STUDY OF THERMAL PERFORMANCE OF THERMOELECTRIC COOLING SYSTEM

Rehab Noor Mohammed Al-Kaby
Babylon University/College of Engineering
Mechanical department

ABSTRACT:

This paper described the theoretical study for heat transfer through thermoelectric cooling system. The effect of the thermoelectric design parameters on the heat transfer and coefficient of performance for thermoelectric cooling system are discussed here with variable TE material parameters such as thermal conductivity, resistivity and Seebeck coefficient. The finite difference method is used to solve the differential equations and calculate the temperature distribution using a Quick Basic computer program. The results show the increase of the input power at small values of P_{in} will increase the Q_c sharply and increase Q_h slowly, from these behaviors, the optimum COP occurs at lower values of P_{in}.

الخلاصة

خلال هذا البحث لقد تم دراسة انتقال الحرارة خلال الانظمة الكهربائية الحرارية (Thermoelectric) . لقد تم دراسة تأثير العوامل التصميمية للانظمة الكهربائية الحرارية (Thermoelectric) على انتقال الحرارة و معامال الاداء للمنظومة وقد تم ايضاً خلال هذا البحث الاخذ بنظر الاعتبار تغير العوامل الداخلية للمعدن مع درجة الحرارة للمعدن وهذه العوامل مثل الموصلية الحرارية للمعدن (Thermal Conductivity) والمقاومة الكهربائية للمعدن (Resistivity) وكذلك معامل سيبك (Seebeck coefficient) . لقد تم استعمال طريقة الفروقات المحددة (Finite Difference) لايجاد توزيع درجات الحرارة داخل النظام باستعمال برنامج حاسوبي بلغة (Quick Basic) . ويمكن من خلال النتائج ملاحظة ان زيادة القدرة الداخلة للنظام وعند القيم المنخفضة من القدرة سوف يؤدي الى زيادة الـ(Q_c) بشكل كبير بينما يؤدي الى زيادة قيمة الـ(Q_h) بشكل قليل (بطيء) ومن خلال هذا التاثير يمكن ملاحظة ان القيمة المثلى للـ(COP) تحدث عند القيم المنخفظة للقدر ة الداخلة.

INTRODUCTION:

Thermoelectric cooling, also called "The Peltier Effect" is a solid-state method of heat transfer through dissimilar semiconductor materials [1]. Thermoelectric coolers TEC are solid state heat pumps used in applications where temperature stabilization, temperature cycling, or cooling below ambient are required. There are many products using thermoelectric coolers, including CCD cameras (charge coupled device), laser diodes, microprocessors, blood analyzers and portable picnic coolers. This article discusses the theory behind the thermoelectric cooler, along with the thermal and electrical parameters involved (see fig. (1)). During operation, DC current flows through the TEC causing heat to be transferred from one side of the TEC to the other, creating a cold and hot side.

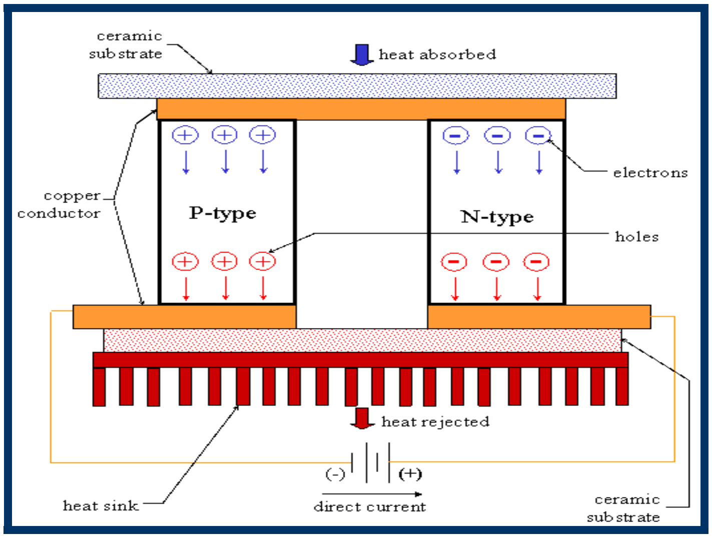

Fig. (1): The Thermoelectric Cooling System

In order to calculate the TES performance and COP, we must firstly identify the hot side temperature (T_h) and the temperature distribution through TES. Finite difference method (Forward Difference) is used in the present study to calculate the temperature distribution through the TES. The variable TE material parameters (thermal conductivity, resistivity and Seebeck coefficient) are taken in the account during the present study. AZTEC software ((version 2.2.0) was developed by Scillasoft Consulting) that used in the present study only to check the validity of the present tecnniques for a constant TEC mateials. In present study, we taken the design parameters value as following: heat load from electronic component (Qc = 15 Watt), maximum ambient air temperature (Ta = 50°C) and required temperature of electronic component (Tc = 25°C). The microscale heat transfer through the TE is discussed in Ref. [1].More website are discussed the TEC operation and design [2], [3], [4], [5]and [6]. R.J.Buist, [7], described a method which enables present or potential users of TE heat pumps, this method was dependent on TE theory applied to a generalized TE heat pump. The transient cool down performance was analyzed for a modified two stage Marlow Industries Model MI2020 TE heat pump are discussed in Ref. [8]. M.J.Nagy [9], discussed a set of correction factors have been developed to address the TES problems, this processes also allows the system designer to troubleshoot their design by using TE Technology Inc. Proprietary Modeling Software. P.G.Lau [10], studied the cooling performance of the TE couple is modeled from mathematical differential equation via finite elements with use of a digital computer. The experimental study of the heat transfer through the TE was studied in Ref. [11]. R.J.Buist [12] use a simplified method that derived through computer analysis of the full temperature dependent TE theory applied to generalized TE heat pump.

Before mathematical discussion, we are defined some of the TE important design parameters that used in the present study.

Ambient Temperature (Ta): It's the temperature of the fluid which will eventually absorb the heat removed at the cold surface of the TEC and the power dissipated by the TEC itself.

Cold Side Temperature (Tc): It's the temperature of the cold face of the TEC, which absorbs heat from its surrounding through convection and conduction.

Heat Pumped at Cold Surface (Qc): It's the amount of heat transferred from the cold side of the thermoelectric cooler (TEC) to the hot side. Qc depends upon the cold side temperature, hot side temperature, and operating point.

Qc max is the maximum amount of heat which can be transferred at the highest practical operating point (Imax and Vmax) at given cold and hot side temperatures.

Coefficient of Performance (COP): It's the amount of heat absorbed (in thermal Watts of heat pumped) at the cold side of the device, divided by the input power.

The optimum COP: is the COP at the operating point, which pumps the greatest amount heat per unit input power at a particular hot and cold side temperature.

MATHEMATICAL ANALYSIS

The heat transfer from the thermal load into the cold side of the TEC consists of the algebraic sum of the heat pumped by the Peltier effect, the heat transferred by a simple thermal conductivity (k_m) through the TEC from the hot side to the cold side and one half of the total Joule heating deposited into the TEC resistance (R) by the current (I). The Peltier effect is driven by the Seebeck coefficient (S). The relevant heat transfer equations are shown in figure (2) and the heat transferred into the cold side when neglected the temperature drop through the TEC is given by [9]:

$$Q_c = SIT_c - \frac{I^2 R}{2} - \frac{T_h - T_c}{R_{TEC}} \quad \ldots\ldots(1)$$

While the heat transferred out of the hot side into the heat sink is given by

$$Q_h = SIT_c + \frac{I^2 R}{2} - \frac{T_h - T_c}{R_{TEC}} \quad \ldots\ldots(2)$$

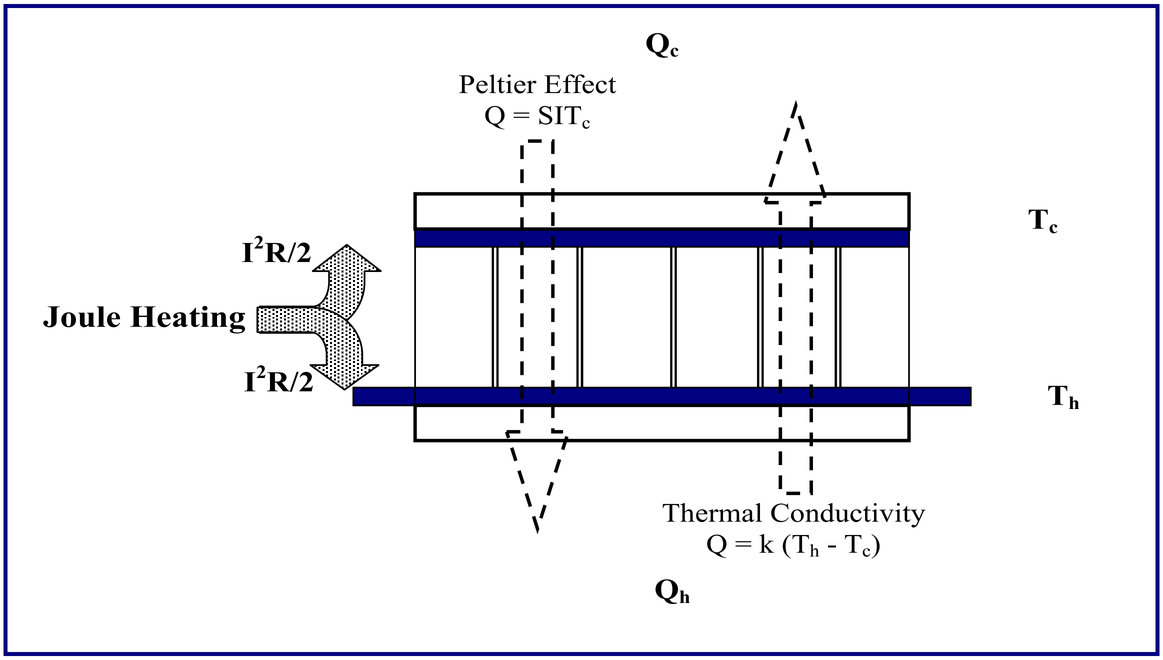

Fig. (2): Heat transfer through TE

Q_h is equal to the cold side heat input plus joule heating. The TEC thermal resistance (R_{TEC}) in Watts/Kelvin, Seebeck coefficient (S) and electrical resistance (R) in Ohms are dependent both on the materials used within the TEC, but also on the geometry of the device, given by the number and dimensions of the individual N and P-type semiconductor elements. The TEC thermal resistance can be written:

$$R_{TEC} = \frac{\delta}{2k_m N_c} \quad \ldots\ldots(3)$$

Where k_m is the material conductivity and δ is the ratio of the elements length L to the area A as:

$$\delta = \frac{L}{A} \quad \text{or can expressed as} \quad G = \frac{1}{\delta} \quad \ldots\ldots(4)$$

And N_c is the number of the P-N elements couples in the TEC, The TEC Seebeck coefficient is given by [ ],

$S = 2S_mN_c$ ……………………………………………………………………………...(5)

Where S_m is the material Seebeck coefficient

The electrical resistance (R) equal

$R = 2\,\rho_m\,\delta\,N_c$ ……………………………………………………………………(6)

Where ρ_m is the material electrical resistively

The total voltage drop across the TEC is then

$V = IR + S\,(T_h - T_c)$ …………………………………………………………………...(7)

The operation efficiency of a TES can be defined by COP which is the rate of heat pump from the cold side (Q_c) divided by the input power as follow:

$COP = \dfrac{Q_c}{P_{in}}$ ……………………………………………………………………….(8)

MATERIAL PARAMETERS

In the present research, we took the TEC material parameters (thermal conductivity, resistivity and Seebeck coefficient) are variables with the TEC temperature as following [13]:

Material Seebeck coefficient:

$S_m = S_o + S_1T_{av} + S_2\,T_{av}^2$ (Volts/K) ……………………………………………(11)

Where

$S_o=2.2224\times10^{-5}$: $S_1=9.306\times10^{-7}$: $S_2= -9.905\times10^{-10}$

Material Resistivity:

$\rho_m = \rho_o + \rho_1T_{av} + \rho_2\,T_{av}^2$ (Ohms - cm) ……………………………………..….(12)

Where

$\rho_o= 5.112\times10^{-5}$: $\rho_1=1.634\times10^{-6}$: $\rho_2= 6.279\times10^{-9}$

Material Thermal Conductivity:

$k_m = k_o + k_1T_{av} + k_2\,T_{av}^2$ (Watt / cm K) …………………………………………..(13)

Where

$k_o= 6.2605\times10^{-2}$: $k_1= -2.777\times10^{-4}$: $k_2= 4.131\times10^{-7}$

All temperatures are in Kelvin and the average temperature is the temperature between the two adjusting nodes.

In order to study the heat transfer throughout the TEC system with allowable to the materials parameters change with temperature, we used the finite difference techniques to study that.

FINITE DIFFERENCE ANALYSIS

This analysis is based on the one dimensional heat flow in the Y-direction and temperature profile through the TE system.

The nodal schema is showing in figure (3).

These equations combined with energy conversion principles for the TES, yields the following:

$$Q_s + Q_e + Q_T = \Delta U \quad \text{……………………………………………………..(14)}$$

$$Q_s = I T_j^i (S_{j+1} - S_j) \quad \text{……………………………………………………………(15)}$$

$$Q_e = \frac{I^2 (R_{j+1} - R_j)}{2} \quad \text{…………………………………………………………….(16)}$$

$$Q_T = k_{j+1} (T_{j+1}^i - T_j^i) \quad \text{…………………………………………………………...(17)}$$

$$\Delta U = \frac{m_j C_{pi} (T_j^{i+1} - T_j^i)}{t_{i+1} - t_i} \quad \text{…………………………………………………...(18)}$$

, for the Ceramic layer, the heat transfer through it

$$Q_C = \frac{\Delta T}{Rc} \quad \text{…………………………………………………………………..(19)}$$

Where $Rc = \frac{\delta_C}{k_c}$ ……………………………………………………………………(20)

, for the Copper tab, the heat transfer through it

$$Q_{CT} = \frac{\Delta T_{CT}}{R_{CT}} \quad \text{……………………………………………………………………...(21)}$$

Where $R_{CT} = \frac{\delta_{CT}}{k_{CT}}$ …………………………………………………………….…(22)

When thermal conductivity for the Ceramic layer (k_C) and copper tab (k_{CT}) are constant and for the heat sink base plate, the heat transfer through it as following [14],

$$Q_f = \frac{\Delta T_f}{R_f} \quad \text{…………………………………………………………..……….….(23)}$$

Where $R_f = \frac{\delta_{jo\,int}}{k_{jo\,int}} + \frac{1}{\eta_f\, A_f\, \bar{h}}$ and $\delta_{joint} = 0.09$ C/W

……………………………(24)

The initial condition (at t = 0), $T_i = T_c$ ……………………………………………(25)

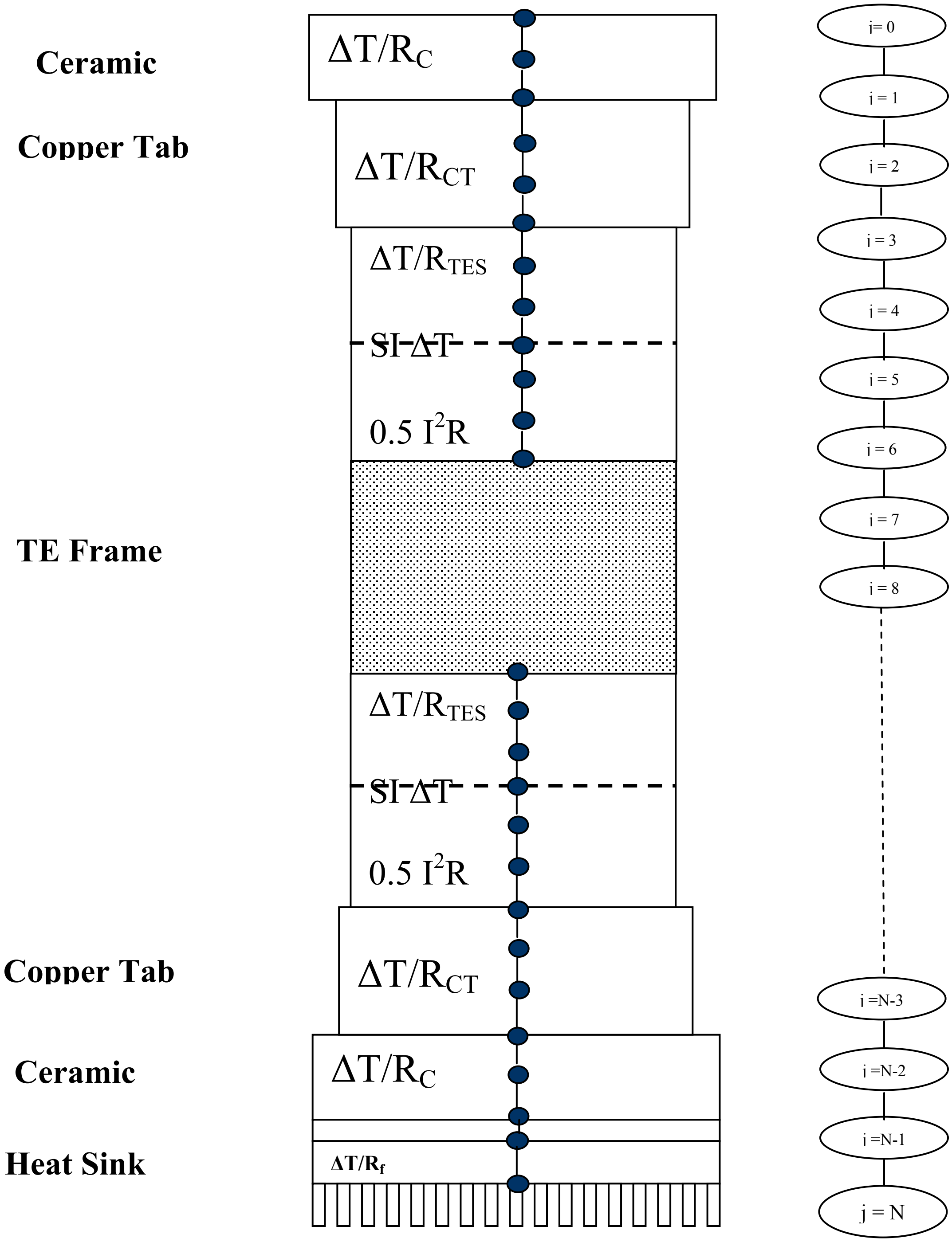

Fig. (3): Finite Difference through Thermoelectric System

After rearranged the above equations, we written Quick Basic computer program to calculate the temperature distribution by using finite difference method. We have taken in our program two nodes for each Ceramic layer, Copper tab and the heat sink and about forty nodes for the TE system.

The solution convergence criterion used through the computer program in order to determine the point in the program execution that the temperature distributions had converged to steady conditions.

The nodals temperature are assumed to be converged to the steady-state values when the difference of the nodals temperature between two time steps (j) and (j+1) satisfies the equation

$$\left| \frac{\left[T_j^{i+1} - T_j^i \right]}{T_j^i} \right| \leq \mu \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (26)$$

In the present research, the value of μ taken as 10^{-7}.

The convergence of the temperature distributions through the computer program was checked, and if convergence had not occurred, the temperature distributions for the previous time step where replaced with the new temperature distributions and recalculated the newest temperature distribution.

DISCUSSION and RESULTS

Firstly, we must check the present numerical solution of Quick Basic computer program accuracy, the results of the present program compared the temperature distribution through TEC [10], the results shown in figure (4). We can note

from this figure, the validity of the present program is acceptable.

Figures (5) and (6) show the effect of the input power on the coefficient of performance, we can note that the COP of TES increase firstly to reach a maximum value and then decrease with further increase of the input power, the maximum point in this curve called optimum value of COP. The maximum values occurs because the increase of the P_{in} will increase the Q_c sharply at small values of P_{in} but for large values of the $P_{in,}$ the increase of P_{in} will produce small increments in Q_c (see figures (7) and (8)). The increasing of the input power will increase the Joule effect and because of the Joule effect is subtract from the Q_c values then the incremental of Q_c value will reduce with further P_{in} increasing.

Figures (9) and (10) described the effect of the input power on the Q_h, the increasing of P_{in} will increase the Q_h. At small values of $P_{in,}$ the increasing of the P_{in} will increase the Q_h slowly and at large values of P_{in} the increase of P_{in} will increase the Q_h sharply because the increasing of the P_{in} will increase the Joule effect and this term is added to the Q_h, then at small values of input power, the Joule effect is small and rapidly increasing with P_{in} increase.

The effect of the T_c on the COP is graphed in figure (11), the increase of the T_c will increase the COP linearly at constant P_{in} because the COP is proportional linearly with Q_c at constant P_{in} and the Q_c is proportional linearly with T_c. The effect of Tc against Qc and Q_h at constant air temperature and input power are plotted in figures (12) and (13), these figures show the effect of the cold side temperature changing on Qcand Q_h.

CONCLUSION

The heat transfer through the thermoelectric system was discussed here and solved numerically by using finite difference method with variable TE material parameters such as thermal conductivity, resistivity and Seebeck effect. The effect of the input power and T_c on the COP, Q_h and Q_c are discussed here and we can observed that the optimum value of the COP occurs at lower values of P_{in} and it decreased as the input power increased.

NOMENCLATURES	
Notation	**Definition**
T_h	Hot Side Temperature (Kelvin)
T_c	Cold Side Temperature (Kelvin)
DT	$T_h - T_c$ (Kelvin)
T_{ave}	$(T_h+T_c)/2$ (Kelvin)
N	Number of Thermocouples
Q_h	Amount of heat transferred from the hot side of the thermoelectric (W)
Q_c	Amount of heat transferred from the cold side of the thermoelectric (W)
C_p	Heat capacity of TE material (Kj / Kg.K)
R	Electrical resistance (ohms)
ΔU	The change of internal energy
R_{TES}	Thermal resistance of TES (°C/W)
R_C	Thermal resistance of Ceramic layer (°C/W)
R_{CT}	Thermal resistance of Copper tab (°C/W)
R_f	Thermal resistance of heat sink (°C/W)
H	The heat transfer coefficient ($W/m^2.°C$)
P_i	Input power
TE	Thermoelectric

TES	Thermoelectric system
TEC	Thermoelectric cooling

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2- www.tetech.com – Weblink to TETECH thermoelectric product manufacturer

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4- www.thermacore.com – Weblink to THERMACORE thermoelectric product manufacturer

5- www.thermoelectric.com – Common weblink to all major thermoelectric product manufacturers

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7- R.J.Buist; **“ Universal Thermoelectric Design Curves”**, In Proceedings of the 15th Intersociety Energy Conversion engineering conference, Seattle, Washington , USA, August, PP. 18-22, 1980

8- T.J.Henricks, R.J.Buist; **“A Study of Thermoelectric Design Criteria For Maximizing Cool Down speed”**, In Proceedings of the 15th Intersociety Energy Conversion engineering conference, Seattle, Washington , USA

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13- J.Alfrey; **“Cooling System Design for Scientific Applications Using Thermoelectric Coolers: A Case Study in Cooling Large Laser Diodes”**, Spin One, Woodside, CA, Technical Notes #1, V.1.03, www.spin1.com, PP. 1-40, 2002

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GRAPHS

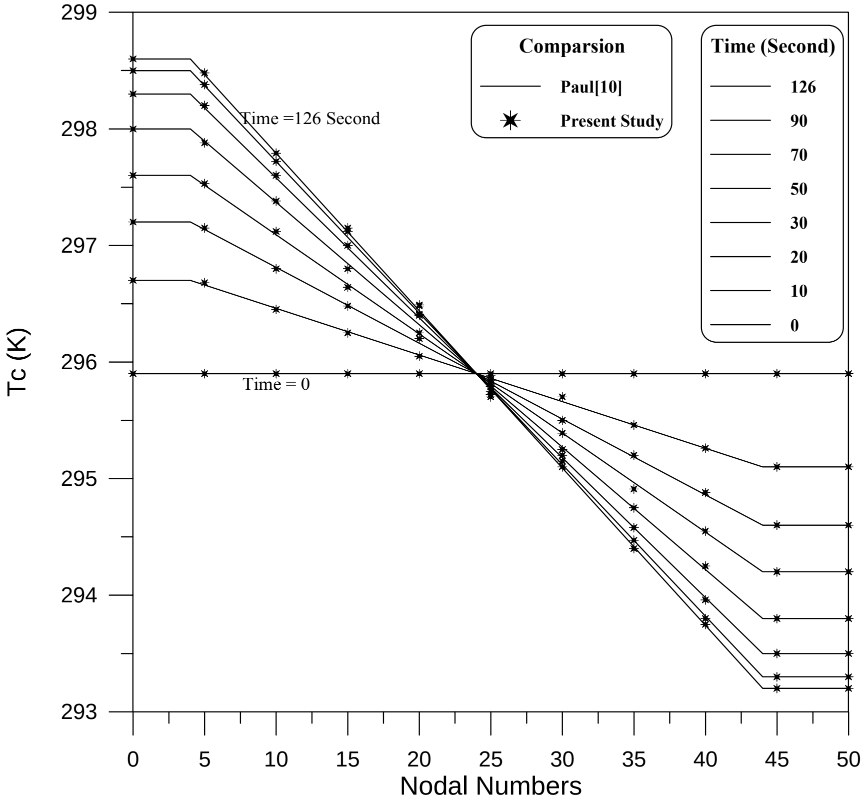
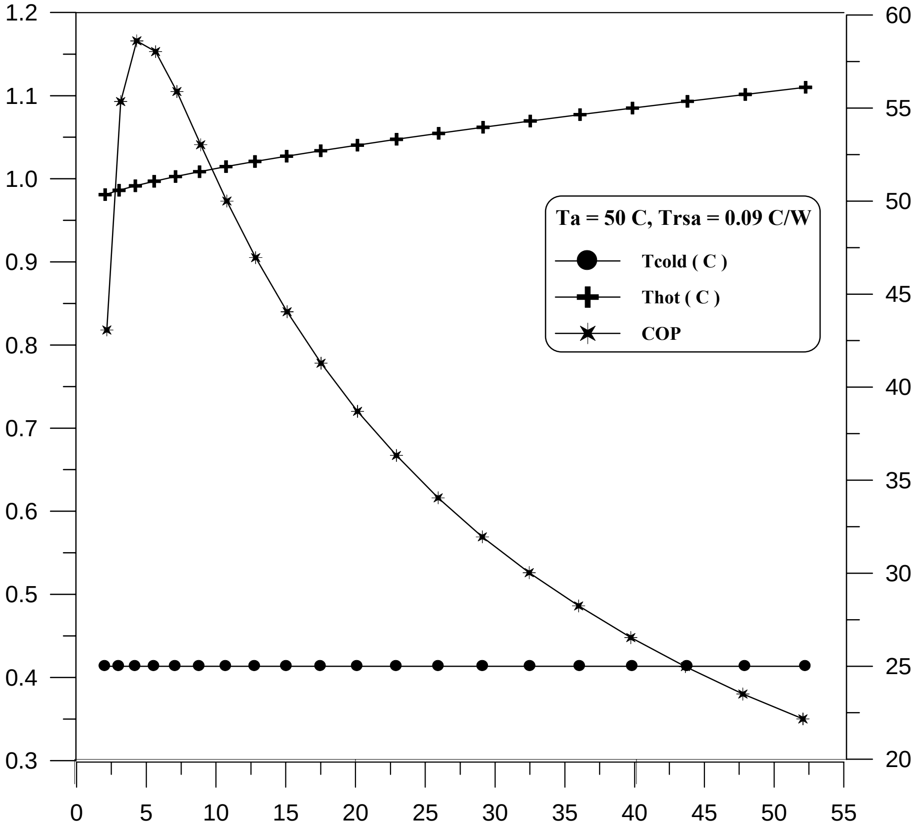


Fig. (4): The comparison between the present study and the Ref. [1] (Current = 0.0885 Amp)


Ta = 50 C, Trsa = 0.09 C/W
Tcold (C)
Thot (C)
COP
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
60
55
50
45
40
35
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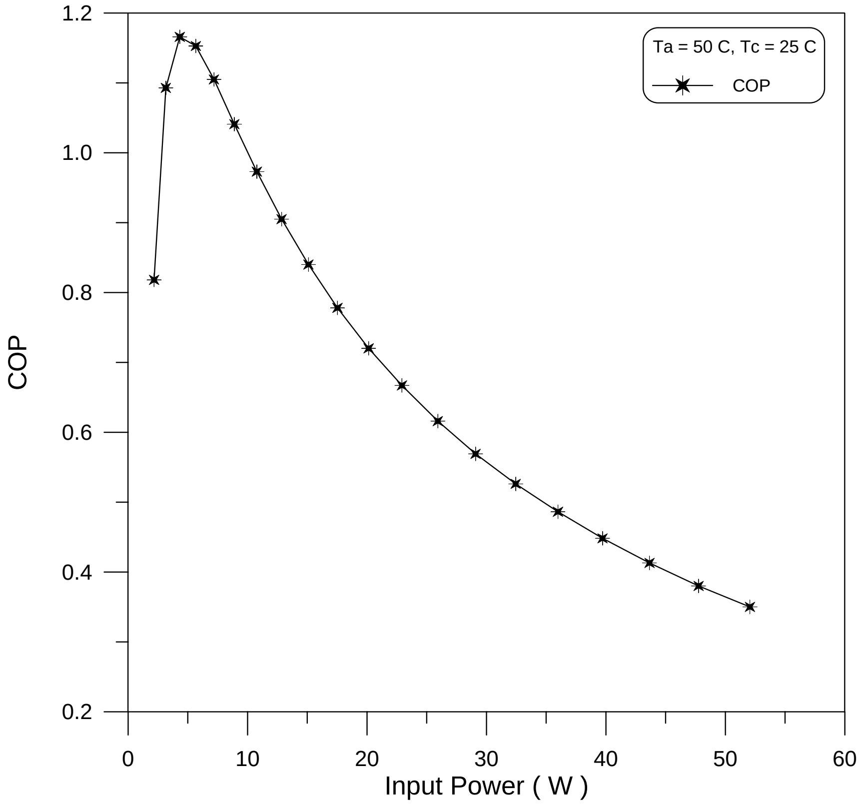

Fig. (5): The effect of P_{in} versus COP

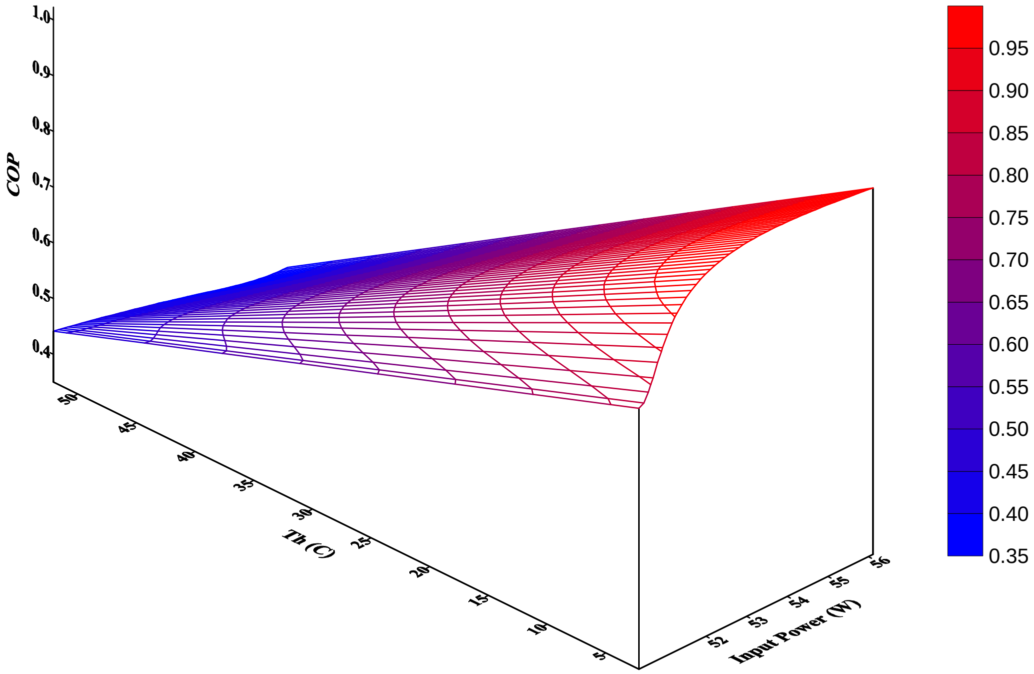

Fig. (6): The effect of P_{in} versus COP and T_h (Contour Lines)

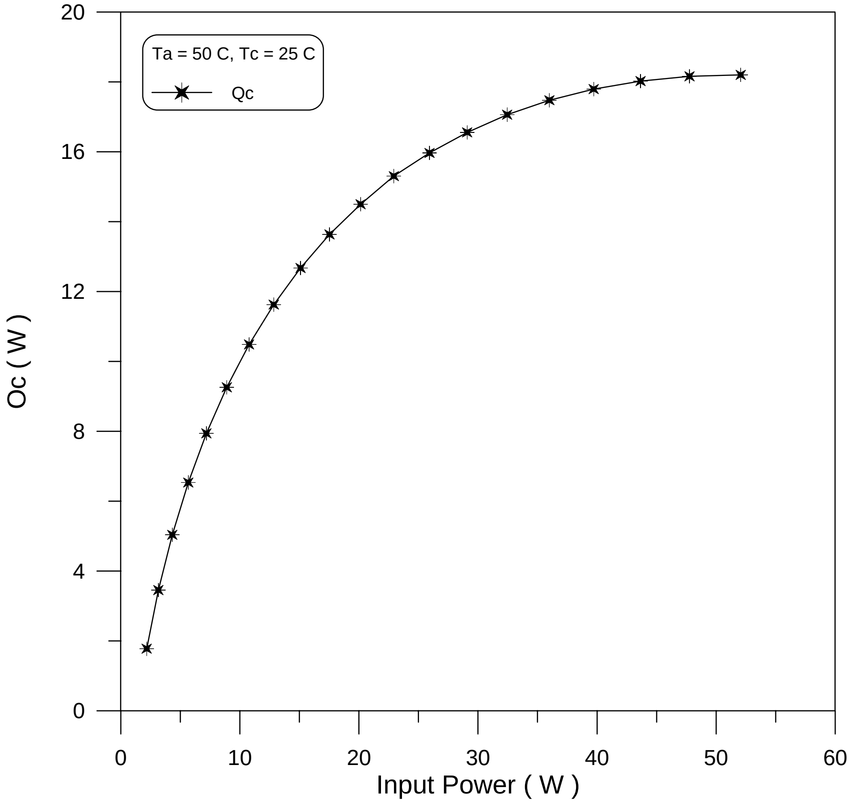

Fig. (7): The variation of Q_c against P_{in}

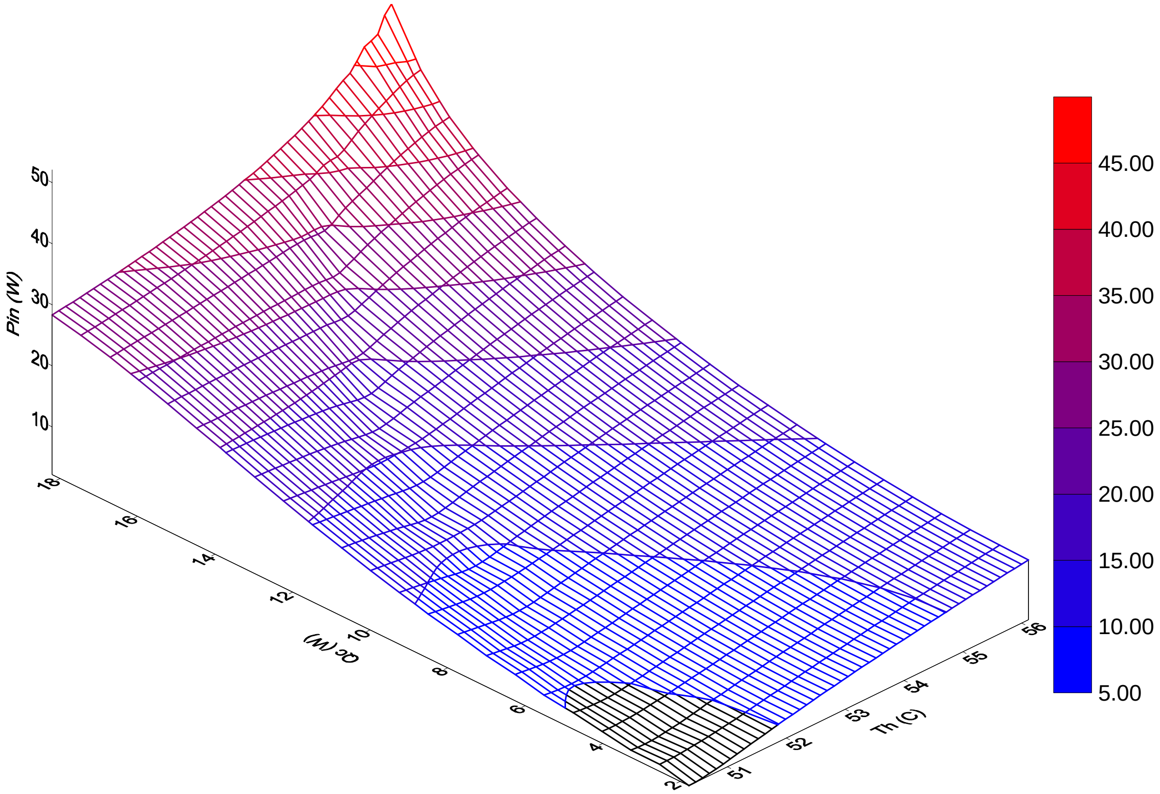

Fig. (8): The variation of Q_c against P_{in} and T_h (Contour Lines)

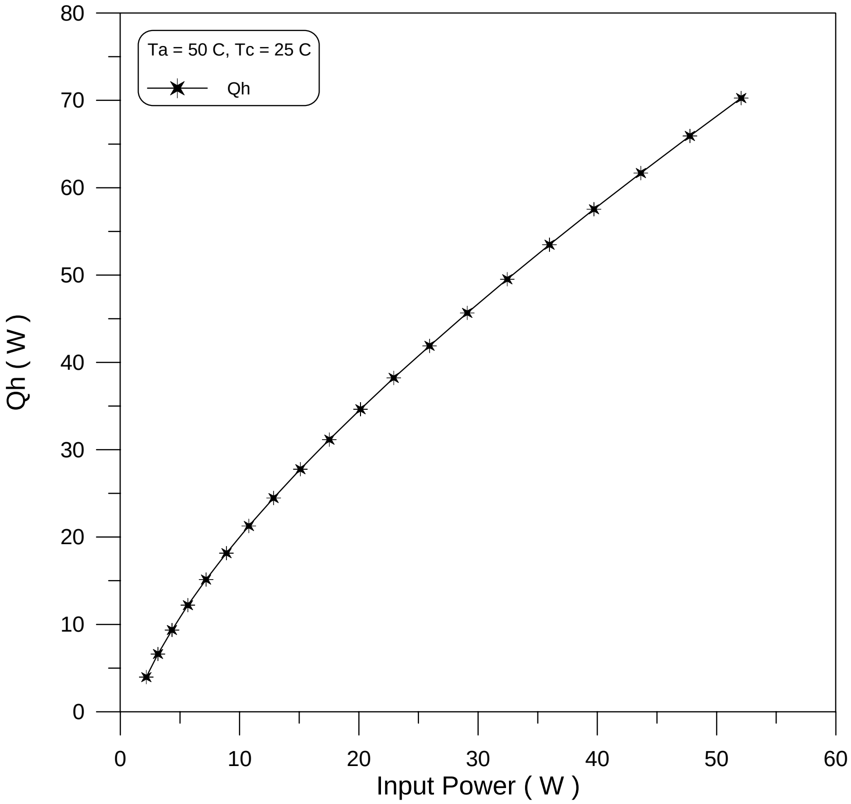

Fig. (9): The variation of Q_h against P_{in}

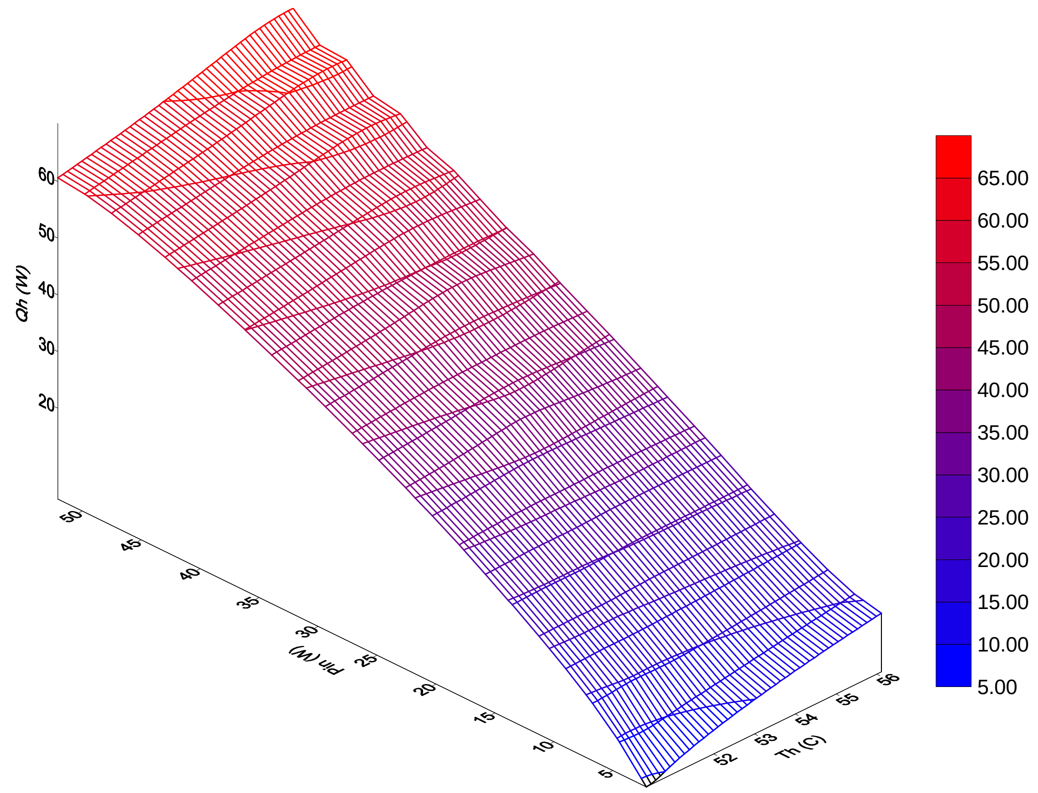

Fig. (10): The variation of Q_h against P_{in} and T_h (Contour Lines)

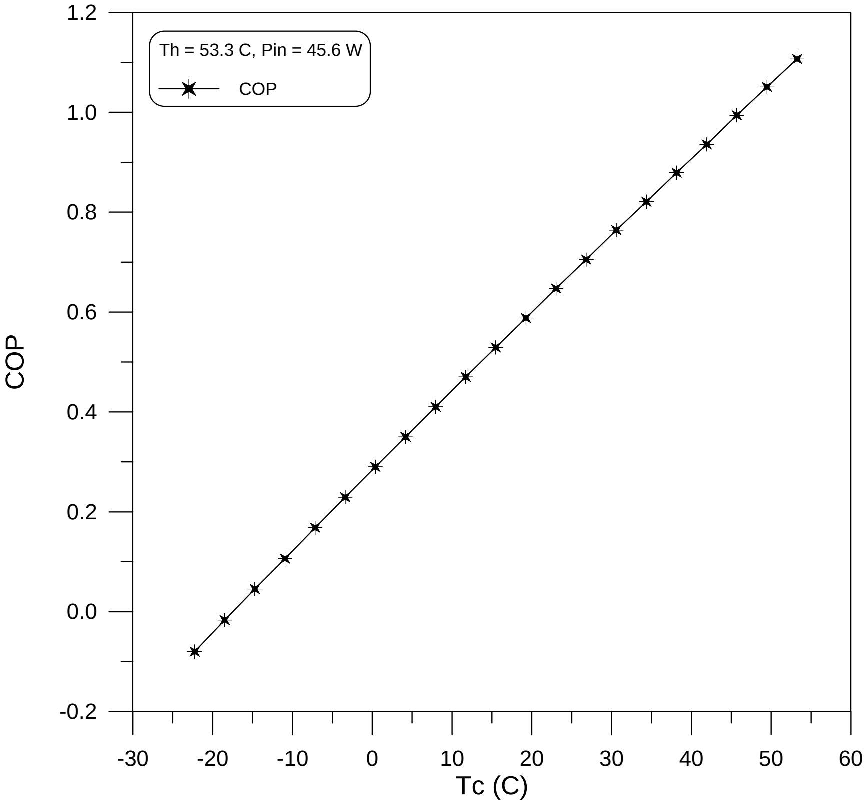

Fig. (11): The variation of T_c against COP

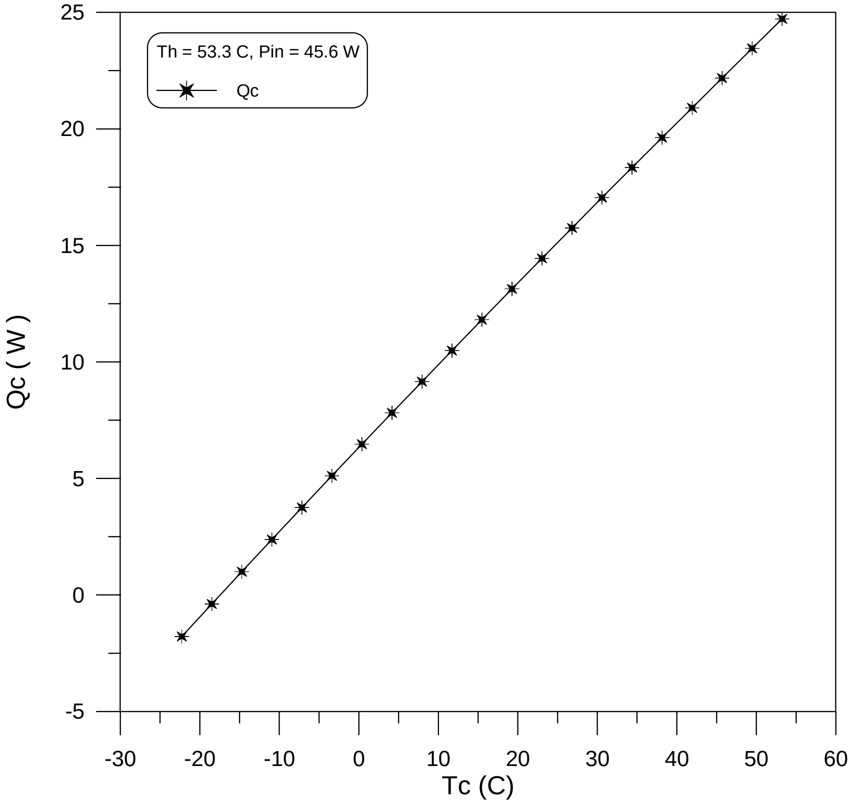

Fig. (12): The variation of Q_c against T_c

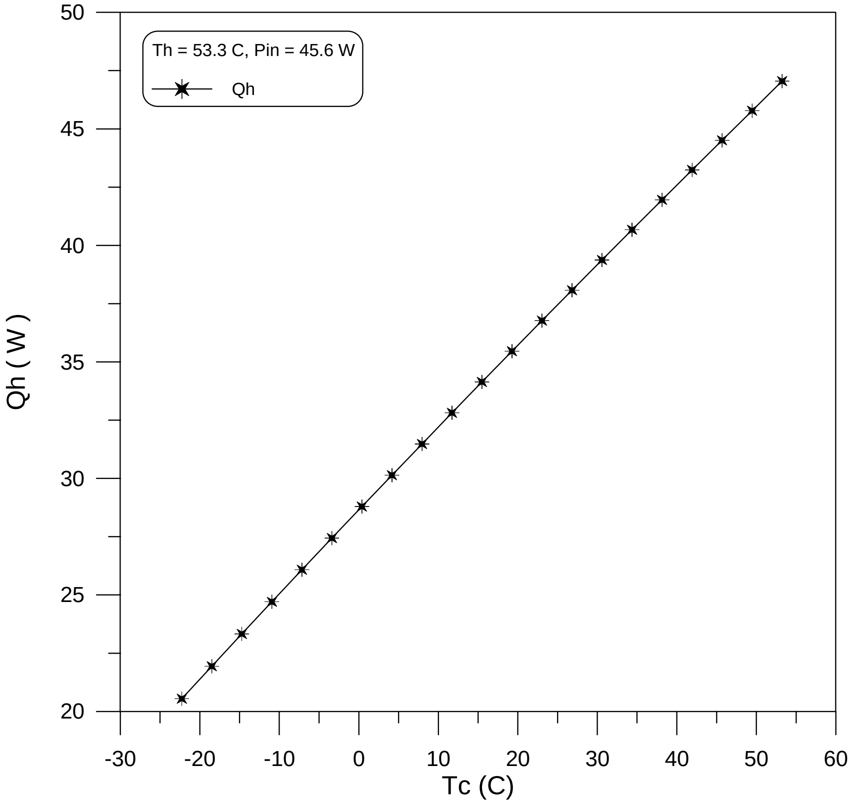

Fig. (13): The variation of Q_h against T_c