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Analysis and Application of Peltier Module for Surface Temperature Measurement in Hybrid Source Thermal Desalination System by Module Parameter Estimation#

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ABSTRACT

This research work explores the integration of Peltier module in hybrid source thermal desalination system for efficient surface temperature measurement. The study investigates the performance of Peltier module that can be used to monitor temperature differentials between the evaporation and condensation chambers and surface temperature of the condensation chamber for the developed desalination unit, enhancing the efficiency of desalination process. An analytical model is derived to link the effective temperature difference within the Peltier module to the load current measured by the true rms multimeter. The module parameter is estimated for the intrinsic and extrinsic values of seebeck coefficient and resistance for the loading condition. The study indicates that the slope of change of internal temperature difference with respect to the load current is 0.8 ^{o}C/A at the boiling point temperature. The hardware setup is designed and developed to verify the analytical value obtained from the derived analytical expression of parameter of the Peltier module. The hardware results are being analysed and will be presented in the future work.

Keywords: hybrid source thermal desalination, Peltier module analysis, seebeck coefficient extraction, electrothermal coupled model, effective Peltier resistance, surface temperature measurement

1. INTRODUCTION

The Peltier module is used in the desalination system for condensation of steam in solar stills to get fresh water [1]. The wide application of the Peltier module as a thermoelectric cooler is used for the controlled cooling of the electronics devices [2]. It is also used as a thermoelectric generator for waste heat recovery in industrial applications [3]. However, the Peltier module may find applications other than thermoelectric cooler and thermoelectric generators. Presently, we have proposed the Peltier module as a temperature sensing element in the desalination system.

Hybrid source thermal desalination systems, which combine multiple energy inputs, require precise thermal management to optimize their performance along with the heat pump application. The optimum performance is obtained when the temperature difference between the evaporation and condensation chamber in the desalination unit is minimum [4]. The mounting of the Peltier module assemblies are already designed and fixed for the developed desalination unit, the traditional temperature measuring methods will be invasive and will create steam loss during the water production. Therefore, we need to have noninvasive techniques which are already integrated into the system for operation. In this context, Peltier modules offer a compelling alternative. By harnessing the Seebeck effect, these modules not only convert thermal gradients into electrical energy but also provide accurate surface temperature measurements.

Traditionally, temperature measurements in Peltier modules have relied on external temperature differences and measurements of open circuit voltage, which do not account for the complexities of internal temperature dynamics [5]. These methods overlook the impact of parasitic thermal resistance and the load current on the effective temperature difference within the module, leading to inaccuracies in parameter extraction. By developing a model to describe the internal temperature difference of thermoelectric modules based on load current, we aim to enhance the reliability of temperature measurements. This model will consider the complexities introduced by parasitic thermal resistance, providing a more accurate

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representation of the thermoelectric parameters under operational conditions.

The authors understand there is no literature available regarding the modelling of the Peltier module where internal temperature difference of the Peltier module in loading condition is used for the surface temperature measurement in desalination system. The envisaged research seeks to bridge the gap in current measurement techniques, offering a comprehensive solution that not only improves parameter extraction of the Peltier module but also directly contributes to the application of the Peltier module in advancement of thermal desalination technologies.

2. METHODOLOGY

2.1 Peltier module integration

The Peltier module is designed with thermoelectric pellets of p-type and n-type material connected electrically in series through plated copper interconnect and connected thermally in parallel where they are sandwiched between ceramic substrate as shown in figure1(a). The temperature difference between the hot ceramic surface (T_H) and the cold ceramic surface (T_C) generates the output voltage(V) as depicted in figure1(a). The thermal resistance network of the Peltier module includes the thermal resistances of the ceramic substrate and Cu interconnection layers (denoted as R_H and R_C at hot side and cold side) and the thermal resistance of the pellets (R_m) as in figure1(b). Electrically, the Peltier module can be modelled as a Thevenin voltage source. The voltage is proportional to the Seebeck coefficient α_m and the intrinsic temperature difference (ΔT_{int}=(T_h−T_c)) between the hot and cold sides temperature of the copper interconnect. The coupled phenomena of thermal where heat form cold side (Q_C) is transported to hot side (Q_h)and electrical effect generating potential (V) is shown in figure1(c).

The integration of the Peltier module into the hybrid source thermal desalination system is crucial for precise temperature measurement and efficient thermal management. The Peltier module is mounted such that its hot side is in direct thermal contact with the evaporation chamber, where the seawater is heated to produce vapor. The cold side of the module is attached to the condensation chamber, where the vapor is cooled and condenses into fresh water.

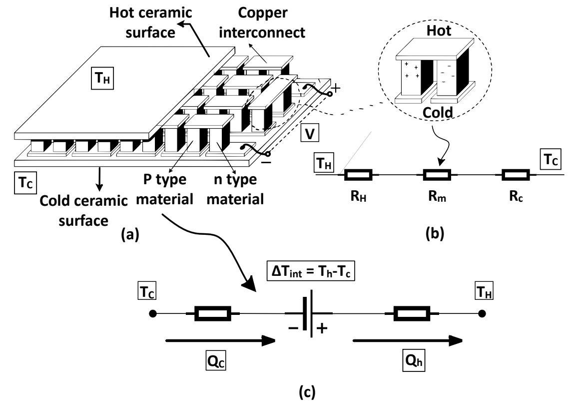


Fig.1 (a) physical interior interconnect and connection of the Peltier module (b) zoomed view of pair of pellets with their thermal network (c) coupled electrical-thermal network representation of the Peltier module.

The cut section view of Peltier module assembly with desalination unit configuration is shown in figure2(a) The thermal coupling is crucial for capturing the actual temperature gradient across the module and ensuring effective heat transfer. Therefore, the overall thermal network for the Peltier module assembly contains the thermal resistance of the upper plate heat sink with the thermal paste (R_{CS}), the thermal resistance of the lower plate heat sink with the thermal paste (R_{HS}) and the thermal network of the Peltier module as shown in the figure 2(b). In the thermal network, the temperature node represents the measuring point for temperature measurement where temperature of evaporation chamber acts as the reservoir temperature during boiling point of water when we need to provide the latent heat. Here, T_{HS} and T_{CS} is temperature of the aluminum plate in the evaporation chamber and the condensation chamber of the desalination unit respectively, T_H and T_C is external hot side ceramic substrate surface and cold side ceramic substrate surface temperature of the Peltier module respectively, T_h and T_c is the internal hot side and cold side temperature of pellet of the Peltier module respectively. The internal temperature node T_c and T_h is impossible to measure when load current is flowing through it without changing the physics of operation of the Peltier module, therefore we need to have analytical expression to find the internal temperature differential in the operating conditions in terms of measurable quantity, here, current and voltage. The electrothermal equivalent circuit model is well developed and used for simulation [6] is shown in the figure 3(a) where the dotted line explains the thermal node point of the thermal network of the Peltier module coupled with the Thevenin source model of the Peltier module.

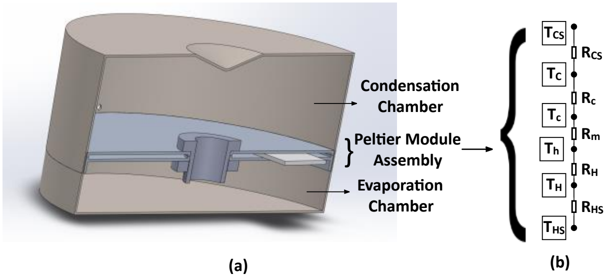


Fig.2(a)cut section view of the hybrid source thermal desalination unit (b) thermal network of the Peltier module assembly mounted in the hybrid source thermal desalination unit.

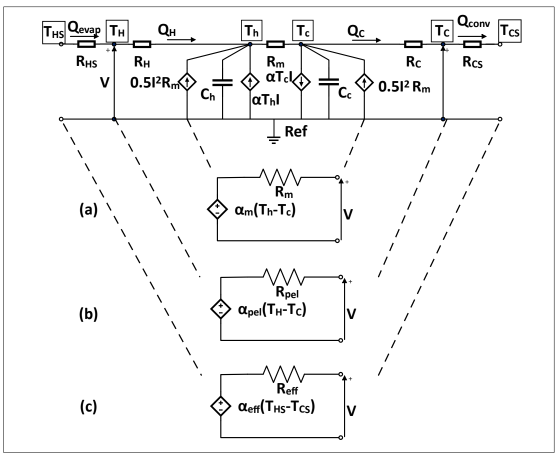


Fig.3(a) Electrothermal model of the Peltier module with internal differential temperature (b) Electrothermal model of the Peltier module with external differential temperature of the ceramic substrate (c) Electrothermal model of the Peltier assembly of the desalination unit.

However, we can measure the terminal voltage and current of the Peltier module, the external seebeck coefficient α_{pel} and Peltier module resistance R_{pel} should be evaluated to get the external generated current-voltage (IV) relationship of the Peltier module as represented in figure 3(b). Further, effective current-voltage relationship pertaining to the aluminum plate temperature difference will be according to the effective seebeck coefficient α_{eff} and Peltier module resistance R_{eff} as represented in the figure 3(c). Although the external seebeck coefficient and effective seebeck coefficient will be same as there is no change in the electrical connection of the Peltier module.

2.2 Modelling of Peltier module with the system

The essence of modelling is to find the differential internal temperature of the Peltier module and cold junction temperature of the Peltier module when the Hot side temperature remains constant. This can be derived by the governing equation of the heat transfer at the both the hot and cold junction of the Peltier module and further extending heat transfer concept to the Peltier assembly through heat conduction. The heat supply at the hot junction Qh will be equal to the heat supply in the evaporator section Qevap of the desalination as they are in thermally series connection. Similarly, the heat removal at the cold junction Qc will be equal to the heat removal at the condensation section Q_{cond} of the desalination unit as in figure3. We get the following governing equation at hot side:

$$Q_H = k_m(T_h - T_c) + \alpha_m I T_h - \frac{I^2 R_m}{2}$$

$$Q_{evap} = k_c(T_H - T_h) + k_{al}(T_{HS} - T_H) \qquad (1)$$

The governing equation at the cold side derived from the principle of conservation of energy are as:

$$Q_C = k_m(T_h - T_c) + \alpha_m I T_c + \frac{I^2 R_m}{2}$$

$$Q_{cond} = k_c(T_c - T_C) + k_{a_l}(T_C - T_{CS}) \qquad (2)$$

Where, k_m, k_c, k_{al} are the effective thermal conductance of the material of the Peltier module, effective thermal conductance of the parasitic component of the Peltier module, effective thermal conductance of the aluminum plate respectively, I is the output current through the Peltier module. For simplicity, the thermophysical and electrical parameters are assumed to be calculated at the average temperature as these parameters are the function of temperature. Since, the parameters of the Peltier module are linearly dependent on the geometry [5] such as the cross-section area(A) of the pellet, leg length of the pellet (L), and the number of the pellets (N), these parameters can be evaluated as:

$$\begin{aligned} k_m &= k\frac{2NA}{L} \\ k_C &= k_{(cu+Cer)}\frac{2NA}{L} \\ R_m &= \rho\frac{2NL}{A} \\ \alpha_m &= (2N)\alpha \end{aligned} \qquad (3)$$

Where k, ρ and α are thermal conductivity, electrical resistivity and seebeck coefficient of the pellet of the Peltier module and k(cu+ceramic) is effective thermal conductivity of parasitic components composed of the ceramic plate and copper interconnect. As the temperature difference at the optimum performance of the desalination unit is minimum, we can assume kc will be equivalent for the both ceramic surface of the Peltier module neglecting the temperature variation on the kc as geometrical structure of the Peltier module is symmetrical.

To find the cold junction temperature, we need to find the expression for T_h+T_c and T_h-T_c. The T_h+T_c can be extracted by subtracting equation (2) from equation (1)

$$\alpha_m I(T_h - T_c) - I^2 R_m = (k_c - k_{\mathrm{al}})(T_H + T_C) - k_c(T_h + T_c) + k_{al}(T_{HS} + T_{cs}) \quad (4)$$

Which can be rewritten as

$$(T_h + T_c) = -\left[\frac{\alpha_m I(T_h - T_c) - I^2 R_m - k_{al}(T_{HS} + T_{CS}) - (k_c - k_{al})(T_H + T_C)}{k_c}\right] \quad (5)$$

The Th-Tc can be extracted by adding equation (2) from equation (1) as

$$2k_m(T_h - T_c) + \alpha_m I(T_h + T_c) = (k_c - k_{al})(T_H - T_C) - k_c(T_h - T_c) + k_{al}(T_{HS} - T_{CS}) \quad (6)$$

From equation (4) and equation (6) we can obtain the internal temperature difference equation. The equation is rewritten in the form given below in equation (7) to have physical significance of the expression. In the equation (7), we can visualize that there are five terms which are affecting the internal temperature difference. The first term is due to thermal network of ceramic substrate , the second term is due to thermal network of aluminum plate , the third term is due to heat generation within the Peltier module due to current flow through the pellets, the fourth and fifth term is due to Peltier effect when load current is flowing due to the temperature difference between the aluminum plate and the external temperature difference between the ceramic substrate temperature respectively.

$$(T_h - T_c) = \frac{k_c}{\alpha_m^2 I^2 - 2k_m k_c - k_c^2}\left[-(k_c - k_{al})(T_H - T_C) + \ k_{al}(T_{HS} - T_{CS}) + \frac{\alpha_m R_m I^3}{k_c} + \frac{\alpha_m I k_{al}(T_{HS} + T_{CS})}{k_c} + \frac{\alpha_m I(k_c - k_{aL})(T_H + T_C)}{k_c}\right] \quad (7)$$

However, if the load current is not flowing, we can neglect the third, fourth and fifth of the equation (7). Therefore, we can obtain the internal temperature difference under open circuit condition as follows:

$$(T_h - T_c)|_{I\to 0} = (\Delta T)_{int}|_{I\to 0} = \frac{kc}{2k_m k_c + k_c^2}[(k_c - k_{al})(T_H - T_C) - k_{al}(T_{HS} - T_{CS})] \quad (8)$$

Equation (8) provides the initial condition value for the internal temperature difference in the Peltier module. However, to get the variation of internal temperature with load current we need to differentiate the equation (7) so that we can the slope for the change in internal temperature difference. The equation (7), can be rewritten as follows:

$$(\Delta T)_{int} = \frac{1}{pI^2 + q}[r + sI^3 + tI] \quad (9)$$

Where

$$p = \alpha_m^2$$

$$q = -(k_c^2 + 2k_m k_c)$$

$$r = -k_c(k_c - k_{al})(T_H - T_C) + k_c k_{al}(T_{HS} - T_{CS}) \quad (10)$$

$$s = \alpha_m R_m$$

$$t = \alpha_m\{k_{al}(T_{HS} + T_{CS}) + (k_c - k_{aL})(T_H + T_C)\}$$

The derivative of equation (10), is evaluated as:

$$\frac{\partial(\Delta T)_{int}}{\partial I} = \frac{3sI^2 + t}{q} \quad (11)$$

The above expression is examined based on the practical value of thermophysical parameters related to the Peltier module [6] [3]and the operating conditions as in table 1. The coefficient parameter p, q, r, s, and t and their product value are calculated for the optimized operating condition of the desalination unit as in table 2.

Table1: Operating Condition and thermophysical Parameter of the Peltier module

Operating Condition	Value	Thermophysical Parameter of the Peltier	Value
T_{HS}	370.6K	k_c	50 W/mK
T_H	370K	k_m	3.52W/mK
T_{CS}	360.6K	α_m	0.07 V/K
T_C	360K	R_m	1.2 ohm
		k_{al}	204 W/mK

Table2: Value of coefficient used for deriving the differential internal temperature expression with respect to load current

Coefficients	value	Coefficients	value
p	4.9*10^-3	qs	240
q	2852	qt	7.2*10^6
r	50000	pr	245
s	8.5*10^-2	pt	12
t	2520	pq	14
ps	4.1*10^-4	q^2	8.2*10^6

The coefficient is neglected if their value is very negligible compared to the other coefficient to derive at the above expression. Finally, the differential internal temperature is written as in equation (11)

$$\frac{\partial(\Delta T)_{int}}{\partial I} = \frac{3\alpha_m R_m I^2+\alpha_m\{k_{al}(T_{HS}+T_{CS})+(k_c-k_{al})(T_H+T_C)\}}{-(k_c^2+2k_m k_c)} \quad (12)$$

Therefore, the final expression for the internal temperature difference with the initial value can be written as:

$$(\Delta T)_{int} = \frac{\alpha_m R_m I^3+\alpha_m I\{k_{al}(T_{HS}+T_{CS})+(k_c-k_{al})(T_H+T_C)\}}{-(k_c^2+2k_m k_c)} + \frac{kc}{2k_m k_c+k_c^2}[(k_c-k_{al})(T_H-T_C)-k_{al}(T_{HS}-T_{CS})] \quad (13)$$

Here, the internal temperature difference is the cubic function of the load current flowing through the Peltier module. For more simplicity, the value of 's' compared to 't' in equation (11) can be ignored. This leads to the expression of differential equation as:

$$\frac{\partial(\Delta T)_{int}}{\partial I} = \frac{t}{q} \quad (14)$$

This differential equation of slope of internal temperature depicts that the slope of internal temperature difference of the Peltier module is independent of load current. Therefore, we can establish the internal temperature difference as linear function of load current as follows:

$$(\Delta T)_{int} = \frac{\alpha_m I\{k_{al}(T_{HS}+T_{CS})+(k_c-k_{al})(T_H+T_C)\}}{-(k_c^2+2k_m k_c)} + \frac{kc}{2k_m k_c+k_c^2}[(k_c-k_{al})(T_H-T_C)-k_{al}(T_{HS}-T_{CS})] \quad (15)$$

From the figure3(a), we gave the terminal voltage can written as:

$$V = \alpha_m(\Delta T)_{int} - R_m I \quad (16)$$

After putting the expression of the internal temperature difference, we get the

$$V = \frac{\alpha_m kc}{2k_m k_c+k_c^2}[(k_c-k_{al})(T_H-T_C)-k_{al}(T_{HS}-T_{CS})] - [R_m + \frac{\alpha_m^2\{k_{al}(T_{HS}+T_{CS})+(k_c-k_{al})(T_H+T_C)\}}{(k_c^2+2k_m k_c)}]I \quad (17)$$

The first term indicates the voltage generated due to the seebeck coefficient and the second term denotes the decrease in the voltage due to voltage drop across the effective Peltier module resistance. Observing the expression of the voltage generated, the effective Peltier module resistance can be written as:

$$Reff = R_m + \frac{\alpha_m^2\{k_{al}(T_{HS}+T_{CS})+(k_c-k_{al})(T_H+T_C)\}}{(k_c^2+2k_m k_c)} \quad (18)$$

3. RESULTS AND DISCUSSION

When aluminum plate is neglected, then output voltage can be written as:

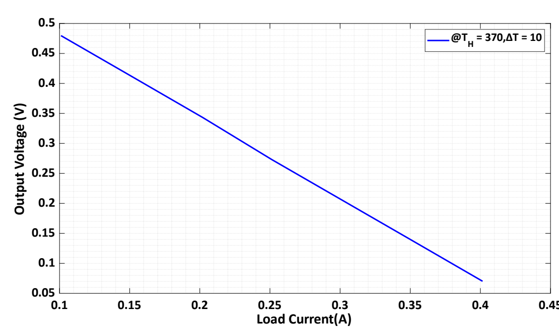
$$V = \frac{\alpha_m kc}{2k_m k_c+k_c^2}[(k_c)(T_H-T_C)] - [R_m + \frac{\alpha_m^2\{(k_c)(T_H+T_C)\}}{(k_c^2+2k_m k_c)}]I \quad (19)$$

Therefore, Peltier module resistance will be

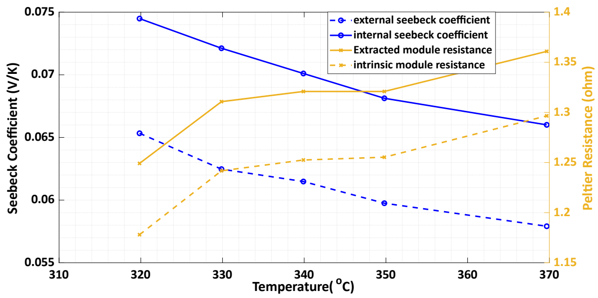
$$Rpel = R_m + \frac{\alpha_m^2\{(k_c)(T_H+T_C)\}}{(k_c^2+2k_m k_c)} \quad (20)$$

And external seebeck coefficient

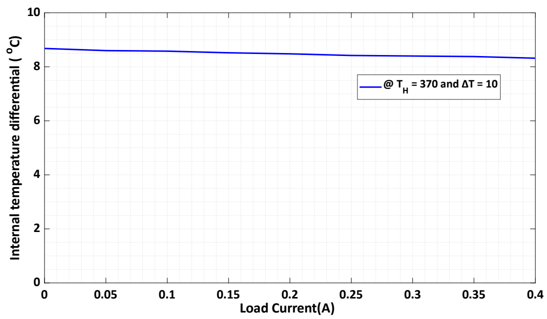
$$\alpha_{pel} = \frac{\alpha_m kc}{2k_m k_c+k_c^2}[(k_c)] \quad (21)$$



(a)



(b)



(c)

Fig4. (a) VI curve of the Peltier module (b) parameters of the Peltier module is extracted and estimated (c)plot of internal temperature difference w.r.t. load current.

From the experimental result of voltage and current relationship [3,6] at T_H = 373 with temperature difference of 10 degree as in figure4(a) and using equation (15),(20) and (21), we can extract the external seebeck coefficient, Peltier resistance with the variation of temperature as in figure4(b)and internal temperature difference with the load current showing a slope of 0.8 °C/A as shown in figure4(c). The figure4(b), shows that the module resistance is greater than intrinsic resistance and external seebeck coefficient is lower than internal seebeck coefficient at all temperature.

4. CONCLUSIONS AND FUTURE WORK

This research successfully integrates a Peltier module into a hybrid source thermal desalination system to enable precise surface temperature measurements. An analytical model was developed to relate the effective temperature difference within the Peltier module to the load current, which can be measured using a true RMS multimeter. This model allowed us to estimate the intrinsic and extrinsic parameters of the Peltier module, specifically the Seebeck coefficient and resistance, under operational conditions. To validate the analytical findings, a hardware evaluation setup is designed and developed as shown in figure 5. The results are being analyzed and will be presented in near future.

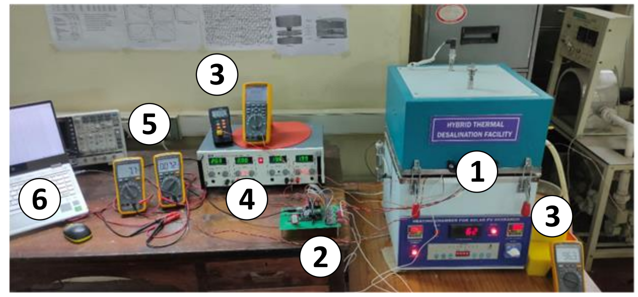


Fig.5: Experimental setup (1) hybrid source thermal desalination unit (2) developed temperature measuring board (3) temperature measuring meter (4) linear power supply (5) true rms multimeter (6) data logging for temperature measuring board

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