot that the C. O. P increases with an increase in input current, gets to a peak value and then begins to decreases at various temperature differences. The unique feature of the graph is with the DT = 20, the smallest temperature difference, it shows that the C. O. P is maximum with a smaller temperature difference between the source and the sink. Therefore, for optimum performance of the thermoelectric cooler, the temperature difference between the source and sink should be kept as low as possible. C. O.P is a measure of modules efficiency and it is always desirable to maximize C.O.P.

B. Q_C versus Current

Fig. 5 is a simulation of the module heat pumping capacity and temperature difference as a function of input current.

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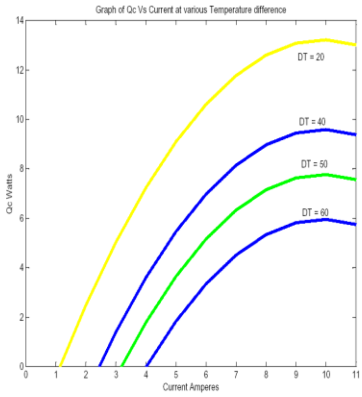

Fig. 5 QC versus Input Current

As can be seen from the plot, the heat pumping capacity of the module increases as the input current increases gets to a peak value and then decreases as the input current increases. The interesting phenomenon however is that the heat pumping capacity is maximum with the lowest temperature difference at any given input current. The optimum performance is obtained from the thermoelectric refrigerator when the smallest possible temperature difference is established between the source and the sink.

C. V_{IN} versus Current

Fig. 6 relates a module's input voltage and temperature difference as a function of input current.

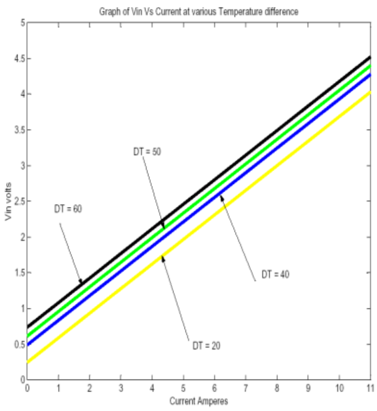

Fig. 6 V_{IN} versus Input Current

Clearly as can be expected, there is a linear relationship between input voltages and input current. As the input current increases so does the input voltage. The interesting thing however is that as the temperature difference decreases, so also is the input voltage decreasing for a given temperature difference.

D. V_{IN} versus T_H

Fig. 7 shows a plot of input voltage V_{IN} and input current as a function of module hot side temperature T_h.

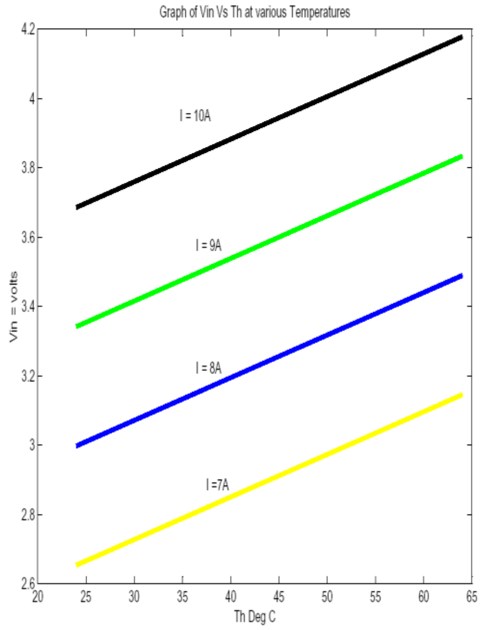

Fig. 7 V_{IN} versus T_h

Due to the Seebeck effect, input voltage at a given value of input current and module hot side temperature is lowest where the temperature difference is equal to zero and highest when the temperature difference is at its maximum point. Clearly there is a linear relationship between V_{in} and T_h at various input current. The interesting phenomenon however is that as the input current decreases so does the input voltage decreases at any given module hot side temperature.

XI. CONCLUSION

A new dimension has been added to the cooling challenge by reduction of temperatures using thermoelectric, with the continued demand for improved cooling technology to enhance performance, reliability and reduction in operating cost, a thermoelectric cooling may be considered a potential candidate. Thus a thermoelectric refrigerator is designed and simulated to maintain the temperature of enclosure at 4^oC. The minimum temperature, allowable module power, current equations presented here provide a useful means to perform trade-off analysis to assess whether or not thermoelectric argumentation will be advantageous over conventional techniques. To use these equations, detailed information in terms of the parameters pertaining to the thermoelectric module under consideration is required, average values of the parameters of Bismuth telluride (Bi_2Te_3) are used for analysis. From the plot of C.O.P against current, the coefficient of performance of such devices is dependent on the temperature difference between the hot and cold side of the module, for maximum C.O.P, the temperature is kept to the barest minimum which is also a function of the ambient condition or room temperature, a figure of 1.3 is obtained for a temperature difference of 20^oC.

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XII. RECOMMENDATIONS

Considering the vast applications of thermoelectric cooling, and the fact that experimental testing will be an important phase of the research, the following are the recommendations: - As at today, there is no single company producing thermoelectric modules in Nigeria, the Federal Ministry of science and technology should see to it that a pioneering plant is installed in the country. - A functional laboratory should be built in Nigeria University where a practical experimentation can be carried out with different module parameters.

XIII. SYMBOLS AND MEANING

Symbols	Meaning	Unit
$\dot{Q}$	Peltier heat	J
π_{AB}	Peltier coefficient	
I	Electric current	A
Z	Figure of merit	/K
α	Seebeck coefficient	V/K
ρ	Electrical resistivity	Ωm
k	Thermal conductivity	W/mK
ΔT'max	Maximum temperature when there is no ripple	°C
ΔTmax	Actual maximum temperature difference	°C
N	Ripple amplitude around average current	m
T_h	Heat sink temperature	°C
T_c	Cold side temperature of module	°C
K_m	Module thermal conductance	W/K
R_m	Module resistance	Ω
x_1,x_2,x_3	Thicknesses of mild steel sheet, polyethane and aluminium respectively	m
Q_{co}	Heat transfer per unit area	W/m^2
h_o,h_i	Heat transfer coefficient of air outside and inside chamber respectively	W/m^2k
Q_{INF}	Heat due to infiltration	W
M_w	Mass of water	kg
Cp_w	Specific heat capacity of water	J/kgK
T_{w2},T_{w1}	Initial and final temperature of water	°C
Q_p	Product load	kJ
Q_T	Total refrigeration load	W
Q_c	Cooling capacity per module	W
V_{IN}	Input voltage	V
P	Electrical power	W
Q_R	Heat rejected	W
C.O.P	Coefficient of performance	

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APPENDIX

DATA FOR COEFFICIENT OF PERFORMANCE

S/N	I	COP_{20}	COP_{40}	COP_{50}	COP_{60}
1	1	-0.6743	-4.8201	-6.0956	-7.0813
2	2	1.3336	-0.4829	-1.1341	-1.6730
3	3	1.3135	0.3074	-0.0830	-0.4192
4	4	1.1153	0.4626	0.2249	-0.0029
5	5	0.9250	0.4939	0.3124	0.1491
6	6	0.7651	0.4548	0.3210	0.1989
7	7	0.6337	0.4012	0.2991	0.2049
8	8	0.5252	0.3456	0.2655	0.1912
9	9	0.4348	0.2926	0.2285	0.1686
10	10	0.3585	0.2438	0.1916	0.1425
11	11	0.2934	0.1993	0.1563	0.1155

DATA FOR COOLING CAPACITY

S/N	I	QC_{20}	QC_{40}	QC_{50}	QC_{60}
1	1	-0.3977	-4.0277	-5.8427	-7.6577
2	2	2.4907	-1.1393	-2.9543	-4.7694
3	3	5.0350	1.4050	-0.4100	-2.2251
4	4	7.2353	3.6053	1.7903	-0.0247
5	5	9.0917	5.4617	3.6466	1.8317
6	6	10.6040	6.9740	5.1590	3.3440
7	7	11.7723	8.1423	6.3273	4.5123
8	8	12.5966	8.9666	7.1516	5.3366
9	9	13.0770	9.4470	7.6320	5.8170
10	10	13.2133	9.5833	7.7683	5.9533
11	11	13.0056	9.3756	7.5606	5.7456

DATA FOR INPUT VOLTAGE AGAINT CURRENT

S/N	I	VIN_{20}	VIN_{40}	VIN_{50}	VIN_{60}
1	1	0.5898	0.8356	0.9585	1.0814
2	2	0.9338	1.1796	1.3025	1.4254
3	3	1.2778	1.5236	1.6465	1.7694
4	4	1.6218	1.8676	1.9905	2.1134
5	5	1.9658	2.2116	2.3345	2.4574
6	6	2.3098	2.5556	2.6785	2.8014
7	7	2.6538	2.8996	3.0225	2.1454
8	8	2.9978	3.2436	3.3665	3.4894

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9	9	3.3418	3.5876	3.7105	3.8334
10	10	3.6858	3.9316	4.0545	4.1774
11	11	4.0298	4.2756	4.3985	4.5214

DATA FOR INPUT VOLTAGE AGAINST SINK TEMPERATURE

S/N	I	VIN_7	VIN_8	VIN_9	VIN_{10}
1	20	2.6046	2.9486	3.2926	3.6366
2	25	2.6661	3.0101	3.3541	3.6981
3	30	2.7275	3.0715	3.4155	3.7595
4	35	2.7890	3.1330	3.4770	3.8210
5	40	2.8504	3.1944	3.5384	3.8824
6	45	2.9119	3.2559	3.5999	3.9439
7	50	2.9733	3.3173	3.6613	4.0053
8	55	3.0348	3.3788	3.7228	4.0668
9	60	3.0962	3.4402	3.7842	4.1282
10	65	3.1577	3.5017	3.8457	4.1897