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COOLING PERFORMANCE OF THERMOELECTRIC COOLER MODULES: EXPERIMENTAL AND NUMERICAL METHODS

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Abstract: A novel pulse-driving method in which the pulse frequency modulation is was developed by optimising the input power owing to the duty cycle of rectangular wave to enhance the cooling efficiency and thermal stability of the thermoelectric module. The aim of this driving method is to have better control of the thermoelectric cooler module temperature and to improve its coefficient of performance. In this method, the average current and the peak of pulse drive are in the 50% duty cycle with the same magnitude and the performance of Peltier module driving with average dc is compared with the pulse driving. The measurement results show that the coefficient of performance of the thermoelectric module with the pulse-frequency modulation driving method increased up to 102% as compared to the constant dc driving method. An artificial neural network has been successfully used to analyse these experimentally collected data and predict the performance of the module. When the developed artificial neural network model was tested using untrained data, the average correlation of the model was 99% and the overall prediction error was 1.38%. An accurate and simple analytical equation based on the predicted and experimental results was determined using the MATLAB® Curve Fitting Toolbox. The average correlation of the analytical model was 0.99 and the root-mean-square error was 0.074.
Keywords: thermoelectric cooler module, cooling performance, drive method, artificial neural network.

TERMOELEKTRİK SOĞUTMA MODÜLLERİNİN SOĞUTMA PERFORMANSI: DENEYSEL VE SAYISAL YÖNTEMLER

Özet: Termoelektrik modülün ısısal kararlılığını ve soğutma verimini arttırmak için, atımlı frekans modülasyonunda yeni bir atımlı sürücü yöntemi dikdörtgen dalga olan girişin en uygun yapılması ile geliştirilmiştir. Bu sürücü yönteminin amacı termoelektrik soğutma modülünün sıcaklığını daha iyi kontrol etmek ve verimini arttırmaktır. Bu yöntemde, %50 çalışma periyodundaki ortalama akım ve sürücü atımın en büyük değeri aynı büyüklüktedir ve dc ile sürülen Peltier modülün performansı atımla sürülen ile karşılaştırılmıştır. Ölçme sonuçları, termoelektrik modülün verim katsayısının, atımlı frekans modülasyonu sürücü yöntemi ile sabit dc sürücü yöntemi karşılaştırıldığında %102'ye kadar arttığını göstermiştir. Yapay sinir ağları, alınan deneysel verileri çözümlemek ve modülün performansını tahmin etmek için başarı ile kullanılmıştır. Geliştirilen yapay sinir ağı modeli öğrenmede kullanılmayan verilerle denendiğinde, modülün ortalama uyumu %99 ve en büyük tahmin etme hatası %1.38 olmuştur. Deneysel ve tahmin verilerine bağlı olarak doğru ve basit bir analitik denklem MATLAB® eğri uyum programı kullanılarak belirlenmiştir. Analitik denklemin ortalama uyumu 0.99 ve etkin hatası 0.074 olmuştur.
Anahtar kelimeler: Termoelektrik soğutma modülü, Soğutma performansı, Sürücü yöntemi, Yapay sinir ağı.

NOMENCLATURE

CFC	ChloroFluoroCarbon
TEC	Thermoelectric cooler
COP	Coefficient of performance
PWM	Pulse width modulation
PFM	Pulse frequency modulation
Q_C	Endothermic quantity, heat dissipative, W
Q_J	Joule heat, W
Q_{hc}	Rate of heat conduction, W
α	Seebeck coefficient, V/K
I	Direct current passing through the module, A
T_C	Cold side temperature of the module, K
ρ	Electrical resistivity, Ω m,
l	Length, m
A	Cross sectional area, m^2,
Q_P	Electrical energy consumption, W
k	thermal conductance, W/K
λ	Thermal conductivity, W/(m K)
NTC	Negative Temperature Coefficient
Z	Figure of merit
P_{pc}	Pulse current power, W
I_{av}	Average current of the module, A
N	Real number
P_{dc}	dc power, W
P_P	Power consumption, W
RMS	Root mean square
f	frequency, Hz
m	Mass of aluminium heated block, kg
C	Specific heat coefficient, J/(kg K)
ANN	Artificial neural network
RAM	Read access memory
T_h	Hot side temperature of the module, K
t	time, s
V	Voltage across the terminals of TEC module, V
ΔT	Temperature difference, K

INTRODUCTION

In recent years, heat dissipation of electronic systems has grown rapidly with improving manufacturing technology. This growth has induced a serious electronic cooling problem. A conventional cooling system includes an evaporator, a compressor and a condenser and they are widely using for many purposes. However, energy costs and environmental regulations regarding the manufacture and release of chlorofluorocarbons (CFCs) are also increasing. These facts are encouraging manufacturers and their customers to seek alternative for conventional cooling technology (Derebasi *vd*, 2015).

Being no moving parts, environmentally friendly technology and requiring almost no maintenance, thermoelectric technology has become one of the most promising alternative methods to solve increasingly serious energy shortage and environmental pollution problems. Thermoelectric cooler (TEC) modules have been applied for electronic cooling in many industries such as medical instrument, aerospace, military, industrial products, offering the advantages of small size, quite operation, long lasting time, ease of use and reliability (Sekiguchi *vd*, 2018).

The coefficient of performance (COP) for the thermoelectric technology is the ratio of output and input energy, which depends on the current through the module and the temperature difference between two sides of the thermoelectric module. The COP of thermoelectric module is smaller than the COP of conventional cooling system has. Therefore, much research has focused on the improvement of the COP of thermoelectric cooling systems by means of developing new materials for the TEC modules, optimization of module systems design, fabrication, improvement of the heat exchange efficiency and optimisation for geometrical dimensions of each p- and n- types semiconductors of TEC (Derebasi *vd*, 2015, Sekiguchi *vd*, 2018, Twaha *vd*, 2016, Song *vd*, 2020, Derebasi *vd*, 2015). However, few studies have been carried out on the performance of cooling modules including the current driving method of them (Sekiguchi *vd*, 2018 , Baubaris *vd*, 2017).

Peltier devices are thermoelectric conversion devices that consist of two types of electric conductors joined by a junction. Heat travels from one of the conductors to the other, when current is applied to the junction. Thermoelectric refrigeration is achieved, when a direct current is passed through one or more pairs of n- and p-type semiconductor materials, primarily comprised bismuth-tellurium alloys. In the cooling mode, direct current passes from the n- to p-type semiconductor materials, which are soldered in series to copper electrodes.

Peltier devices are used to cool electrical components, because they are capable of localised cooling. The refrigeration capability of a semiconductor material is dependent on the combined effect of the material's Seebeck voltage, electrical resistivity, and thermal conductivity over the operating temperature range between the cold and hot ends (Guclu and Cuce 2019).

One method of driving Peltier devices is on-off control in which constant dc current interrupted according to a set temperature. In this on-off control, the ripple component in the output voltage of power supply comprised a switching converter and the like increases the self-heating of the Peltier device. To resolve this, an extra electronic filter circuits are used to attenuate the ripple component.

Another method of driving Peltier devices is the Pulse Width Modulation (PWM) control in which repetitive pulse current with a constant amplitude is controlled with a high precision. However, in the on-off and the PWM control, cooling efficiency decreases due to the self-heating of the Peltier device increasing as a result of the intermittent control of driving current (Sekiguchi *vd*, 2018). Moreover, the electromagnetic interference issues have raised considerable limitations on PWM applicability, especially high switching frequencies. Therefore, an extra electronic circuitry are necessary (Baubaris *vd*, 2017).

The use of Artificial Neural Networks (ANN) has grown in popularly during the last decade. The reason for this is that neural networks represent a novel and modern approach that can provide solutions to problems for which conventional mathematics, algorithms and methodologies are unable to find a satisfactory and acceptable solution. ANNs are inspired by the human brain functionality and structure, which can be imagined as a network that comprises of densely interconnected elements called neurons. Despite this fact, the ANNs' objective is not to model it.

Instead, their purpose is to be useful models that can be used for problem solving and knowledge engineering, in a way that resembles the human process for problem solving and knowledge acquisition. Both biological and artificial networks have the following main and important features: learning adaptation, generalization, massive parallelism, robustness, associative storage information and spatiotemporal information processing (Laidi and Hanini, 2013).

Furthermore, for the numerical analysis, the MATLAB® Curve Fitting Toolbox™ can be used to determine an accurate and simple analytical equation for the performance of TEC module corresponding to experimental and predicted data obtained.

Many researches have been carried out to control the temperature of TEC module using the on-off and PWM driving current methods. However, this research concentrates on the pulse frequency modulation (PFM) current driving method of TEC module to control its temperature and to improve its COP. An optimised PFM driving current is proposed and applied to the module to reduce the Joule heating and then to control the temperature of TEC module and improving the COP. Furthermore, the ANN has applied to the experimental data to estimate the performance of the TEC module and the MATLAB® Curve Fitting Toolbox™ was also used to define an accurate and simple analytical equation for the performance of TEC module corresponding to experimental and predicted data.

This investigation particularly highlights an optimised PFM driving method, which provides to control of temperature of TEC module and improve the COP. Moreover, an ANN model and an analytical equation were obtained to predict the performance of the TEC module corresponding to experimental data.

THEORY OF THERMOELECTRIC COOLING

A typical TEC module (Peltier module) consists of p- and n-types semiconductors connected electrically in series and thermally parallel sandwiched between two ceramics substrates [Fig. 1]. Whenever direct current passes through the circuit of thermoelectric heterogeneous conductors, it causes temperature differential between TEC module sides. As a result, one TEC face, which is called cold side, will be cooled while its opposite face, which is called hot side, is simultaneously heated. This phenomenon is known as the Peltier effect (Sulaiman vd, 2018, Rowe, 2006). The thermoelectric heat (Q_c) pumped by the Peltier effect at the cold end of a thermoelectric couple as shown in Fig. 2 is given by;

$$Q_C = \alpha I T_C \quad (1)$$

where α, I, and T_c are the Seebeck coefficient, which is dV/dT [V/K], the direct current in Ampere passing through the thermoelectric material and the cold-side temperature in Kelvin, respectively. Current flow generates Joule heat (Q_J) in the thermoelectric material, which goes equally to the cold and hot ends:

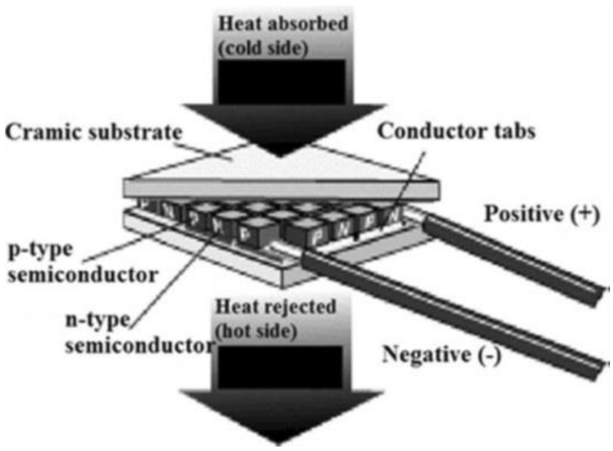

Figure 1. Typical TEC module.

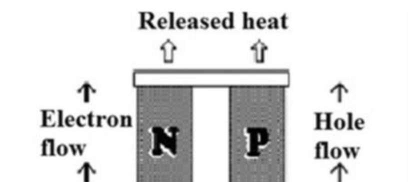

Figure 2. Thermoelectric heat pumping by the Peltier effect in a thermoelectric p-n couple.

$$Q_J = \frac{I^2 \rho l}{2A} \quad (2)$$

where ρ, *l* and A are the electrical resistivity [Ω m], length [m] and cross sectional area [m^2] of thermoelectric material. During operation, heat is conducted by electrons from the hot to the cold end through the thermoelectric material. The rate of heat conduction (Q_{hc}) is given by;

$$Q_{hc} = k(T_h - T_c) = k\Delta T \quad (3)$$

where k and ΔT are the thermal conductance [W/K] and the temperature difference [K] between the hot and cold sides of thermoelectric couple, respectively. k can be defined as;

$$k = \lambda \frac{A}{l} \quad (4)$$

where λ is the thermal conductivity in W/(m K), A is the cross sectional area and l is the length of the thermoelectric material. Combining Eqs. (1, 2, 3 and 4) into an energy balance at the end of the thermoelectric couple gives;

$$Q_c = \alpha I T_c - \frac{I^2 \rho l}{2A} - k\Delta T \quad (5)$$

The refrigeration capability of a semiconductor material is dependent on combined effect of the material's Seebeck voltage, electrical resistivity, and thermal conductivity over the operational temperature range between cold and hot ends (Derebasi *vd*, 2015, Sekiguchi *vd*, 2018, Rowe, 2006, Riffat and Ma, 2003).

The first term on the right hand side of Eq. (5) represents the Peltier effect, and is thought to generate heat flow proportional to the average current I. The second term represents the reduction in endothermic quantity due to the heat generation of the Peltier device itself and corresponds to the half of the Joule heating of the Peltier device. The last term describes the reverse heat flow from the high temperature part due to the low temperature part.

The electrical energy consumption (Q_p) [W] of a couple is given by;

$$Q_P = \frac{I^2 \rho l}{A} + \alpha I \Delta T \quad (6)$$

The electric power consumption of a thermoelectric couple is used to generate the Joule heat and overcome the Seebeck effect, which generates power due to the temperature difference between two junctions of the couple. The coefficient of performance (COP) of the thermoelectric couple for cooling is given by;

$$COP = \frac{Q_c}{Q_P} = \frac{\alpha I T_c - \frac{I^2 \rho l}{2A} - k\Delta T}{\frac{I^2 \rho l}{A} + \alpha I \Delta T} \quad (7)$$

The COP of a thermoelectric material is a combined effect of the material Seebeck coefficient, electrical resistivity, geometrical dimensions of thermoelectric material and thermal conductivity over the operational temperature range between the cold and hot ends. The performance of thermoelectric material is called as a figure of merit (Z) and expresses;

$$ZT = \frac{\alpha^2 A}{k \rho l} T = \frac{\alpha^2}{kR} T \quad (8)$$

Each of the n- and p-type semiconductor thermoelectric material properties varies as a function of temperature and therefore the figure of merit for each material is temperature dependent. Maximising the figure of merit is larger objective in the selection and optimising of thermoelectric materials and then it limits the temperature differential, whereas the geometrical dimensions for each n- and p-type of semiconductor material define the heat pumping capacity. The most widely used thermoelectric semiconductor material for cooling in the temperature range of 0-200 ºC is the Bismuth-Telluride (Bi_2Te_3) due to its thermal properties at room temperature as compared to other thermoelectric materials (Bar-Cohen *vd*, 2005).

DRIVING METHOD

Analysing the pulse current driving with constant amplitude the reduction in pulse current power (P_{pc}) can be understood in the endothermic quantity due to the heat generation of the Peltier device itself during the pulse driving. The duty cycle (one period) of the pulse driving is based on the driving current waveform of the Peltier device shown in Fig. 3. The reduction in the endothermic quantity can be explained in terms of average current applied to the Peltier device (I_{av}) as;

$$\frac{P_{pc}}{N} = \frac{\rho l}{2A} N \left(\frac{I_{av}}{N}\right)^2 = \frac{\rho l}{2A} \frac{I_{av}^2}{N} \quad (9)$$

where N is a real number between zero and one.

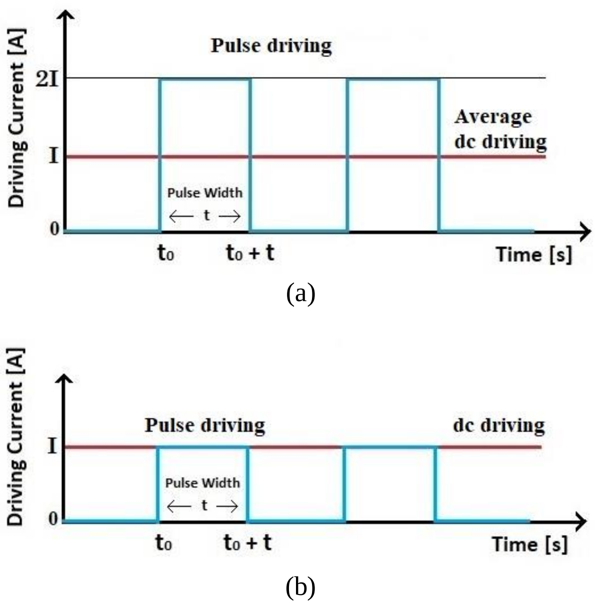

Figure 3. Driving current waveforms in different magnitudes, a) average and b) constant

The reduction in power using the PWM control is analysed in the endothermic quantity due to heat generation of the Peltier device itself during pulse driving with 50% duty cycle (Sekiguchi *vd*, 2018). In addition, it is compared to the same average current as dc to obtain the same Peltier effect. In this case, when the average current is I, the peak of pulse drive must be 2I in the 50% duty cycle of PWM [Fig 3 (a)]. However, in this research, the average current and the peak of pulse drive are in the 50% duty cycle with the same magnitude and the performance of Peltier module driving with average dc is compared with pulse driving [Fig. 3 (b)].

Accordingly, it is clear that the reduction in driving power of endothermic quantity can be reduced N times regarding the driving direct current. The COP of the Peltier device (TEC module) can be expressed by;

$$COP = \frac{Q_c}{P_p} \quad (10)$$

where Q_c and P_p are the heat dissipation and power consumption of the Peltier device respectively. The heat dissipation can be calculated as;

$$Q_c = m\,C\,\Delta T \quad (11)$$

where m is the mass of heated side of the Peltier device [kg], C is the specific heat [J/(kg K)] and ΔT is the temperature difference between hot and cold sides of Peltier device. The power consumption of the Peltier device can be calculated by input power as;

$$Q_p = IV \quad (12)$$

EXPERIMENTAL SET UP

The measurement system consists of 3 parts: driving of Peltier module, signal processing and temperature control. Fig. 4 shows a block diagram of the system. The Peltier module, type Z-MAX TEC1 – B12708AC, which has an aluminium layer on both sides is used. This Peltier module is a special production and has higher efficiency than the other modules. Aluminium layers on two surfaces of module were originally fitted to the module surface using thermal paste to have better heat transfer (Fig. 5). In addition, the module was also fitted to the heat sink using thermal paste. Thus, it is ease of fitting to the heat sink and minimises the heat losses between the module and heat sink.

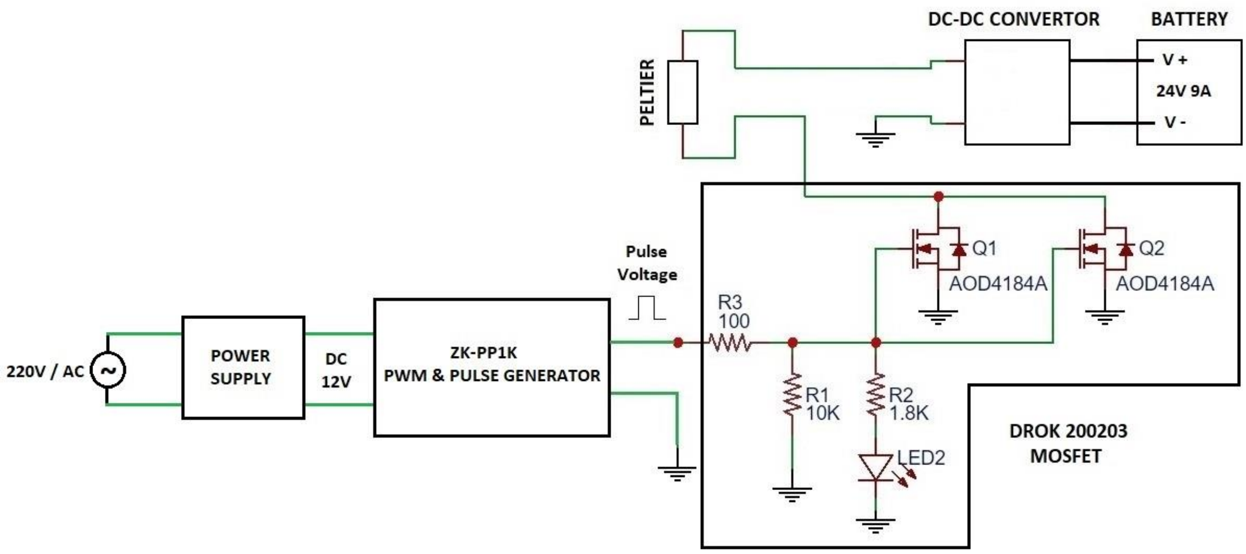

Figure 4. Block diagram of measurement system.

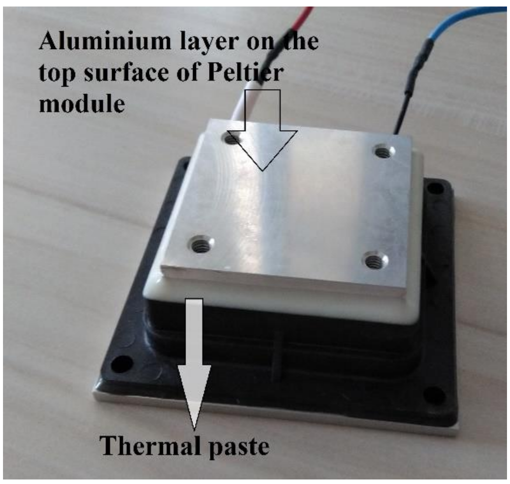

Figure 5. The Peltier module, type Z-MAX TEC1 – B12708AC.

The voltage across the module was measured by a digital multimeter, type AN8002. Table 1 shows the technical specifications of the Peltier TEC module used. Peltier TEC modules are very sensitive for the waveform of driving current and then, their performance can be affected, if the driving current waveform has any harmonic or noise. Two batteries, which are 12 V 9 A in power, are used as a power supply. They are connected in series to increase the output voltage and can be provided a continuous noiseless power to be able to tolerate the power loss of Peltier TEC module.

A DC-DC converter, [Fig. 4] type DPS5015, is connected to the batteries in series to limit the driving current of the Peltier module at varied current values in the range of 0.5 to 5 A.

In signal processing part, a signal generator, type ZK-PP1, produces a rectangular wave signal 0 – 5 V, 30 mA, from 1 Hz to 150 kHz operating frequency. Its duty cycle can be arranged from 1% to 100%, but in this system, 50% duty cycle was chosen to drive the module at varied frequency. The output of rectangular wave generator is connected to the MOSFET transistors, type DROK 200203. They can be operated from 5 – 36 V up to 15 A current and 20 kHz frequency as an output. Since the tested Peltier module operates 12 V 6 A power. The MOSFET transistors are increased the peak of rectangular wave signal to this level of power.

In the temperature control part, two digital thermometers, type LT172N, measured the temperature on hot and cold sides of the Peltier device. The initial temperature was recorded as a room temperature by means of a digital thermometer, just before the tests were begun to keep the thermal stability of hot and cold surfaces of the module. The digital thermometers LT172N have ±3% sensitivity in full scale due to their temperature sensors used, which are the NTC thermistor, type GM-NTC-105C. The sensitivity of other measurement devices is less than ±0.1 in full scale. Therefore, the maximum overall measurement error of the system is found to be about ±3%. Fig. 6 and Fig. 7 show the general view of measurement system and Peltier device system respectively.

Table 1. Technical specifications of the Peltier module used.

Dimensions	W70xD70xH27 (mm)
Cooling performance	57.8 W
Rated voltage	DC ±12 V
Rated current	6 A
Inner resistance	1.35 – 1.65 Ω

The system was tested using an aluminium mass, which has the mass of 0.193 kg and the specific heat coefficient of aluminium is 903 J/(kg K). The heat dissipation Q_C was calculated by Eq. (11) in the measured temperature range and power consumption of Peltier device Q_P was obtained by the recorded voltage across the module and current passing through the module. Then the COP was calculated by the ratio of Q_C/Q_P, which is given in Eq. (10).

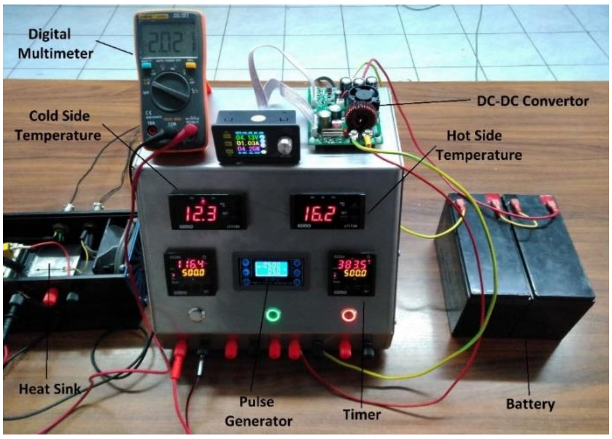

Figure 6. View of measurement system.

ARTIFICIAL NEURAL NETWORK MODEL

Neural networks represent a novel and modern approach that can provide solutions to problems, for which conventional mathematics, algorithms, and methodologies are unable to find a satisfactory and acceptable solution. ANNs are inspired by the functionality and structure of the human brain, which can be imagined as a network comprising densely interconnected elements called neurons (Graupe, 1997).

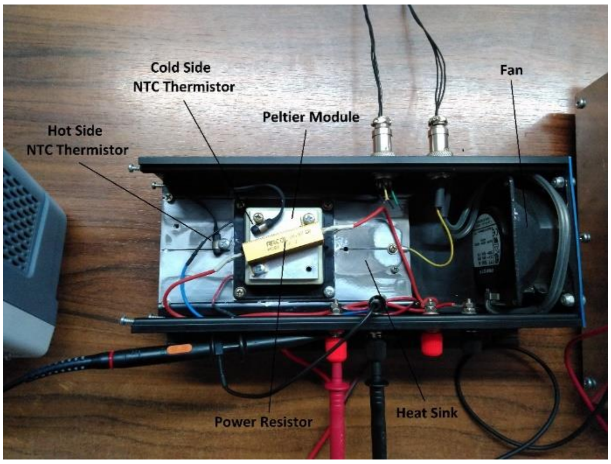

Figure 7. Peltier device system.

The most popular neural network is the multilayer perceptron, which is a feed-forward network; i.e., all signals flow in a single direction from the input to the output of the network. It consists of neurons organized in a number of layers that can be categorized into three parts: the first part is the input layer, which allows the network to communicate with the environment; the second part is commonly known as the hidden part, in which one or more layers of neurons exist depending on the problem's demands and requirements for generalization; and the third part is the output layer.

The artificial neurons are arranged in layers, wherein the input layer receives inputs from the real world and each successive layer receives weighted outputs from the preceding one as its input, thereby resulting in a feed-forward ANN, where each input is fed forward to the subsequent layer for treatment. The outputs of the last layer constitute the outputs to the real world.

The main problem with an ANN model has been to establish representative training data, particularly, when a large number of variables are considered as being in this study. Training data from the experimental work on TEC modules was obtained for dimensions with the length, width and height 70x70x27 mm. In the proposed neural network models, the input parameters were the cold side temperature (T_c), the hot side temperature (T_h), the temperature difference between cold and hot side of TEC module (ΔT), the driving current (I), voltage across the terminals of the TEC module (V), the driving time (t) and frequency (f), while the output parameter was the performance of TEC module (COP) (Fig. 8).

Qnet 2000®, a commercial neural network package, was used for the prediction of the performance of TEC module, offering the advantage of rapid network development through flexible choices of algorithms, output functions, and other training parameters, thereby enhancing accuracy (Qnet2000). A total of 150 input vectors obtained from the TEC module for the COP, and it was available in the training set for a back-propagation neural network. The number of hidden layers and neurons in each layer were determined by trial and error to be optimal, including different transfer functions such as hyperbolic tangent, sigmoid, and hybrid. After the network had been trained, better results were obtained from the network formed by the hyperbolic tangent transfer function in the four hidden layers as well as in output layer for prediction of the COP. The hyperbolic tangent transfer function is

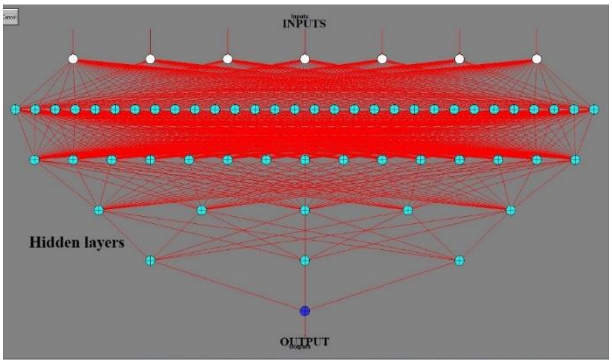

Figure 8. The developed ANN for performance of TEC module.

$$tanhx = \frac{e^x - e^{-x}}{e^x + e^{-x}} \qquad (13)$$

The networks included 7 input neurons, 1 output neuron, and four hidden layers with 53 neurons for the COP, with full connectivity between nodes [Fig. 8]. Back-propagation ANNs require that all training input data must be normalized to improve the training characteristics. Therefore, all data for the nodes in the input layer and training targets for the output layer were normalized between the limits of 0.15 and 0.85. In training of networks, a HP workstation, which had an Intel® core i7-720QM microprocessor, 1.6 GHz, 6 MB L3 cache, and 16 GB RAM, was used. The calculation time was about 10 hours for each trained network.

ANALYTICAL ANALYSIS WITH MATLAB®

The MATLAB® Curve Fitting Toolbox™ was used to determine an accurate and simple analytical equation for the performance of TEC module corresponding to experimental and predicted data. It provides graphical tools and command-line functions for fitting curves to data. The toolbox performs exploratory data analysis, pre-processes and post-process data; compares candidate models and removes outliers and allows working an interactive environment with graphical user interface.

The regression analysis using the library of linear and nonlinear models provided can be conducted or specified own custom equations. The library provides optimized solver parameters and starting conditions to improve the quality of your fits. The toolbox also supports nonparametric modelling techniques, such as splines, interpolation, and smoothing. After loading some data, a fit can be created using a fit function, specifying variables and a model type including exponential, Fourier, Gaussian, polynomial, power, etc (MATLAB® R2018b).

RESULTS AND DISCUSSIONS

When the Peltier module is operated, it is heated up itself due to current passing through it and then, its resistance changes. The voltage across the module varies with temperature, because the current passing through the module keeps constant consistently. Fig. 9 shows the variation of module resistance with the temperature difference between the cold and hot sides of the TEC module under constant 1 A dc current and in 500 seconds test time.

The resistance of the module slightly increases with the temperature difference up to about 1 °C, whereas it keeps almost constant at higher temperature difference values above 1 °C. The maximum change was about 0.59 ohm with the temperature difference 8.2 °C.

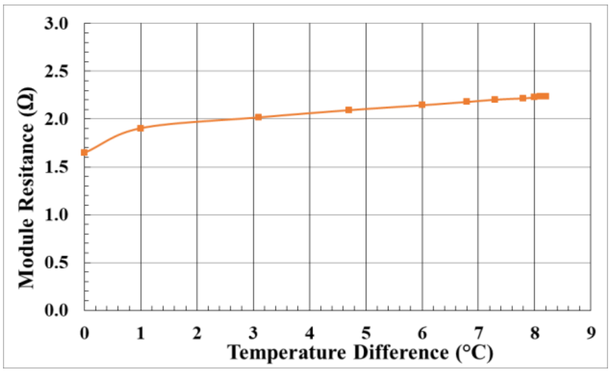

Figure 9. Variation of module resistance with temperature difference ΔT under constant dc current 1 A and in 500 seconds test time.

Fig. 10 shows the variation of module resistance with the driving current for the constant dc current and PFM. The module resistance slightly decreases with the driving current up to 2 A, while its maximum variation is about 0.06 ohm between 2 A and 6 A. The constant module resistance yields to the thermal stability of the module and then, it affects its efficiency.

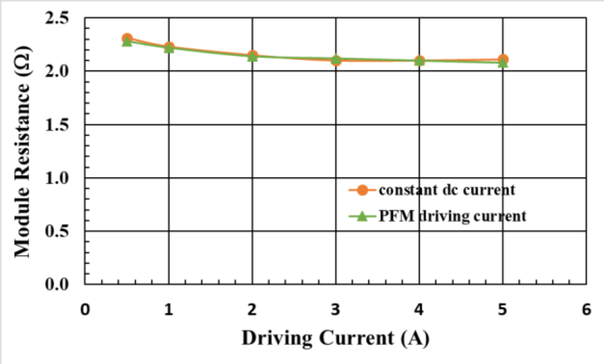

Figure 10. Variation of module resistance with driving current for constant dc current and PFM.

The aim of the research is to compare the performance of the module between the driving methods with constant dc current and optimised rectangular wave. The dc current value corresponding with the peak value of the rectangular waveform was chosen. Thus, the driving of the module with both methods was realised using the same system and conditions during the tests and they can be appropriately comparable. The measurements were carried out using constant dc driving current values with 0.5, 1, 2, 3, 4 and 5 A and the obtained results were summarised in Table 2. The temperature difference (ΔT) increases with increasing dc current and voltage of the module, whereas the COP value decreases. The COP value was dramatically reduced after 1 A dc current.

The Peltier module was also derived by the rectangular wave (50% duty cycle) with frequency values at 50, 100, 200, 300, 400, 500 and 1000 Hz. The operating frequency was comparatively determined by means of the COP values among experimental data. Although they are very close to each other as shown in Table 3. The thermoelectric module has the best COP value at 500 Hz for the rectangular wave driving current.

Electromagnetic interference is a critical issue during experiments due to high frequency current pulses at Peltier modules. An appropriate shielding and smart control techniques are the tools for the employment of higher switching frequencies above 10 kHz (Baubaris *et al*, 2017).

Table. 2. Measurement results at varied constant dc driving current values in 500 s test time.

Dc current (A)	Cold side temperature (°C)	Hot side temperature (°C)	Room temperature (°C)	ΔT (°C)	Module Voltage (V)	Module Resistance (Ω)	COP
0.5	14.6	18.5	17.8	3.9	1.16	2.31	2.55
1	10.0	18.2	17.3	8.2	2.23	2.23	1.38
2	6.4	19.8	17.6	13.4	4.30	2.15	0.58
3	3.2	22.3	17.6	19.1	6.31	2.10	0.37
4	0.3	25.0	17.6	24.7	8.40	2.10	0.27
5	-0.9	27.9	17.6	28.8	10.57	2.11	0.20

Therefore, the electromagnetic interference issues, which emerged during experimental process, have raised considerable limitations on the PWM applicability. However, the electromagnetic interference can be ignored on the PFM applicability due to its low switching frequency. Moreover, the system does not require extra electronic circuit protection such as shielding, filtering, wire length and appropriate location of them.

When the COP value in the PFM driving method was compared with the COP value in the constant dc driving method has, it is almost double and shows that the PFM driving method improves the cooling efficiency by reducing the input power due to duty cycle in the Peltier device.

Table 3. Measurement results at varied frequency and 1 A constant current in 500 s test time.

Frequency (Hz)	Cold side temperature (°C)	Hot side temperature (°C)	Room temperature (°C)	ΔT (°C)	Module Voltage (V)	Module Resistance (Ω)	COP
50	14.5	21.9	20.4	7.4	2.26	2.26	2.46
100	14.3	21.8	20.4	7.5	2.26	2.26	2.48
200	14.2	21.5	20.3	7.3	2.26	2.26	2.42
300	14.1	21.5	20.0	7.4	2.26	2.26	2.45
400	14.3	21.8	20.0	7.5	2.27	2.27	2.48
500	13.7	21.2	20.0	7.5	2.26	2.26	**2.49**
1000	14.6	22.0	20.9	7.4	2.27	2.27	2.45

The experimental data driving the PFM method with 50% duty cycle during 500 s test time were summarised in Table 4. It is clear that the COP was improved by the PFM driving method. Improvement of COP was maximum at driving current 0.5 A with 102%, whereas it was minimum at 5 A with 55% as compared to the constant dc driving current method.

Fig. 11 shows the variation of COP with the constant dc and pulse driving method and improvement % between them. The percent COP improvement was dramatically fallen after 0.5 A driving current and it keeps almost constant until 4 A, finally, it was sharply dropped at 5 A again. The COP values at low driving current were found to be higher than the COP values at high driving current due the input power and the Joule heating. The variation of COP with the driving current is not linear; it seems, an exponential change exists, since the thermoelectric semiconductors have a non-liner property.

The ANN model was trained in the range of 0.5 – 5.0 A driving current and 100 – 500 Hz frequency up to 500 s operation time. The performance of the ANN model was statistically measured by the RMS error and average correlation. After the network was trained by 10 million-iteration number, the linear correlation coefficient and RMS errors were found to be 99.99% and 2.88% for the COP. Table 5 also shows the percent contribution of input nodes.

Table 4. Measurement results at rectangular wave driving current with 50% duty cycle in 500 s test time.

Current (A)	Cold side temperature (°C)	Hot side temperature (°C)	Room temperatu re (°C)	ΔT (°C)	Module Voltage (V)	Module Resistance (Ω)	COP	Improvement %
0.5	14.0	17.9	17.6	3.9	1.14	2.28	5.15	102
1	11.2	18.7	17.6	7.5	2.22	2.22	2.53	83
2	8.2	20.7	17.7	12.5	4.28	2.14	1.08	80
3	7.4	24.3	17.6	16.9	6.36	2.12	0.65	76
4	8.6	28.6	17.7	20.0	8.69	2.10	0.47	74
5	11.5	33.5	17.6	22.0	10.39	2.08	0.31	55

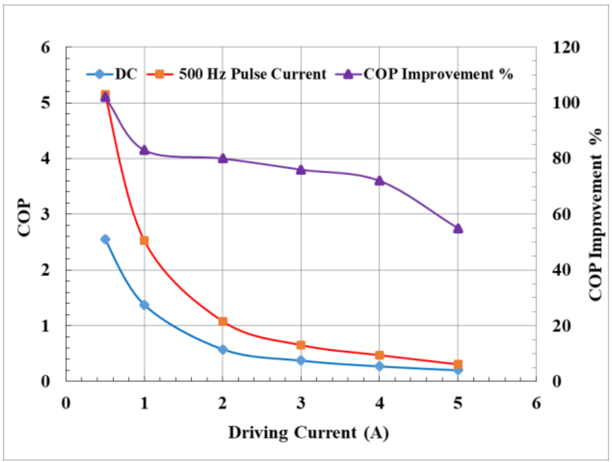

Figure 11. Variation of COP with constant dc and pulse driving current and improvement % of COP.

From Table 5, the frequency has a minimum contribution, while the temperature differentiation has the major contribution for the performance of the TEC module. It is clear that the temperature differentiation, voltage, cold and hot surface temperatures and current are very effective individually for estimation of the COP. The frequency makes a 0.54% contribution, which is significant among the input parameters, while the temperature differentiation also makes a major contribution about 28% to the prediction of the COP. The voltage across the module, current passing through the module and time 20.73%, 17.68% and 2.18% respectively also make significant contribution to the prediction of the COP. The cold and hot surfaces temperatures make 16.9% and 14.42% contributions, respectively.

A set of test data, different from the training data, was used to investigate the network performance. The average correlation and maximum error for prediction were found to be 99.99% and 1.38%, respectively, for the tested TEC module. The ANN model was assessed with 0.5 and 1 A current value and 100 and 500 Hz frequency at varied cold and hot surfaces temperatures, voltage and time, which were outside the range of the training dataset.

The results show that the developed ANN model has an acceptable prediction capability for the performance of TEC modules within the defined training dataset and good correlation with acceptable accuracy between measurement and predicted results (Fig. 12). Table 6 was summarised the measurement and predicted data for the tested sample. Therefore, the ANN model can be efficiently used to estimate for the performance of the TEC module.

Table 5. Contribution of input nodes to COP in the ANN model.

Input nodes	Contribution % for COP
I (A)	17.68
T_c (°C)	16.90
T_h (°C)	14.42
ΔT (°C)	27.97
V (V)	20.32
t (s)	2.18
f (Hz)	0.54

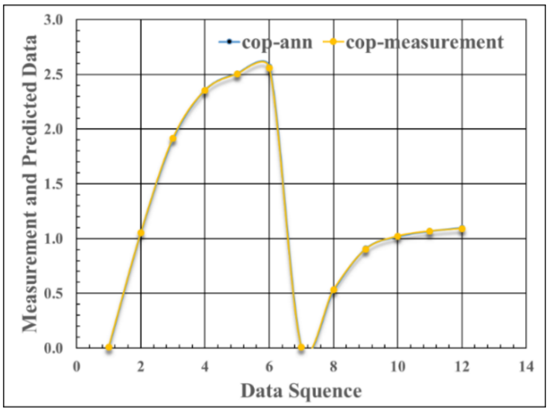

Figure 12. Correlation between measurement and predicted results.

The goodness of fit should be evaluated, after fitting data with one or more models using the MATLAB® Curve Fitting Toolbox™ is carried out. When several fits have executed by the goodness-of-fit statistics, to look for the smallest number of coefficients help to decide, which fit is the best. Exponentials are often used, when the rate of change of a quantity is proportional to the initial amount of the quantity. Thus, the best curve fit for the ANN data was found to be a two-term exponential model as given by;

$$f(x) = ae^{bx} + ce^{dx} \tag{14}$$

where the coefficients with 95% confidence bounds are a= $1.725\text{x}10^4$, b= -0.2, c= $-1.726\text{x}10^4$ and d= -0.2 respectively. The RMS error was 0.074, whereas the correlation between the predicted from ANN and calculated from exponential model values was 0.99, which shows a good agreement between them (Fig. 13).

Table 6. Measurement and predicted data for the test sample.

Data no	COP	
	measurement	predicted
1	0.01	0.01
2	1.05	1.06
3	1.92	1.91
4	2.35	2.36
5	2.50	2.51
6	2.56	2.57
7	0.01	0.01
8	0.53	0.53
9	0.90	0.91
10	1.02	1.02
11	1.07	1.07
12	1.09	1.10

All values obtained from measurements, prediction with ANN, and analytical equation with curve fitting are in good agreement with the average correlation 99% and maximum RMS error 1.38. It is clear that both numerical models, which are the ANN and analytical equation, are working well and verifying the experimental results.

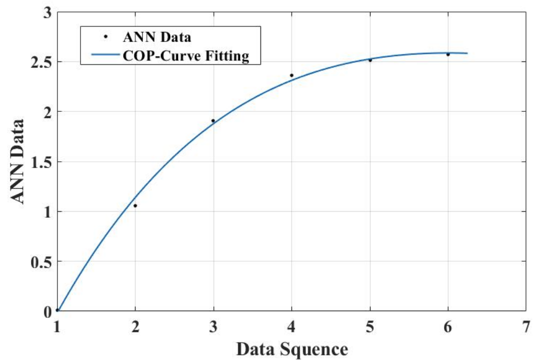

Figure 13. The best curve fit for predicted data.

CONCLUSIONS

The present research highlights the improvement efficiency and thermal stability of the TEC module driving with the PFM method. The PFM and constant dc driving methods can be applied to the module using the system at the same operation condition. Therefore, the results are accordingly comparable to each other. Although, the COP was improved the on-off control with constant dc current and the PWM methods. There are some disadvantages for them such as reducing the lasting time and considerable limitations due to high switching frequencies.

The PFM driving method was developed by optimising the input power owing to duty cycle of the rectangular wave and increased the cooling efficiency up to 102% as compared to the constant dc current driving method. Moreover, the driving system does not require an extra electronic circuitry for the electromagnetic interference due to its operating frequency.

One of the significant contribution to the module resistance is to keep it almost constant at high ΔT values above 1 °C and thermal stability of the module due to driving current. High COP value obtained by the PFM method using the heat dissipation and power consumption of the module indicates that there can be made a significant contribution to the cooling challenges and cooling technology in the field of semiconductor applications and technology. The PFM driving method can be useful for cooling and temperature stability of electronic devices by means of Peltier module.

The performance of a TEC module was investigated for optimum operating energy corresponding to surface temperatures, the temperature differentiation, the driving time and frequency. Increasing temperature differentiation is the major effect on performance, while the driving time and frequency also have a significant effect on it. The developed ANN model has a good prediction capability with acceptable accuracy. When the model was tested by untrained data, the linear correlation coefficient and RMS error were found to be 99.99% and 1.38% respectively for the COP. The analytical equation for performance as depending on prediction results has been determined by using MATLAB® Curve Fitting Toolbox™. The average correlation of the two-term exponential model was found to be 0.99 and the overall calculation error was 0.074, which are within acceptable limits for the COP. The experimental results are in good agreement with the predicted and calculated data, which are useful for manufacturers working in this field.

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