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International Journal of Thermal Sciences 46 (2007) 717–725

International Journal of Thermal Sciences

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Design of a thermoelectric module test system using a novel test method

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Received 3 March 2006; received in revised form 5 October 2006; accepted 11 October 2006

Available online 28 November 2006

Abstract

In this study, a universal microcontroller test system, which is aimed to determine the dynamic parameters of thermoelectric modules, has been designed and realized using a novel test method. For the purpose of this work, the test system has been designed according to a more simplified form of the present formula set, which has been made to accept minimum variables as input to obtain more precise results. As a result, a test system, which can measure the dynamic parameters of a thermoelectric module universally by measuring only the hot side temperature, module operation voltage, module's current and thermoemf values of the module, has been produced. Also, the realized new test system has been used to measure a standard thermoelectric module (Melcor CP 1.4-127-10L) in order to verify its performance.

Keywords: Measurement; Test system; Peltier module; Thermoelectric performance analysis

1. Introduction

Since 1960s, the thermoelectric modules have been in widespread use in military, aerospace, science and medical technology fields as a cooler, heater and thermoelectric generator, because of their properties such as compactness, static operation, reliability, suitability for effective temperature control and dc operation [1–3].

The studies made on thermoelectric coolers are densely populated on the development of new thermoelectric materials and production techniques. On the other hand, the methods, used to analyze the performance of the modules effectively, are as important as new materials [4–6]. The studies on this subject are focused on obtaining the measured microparameters of the module (α: Seebeck coefficient of the semiconductor material, ρ: resistivity of the material, K: thermal conductance of the material, and z: figure of merit), which cannot be extracted easily. These parameters are important to find the thermal characteristics of the module. Since these parameters are highly dependent on the temperature and the physical dimensions of the elements, the classic methods occasionally fail to accurately determine the actual thermal parameters of modules, if not impossible because the module is installed in an appliance. So, it is necessary to develop new methods to investigate the thermoelectric properties of semiconductor materials and thermal parameters of modules, which are in operation in some appliance such as a refrigerator.

There are various methods and devices for the measurement of α, σ, λ, and z of semiconductor materials [7–11]. Similarly, there exists methods and devices for the measurement of the thermal parameters of modules [12,13]. In addition, special computer simulation programs, which use the same theoretical foundations as above, have been developed [14]. However, as it is pointed above, it is generally impossible to use an equation set that solely depends on these parameters to determine the performance of an operational module. Because most of the cases it is impossible to reach the module and determine the condition of the materials used.

In this study, easily and accurately measurable parameters of an operational thermoelectric module such as thermoemf, hot side temperature, terminal voltage and current are measured automatically with the aid of a microcontroller system and these parameters are translated into dynamic output parameters of the module in a very short time. The main advantage of the

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1290-0729/$ – see front matter
doi:10.1016/j.ijthermalsci.2006.10.008

proposed system is that you can evaluate the performance of an actual working module with minimum interference with the equipment being investigated.

2. Method

According to the classic method, the thermal balance equation of a thermoelectric module which shows the heat absorbed from the cold side is presented in Eq. (1) as

$$Q_C = \alpha I T_C - 0.5 I^2 R - K(T_H - T_C) - Q_L \tag{1}$$

where Q_C is the total thermal load presented to the cold side in Watts, I is the current applied to the module in Amperes, R is the resistance of the thermoelement in ohms, K is the thermal conductance of the thermoelement in W °C, α, is the total Seebeck coefficient of the thermoelement. Additionally, $\Delta T = (T_H - T_C)$ and T_H, T_C are the temperature difference, hot side and cold side temperatures respectively. Here Q_L represents total external thermal load in Watts.

The power consumed by the module is expressed as

$$P = I^2 R + \alpha(T_H - T_C) I \tag{2}$$

One of the thermal characteristics of a thermoelectric module is the coefficient of performance-COP. COP of a thermoelectric module is expressed as the ratio of cold side heat, Q_C to the power consumption, P:

$$\text{COP} = \frac{Q_C}{P} \tag{3}$$

The figure of merit, Z of a module is represented by Eq. (4);

$$Z = \frac{\alpha^2}{RK} \tag{4}$$

These equations establish the basis in the analysis of the thermal performance of a thermoelectric or a cooling system constructed with these modules. Present methods use this equation set to calculate thermal parameters. These formulas do not always provide accurate results, since they do not represent dynamic thermal parameters of an actual working module. The reason behind this is that the variations in α, σ, λ, and z of a semiconductor pellet are dependent to the temperature [6,15,16]. Additionally, the technological and structural factors are not considered in these equations. The classic method can only produce accurate results, if every thermoelement is equipped with a pair of thermocouples, one measures T_H and the other T_C temperatures separately. If the high number of thermoelements in a typical thermoelectric module is considered, it is seen that the practicality and the cost of the classic method is unfeasible. Also, it is very hard to calculate the thermal load over the module, Q_L, using Eqs. (1)–(4), because, it is not easy to measure the cold side temperature, T_C and thermal conductance, K of an operational module in many cases, since the system is developed primarily to test or gather the performance of a module which is installed in a refrigerator or similar appliance.

So, it is imperative to develop a new, low cost and practical method to investigate the real dynamic thermal properties of a working module from the point of view of both practical applications and theoretical studies. Despite, the basic principles of the newly proposed method depends on Eqs. (1)–(4), these equations are modified to reach the objectives of this study. The result of these equivalent modifications is that, only the applied current and generated thermoemf, E is sufficient to calculate all the thermal parameters of a working module. The temperature, current and thermoemf are properties of a module that can be measured very accurately and easily.

As it is known, when Q_L is zero in an ideal thermoelectric module under no-load conditions, Q_C is zero. In this case the temperature difference T will be $\Delta T_{\max}$ and the cold side temperature, T_C will be $T_{C\min}$. Under these conditions, the current and voltage of the module will be $I_{\max}$ and $V_{\max}$ respectively and the generated thermoemf by the module will be $E_{\max}$. The thermal properties of a module can be obtained by employing these macroparameters in Eqs. (1)–(4). At this point it is well known that:

$$V_{\max} = \alpha T_H \tag{5}$$

On the other hand, maximum voltage can be expressed as follows:

$$V_{\max} = I_{\max} R + \alpha \Delta T_{\max} = I_{\max} R + E_{\max} \tag{6}$$

$E_{\max}$ can also be expressed as

$$\alpha \Delta T_{\max} = \alpha(T_H - T_{C\min}) = E_{\max} \tag{7}$$

So, R can be rewritten according to these equations as

$$R = \frac{V_{\max} - E_{\max}}{I_{\max}} \tag{8}$$

If we put all these in the thermal equilibrium equation of module, Q_C can be expressed as below;

$$Q_C = \alpha I_{\max} T_{C\min} - 0.5 I_{\max}^2 R - K \Delta T_{\max} = 0 \tag{9}$$

Also from Eq. (7) it can be written:

$$T_{C\min} = T_H - \frac{E_{\max}}{\alpha} \tag{10}$$

If we put Eqs. (8) and (10) in Eq. (9) we find an alternative expression for Q_C as

$$(V_{\max} - E_{\max}) I_{\max} - 0.5(V_{\max} - E_{\max}) I_{\max} = \left(\frac{K E_{\max}}{\alpha}\right) \tag{11}$$

Now, we have withdraw the term K from this expression;

$$K = \frac{0.5\alpha(V_{\max} - E_{\max}) I_{\max}}{E_{\max}} = \frac{0.5(V_{\max} - E_{\max}) I_{\max}}{T_H E_{\max}} \tag{12}$$

If we assume $QL = 0$ and put Eqs. (8) and (12) in the first classical equation of Q_C, Eq. (1);

$$Q_C = \alpha T_C I - \frac{0.5 I^2 (V_{\max} - E_{\max})}{I_{\max}} - \frac{\alpha \Delta T (V_{\max} - E_{\max}) I_{\max}}{E_{\max}} \tag{13}$$

We can generalize Eq. (7) and use it to obtain cold side temperature for any value of thermoemf of the module, E;

$$T_C = T_H - \frac{E}{\alpha} \tag{14}$$

Using Eqs. (13) and (14), we can eliminate the term T_C from Eq. (13);

$$Q_C = \alpha\left(T_H - \frac{E}{\alpha}\right)I - \frac{0.5I^2(V_{\max} - E_{\max})}{I_{\max}} - \frac{E(V_{\max} - E_{\max})I_{\max}}{E_{\max}} \tag{15}$$

In many cases the hot side temperature of the module is held at a constant value and is seldom changed. So, the changes in the current and heat transfer rate of the module effects T_H very little and thus it is suitable to employ the expression of $I_{\max}$ given in Eq. (5), in Eq. (15). In this case the final modified expression of Q_C is:

$$Q_C = V_{\max} I - \frac{0.5I^2(V_{\max} - E_{\max})}{I_{\max}} - \left[I + \frac{0.5(V_{\max} - E_{\max})I_{\max}}{E_{\max}}\right]E \tag{16}$$

Similarly, the power consumption of the module can be expressed as

$$P = \frac{I^2(V_{\max} - E_{\max})}{I_{\max}} + EI \tag{17}$$

The COP is already given in Eq. (3) and the figure of merit can be expressed as below:

$$Z = \frac{V_{\max} E_{\max}}{0.5(V_{\max} - E_{\max})^2 T_H} \tag{18}$$

And last, the cold side temperature, T_C can be written as

$$T_C = T_H\left(1 - \frac{E}{V_{\max}}\right) \tag{19}$$

By measuring T_H and E parameters at any time, one can calculate the cold side temperature at that time. In this study, a microcontroller based multifunction test system has been realized using the newly developed method, whose basic principles have been explained above, and then it has been tested using a standard thermoelectric module.

3. Thermoelectric module test system

Thermoelectric module test system consists of 3 main blocks; power supply, cooling system, and electronic control and data acquisition unit. Power supply is a switched mode type and cooling system is a water circulation type heat exchanger. Temperature measurements are taken via a K-type thermocouple and current is sampled by a Hall-effect sensor. The front end for temperature measurements is also suitable for T-type thermocouples. All the test system is being controlled via a microcontroller board. The system is also being capable to make all the necessary calculations and it can show the measurement and calculation results on a built-in LCM (Liquid Crystal Module) display.

3.1. Cooling system and power supply

A schematic diagram of the mechanical structure of the test system is shown in Fig. 1. Hot side of the thermoelectric module is cooled by water circulating cooling system. There is a thin layer of copper sheet between the brass cooling plate and hot side of the thermoelectric module. Its purpose is to provide a thermally conductive means in which the thermocouples can be attached freely to measure the hot and cold side temperatures and also this layer serves to distribute the heat uniformly all over the surface of the contact area with the aid of a thermally conductive paste. There is a heater plate made from brass between the cold sides of two thermoelectric modules. One of the thermoelectric modules is the device under test, while the other one, which is identical with the module under investigation, is

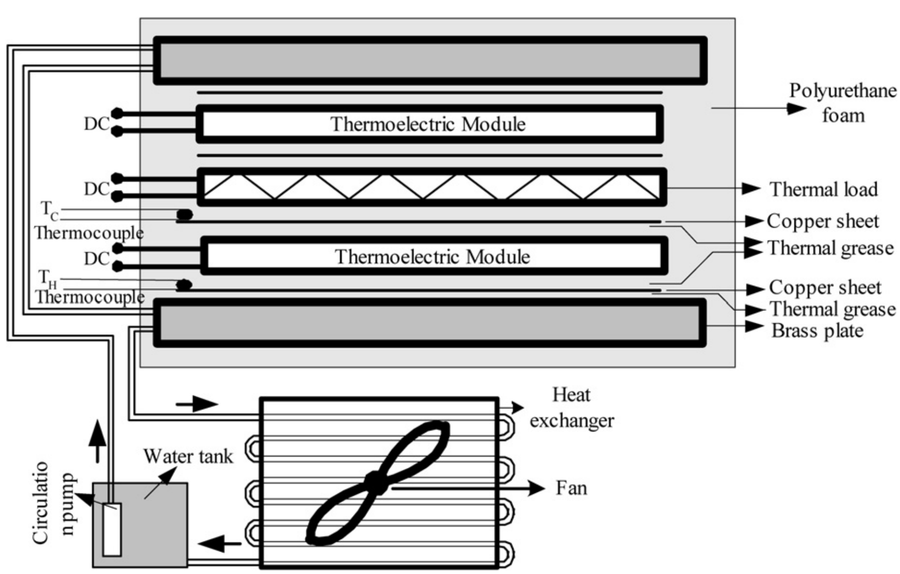

Fig. 1. Cooling unit of microcontroller test system.

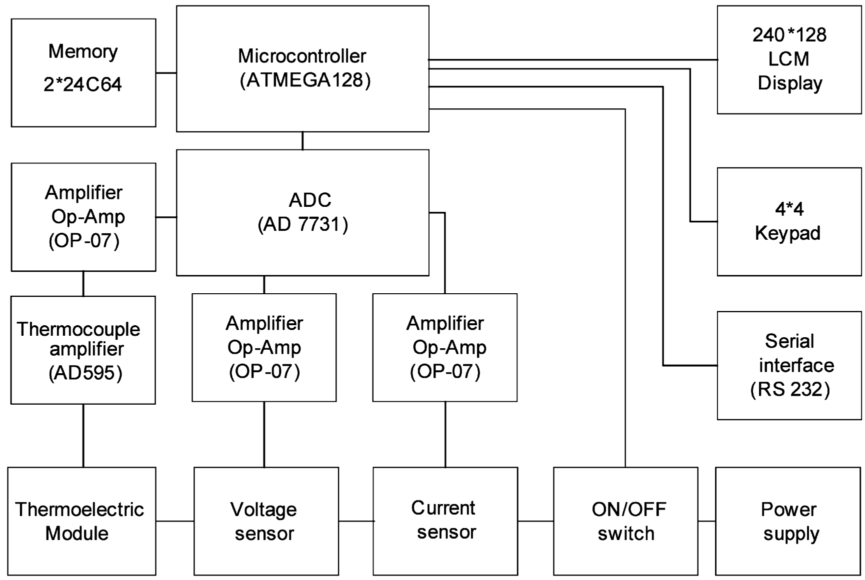

Fig. 2. Schematic diagram of the electronic measurement and control system.

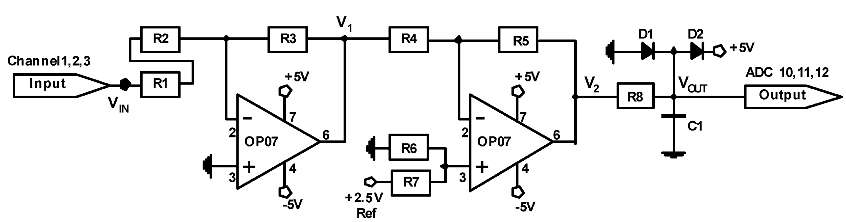

Fig. 3. Amplifier schematic.

used to distribute the heat load posed by the heater equally between its two sides. All the test apparatus is covered by a 5 cm polyurethane coating to minimize the external heat load and the internal heat losses. Thermoelectric modules and the heater are powered from 3 separate SMPS type adjustable and regulated dc power supplies rated at 40 Vdc/10 A.

3.2. Electronic measurement and control system

Electronic measurement and control system is the most important part of the test system and its schematic diagram is shown in Fig. 2.

3.3. Amplifier circuit

The amplifier, whose schematic is shown in Fig. 3, is based on two OP-07 op-amps, whose purpose are to translate ± 1.28 V input voltage range to the 1.22–3.78 V input voltage range of the A/D converter. The first stage is an inverting mode input buffer. It also attenuates the high level of input to specified ± 1.28 V input range. The attenuation factor for the thermocouple input channel is 0.5, while it is 0.05 for the voltage and current sensor input channels since the level is higher. The output voltage at the first stage is calculated as

$$V_1 = -V_{\mathrm{IN}} \frac{R_3}{R_1 + R_2} \tag{20}$$

The resistance values for the voltage and current sensor inputs is selected as $R_1 = R_2 = 47$ K, $R_3 = 4.7$ K and for the thermocouple input amplifier, $R_1 = R_2 = R_3 = 47$ K. The second stage is a unity gain subtracter which subtracts the V_1 input from the voltage $V_{\mathrm{ref}} = 2.5$ V which is applied to the non-inverting input of the op-amp. The resulting output voltage, V_2 is calculated from

$$V_2 = 2.5V\left(1 + \frac{R_5}{R_4}\right)\left(\frac{R_6}{R_6 + R_7}\right) - V_1\left(\frac{R_5}{R_4}\right)$$

$$V_2 = 2.5V + V_{\mathrm{IN}} \frac{R_3}{R_1 + R_2} \tag{21}$$

As it is seen from the above discussion, the purpose of this second stage is to translate the ± 1.28 V input voltage range to the 2.5 ± 1.28 V voltage range in which the A/D converter necessitates to produce signed binary words using pseudo differential inputs. The resistance values are selected as $R_4 = R_5 = R_6 = R_7 = 4.7$ K.

The voltage, V_2, is applied via a low pass filter to the input of A/D converter. Low pass filter serves to pass the intended signal frequency band (0–33 Hz) while it attenuates the high frequency noises, largely produced by the system itself. Low pass filter is a further measure to prevent any malfunctions that can arise from electrostatic discharges, collected by the sensor cables from environment. The cut-off frequency and thus the

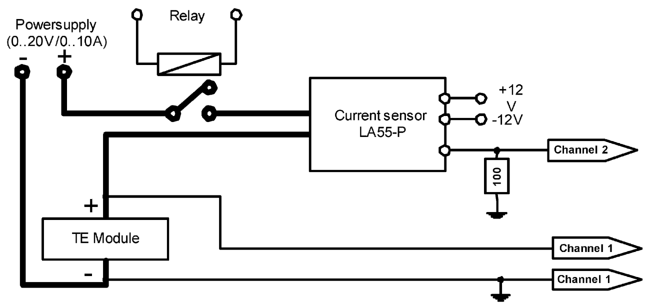

Fig. 4. Voltage and current sensor and connection diagram of thermoelectric module.

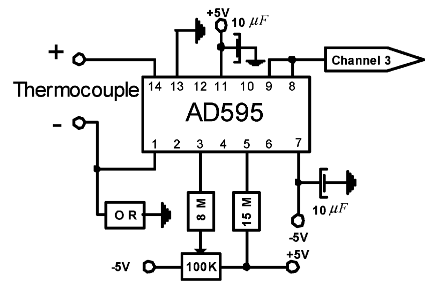

Fig. 5. Thermocouple amplifier.

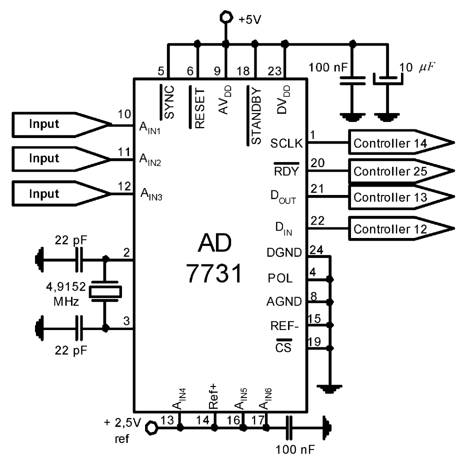

Fig. 6. A/D converter schematic.

component values are calculated from Eq. (22):

$$f_C = \frac{1}{2\pi R_8 C_1} \tag{22}$$

Since the input impedance of the A/D converter is very high, the value of R_8 may be very high. The values $R_8 = 47$ K and $C_1 = 100$ nF provides a cut-off frequency $f_C = 33$ Hz.

There is also a pair of silicon diodes from the A/D converter input to the supply rail, whose purpose is to arrest any electrostatic discharge. Thus the input voltage range is limited to the safe from -0.7 to $+5$ V range.

3.4. Voltage and current sensors

Shown in Fig. 4 is the electrical connection diagram of thermoelectric module, voltage and current sensors.

There is nothing special with the voltage sensor. Despite there is a cable connection from system to the module which carries supply current, a separate cable is used to carry the voltage signal. It is because there is a voltage drop over the supply line which is superimposed on the voltage signal and affects the measurement.

Current sensor is a Hall Effect type and thus its insertion error is very low. LEM LA55-P current sensor used here provides an output sensitivity of 100 mV A^{-1}. In other words, for a current of 5 A, voltage of 0.5 V is obtained at the output. Current signal is fed to second channel of the A/D converter via the channel amplifier.

The relay is used to cut the current. Power supply is a separate one which is isolated from the circuit supply. The voltage and current limit of the power supply can be adjusted from 0–20 V, 0–10 A respectively according to the circuit conditions and module requirements. Ripple factor of the power supply is below 1%.

3.5. Thermocouple amplifier

Temperature measurement is realized through a thermocouple amplifier which uses a K-type Chromel–Alumel thermocouple to measure the hot side temperature of the thermoelectric module. Thermocouple amplifier utilizes the Analog Devices AD595 chip which has cold junction compensation built-in. The schematic diagram of the thermocouple amplifier is shown in Fig. 5. At an ambient temperature of $+25\,^\circ$C, it provides an output sensitivity of 10 mV $^\circ C^{-1}$ with a K-type thermocouple. Between the 0–50 °C ambient temperature range, the measurement error of the temperature measurement system is $\pm 0.6\,^\circ$C. Total measurement error including thermocouple is $\pm 1.2\,^\circ$C. The output voltage is fed to the third channel of the A/D converter via input channel amplifier.

3.6. A/D converter

The A/D converter used in the system is a 24-bit Sigma–Delta type converter. It has a programmable gain differential input amplifier, a 5-channel input multiplexer, a Sigma–Delta modulator, internal FIR filters, choppers used to decrease dc shift, and an internal microcontroller which is responsible for housekeeping functions. All the sampled data is transferred via a 3 wire serial data bus to the system microcontroller. Analog devices AD7731 chip is used as the A/D converter (Fig. 6).

A/D converter is programmed to sample at a rate of 600 Hz and a resolution of 24-bits, and its inputs are set to accept bipolar inputs ranging ± 1.28 V.

3.7. Microcontroller

Microcontroller is responsible of all the control functions needed in the system; it controls the current of the thermoelectric module across the relay, stores voltage, current and temperature sensor data, coming via the A/D converter, in EEPROM, it shows all the records via a LCM display, or it can represent the data over a serial RS232 link, it warns the user of the events

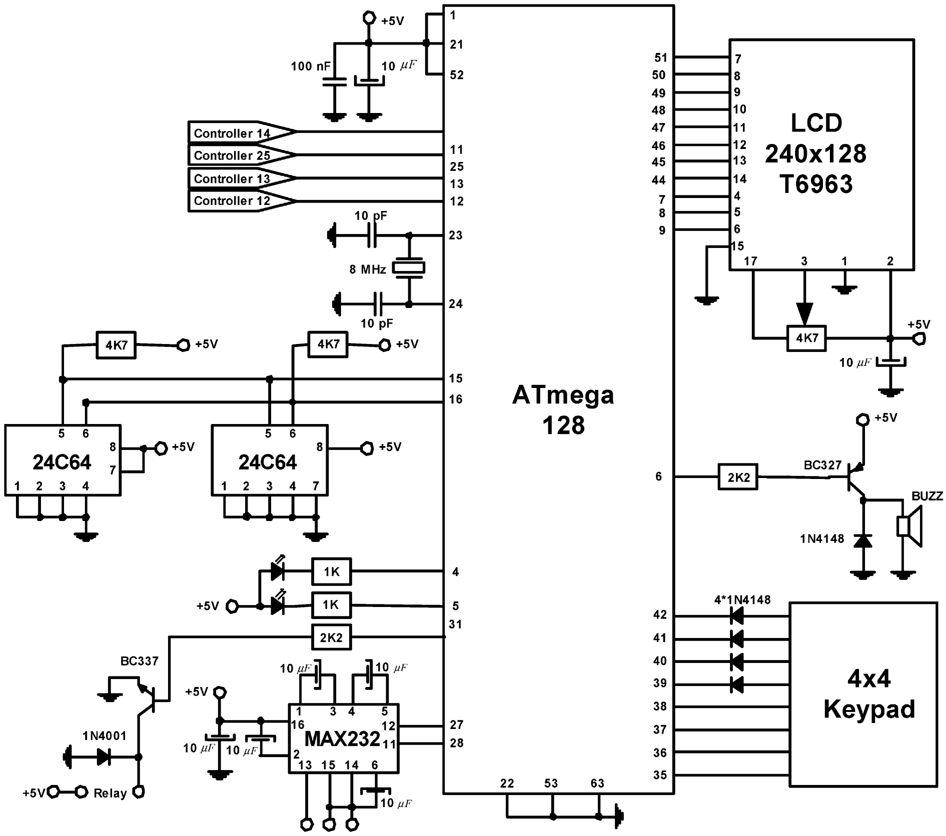

Fig. 7. Microcontroller schematic.

audio visually and it accepts commands presented by the user via a keypad.

A RISC architecture microcontroller, ATMEL ATMega128 chip is used to cope with this process intensive work load (Fig. 7). This processor has a instruction execution speed of 8 MIPS at 8 MHz clock speed. Processor has 128 KB program memory, 4 KB internal data memory, and 4 KB internal SRAM memory. It has an external EEPROM memory addressing capacity of 64 KB.

All the results of the measurements and calculations are presented via a LCM (Liquid Crystal Module) display which has a resolution of 240×128 pixels. Q_C, T_H, COP, power consumption (P), and figure of merit of the module (Z) are shown on this display after the tests are concluded.

Temperature, current and voltage sampling intervals and digital calibration data and all the commands are entered via a 4×4 matrix keypad.

All the temperature, current and voltage measurements are logged by the system and these data can be transferred to an external computer terminal via a serial link for further analysis.

In order to use in the calculations, the operational current and voltage of the module and the voltage after the module's current is cut must be measured. This data is transferred to the microcontroller via the data acquisition system.

Testing of a module consists of 2 stages. In the first stage, module is operated with a suitable voltage level, which is set according to the module's catalog data. Under unloaded thermal conditions the $V_{\max}$, $I_{\max}$, $E_{\max}$ parameters of the modules are obtained in the first stage. In this stage, system closes the relay contacts and thus applies current to the module. At the same time, current, voltage and hot side temperature of the module are sampled with predetermined intervals. Microcontroller compares every temperature sample with previous ones by using a predetermined tolerance factor, and for a predetermined sample count it looks for a zero difference. When this condition is satisfied, microcontroller cuts the current of the module. Microcontroller waits for a short delay which is necessary for the measurement system to take a good sample proof from switching noise and the retention artifact of contacts. This time delay is kept sufficiently small to ensure that it does not effect the measurements ($t = 0.5$ s). After this time delay microcontroller takes a final voltage reading. This value is recorded as $E_{\max}$. The voltage and current reading just before the current is cut off are recorded as $V_{\max}$ and $I_{\max}$ respectively.

The first stage of the testing procedure necessitates connecting the module to the measurement apparatus shown in Fig. 1. However, the values obtained at the end of this stage can also be entered manually by taking these data from module's datasheet. In this case it is not necessary to take off the module from its place. If the operational performance of the module which is attached to a system is the one which is in question, the second stage of the test procedure can be easily realized with the module operating in its place.

It is assumed that the cold side temperature is constant and the thermal load is zero when deriving Eq. (5), which is principal in the first stage calculations. It is not possible to held cold side temperature constant in many cases, but its effects will be small on the end results. This condition can also be seen clearly from the graphs given in the results and discussion section.

In the second stage, microcontroller applies current again. But in this stage the module is thermally loaded by a suitable thermal load which is determined by looking to the datasheets of the module. This thermal load may also be the natural thermal load in which the module sees in its position in the system where it is attached. User commands the controller to cut off the current via the keyboard at a suitable time. In this case the voltage, current and hot side temperature of the module is sampled and then the thermoemf, E of the module is also sampled after current is cut off. However, just after the sampling of the thermoemf of the module, the current is applied again. If user wants to take another sample the above mentioned procedure is repeated. Thus, after every sampling, the data obtained from both first and second stages are processed by the equation set and the calculation results are displayed immediately.

Measured $V_{\max}$, $I_{\max}$, $E_{\max}$, T_H, I, V and E values are put in their places in Eq. (16) to calculate cooling energy Q_C, in Eq. (17) to find power consumption, P, in Eq. (3) to find module's COP, in Eq. (18) to find figure of merit, Z, and in Eq. (19) to find cold side temperature, T_C by the microcontroller system automatically and the calculated values are displayed.

4. The determination of performance of thermoelectric test system

A series of experiments have been carried out to determine the performance of this newly developed system. Two thermoelectric modules (Melcor CP 1.4-127-10L), whose specifications are well known from manufacturer's datasheet, have been used in the experiments [14]. Test apparatus in which the modules have been attached is shown in Fig. 1. One of the modules has been used as a cooler in the second stage which has cooled the heater in order to distribute its heat equally between the cold sides of two modules. The other one has been attached as the real tested one, of which current, voltage and temperature has been monitored by the system during experiment. Both modules have been supplied with same voltage and current.

Power to the heater has been applied from an adjustable dc power supply. Heater power is determined according to the voltage and current measurements taken by two Philips Fluke 45 digital multimeters. Voltages and currents of both modules have been measured by separate Philips Fluke 45 multimeters at the same time with the system. The hot side temperature of the tested module has been measured simultaneously by the test system and a data acquisition system Hewlett-Packard Agilent 34 970 A with the cold side temperature is also measured with the data acquisition system for control purposes. All the measured values have been compared with the ones taken by the system itself. 21 measurement points have been taken including the loadless case. Every measurement has been repeated at least 5 times and their average has been taken as the actual value.

5. Results and discussion

The performance of the realized system has been tested using a pair of thermoelectric modules (Melcor CP 1.4-127-10L) and then the acquired data has been compared with manufacturer's datasheet of these modules. At first, thermal load has been minimized and $V_{\max}$ and $I_{\max}$ parameters have been measured at $T_C = T_{C\min}$. These parameters have been recorded as input parameters by the microcontroller system. Secondly, further measurements have been made due to increasing thermal load while the modules have been in operation. Since we want to make a comparison, the module has been attached to the test system. However, it is not necessary in regular use, where the module under test is intact in a fully operational cooling system such as a refrigerator. Hence, "Universal" in the name, refers to this argument as well as regarding the testing of every shape and dimension of modules. When $T_{C\min}$ condition has been reached for every thermal load point, module's emf, I and T_H values have been measured and then the dynamic output parameters such as Q_C, T_C, P, COP, Z parameters of the module have been calculated and recorded automatically by the system. Also, all the output parameters have been calculated using manufacturer's datasheet values as input parameters and they have been compared with the ones that had been collected and calculated by the system. Also, a last calculation has been made using classical equations (Eqs. (1)–(4)) [6–16]. Thus, the authors have attempted to make a comparison of the newly developed system and the classical method.

Shown in Fig. 8 is the graphical representation of change in Q_C, which is the heat transfer rate of the module measured by the test system vs applied thermal load, Q_L, with the Q_{CM} value, calculated according to classical equations (Eqs. (1)–(4)), added. The microparameters of the module, which is necessary in calculating the Q_C of the module (Q_{CM}) using classic equations, are extracted from manufacturer's datasheet of the reference module (Melcor CP 1.4-127-10L), [14]. T_H and T_C are the other parameters that are required in the classic equations. The directly measured T_H and T_C values, which are recorded by data acquisition system Hewlett-Packard Agilent 34 970 A during the rest of the experiment, are used in the calculation. As it is seen from the graph, the average of differences between these parameters does not exceed 0.7 W. It is also seen clearly from the graph that, when the thermal load is zero, calculated and measured Q_L values are non-zero. The

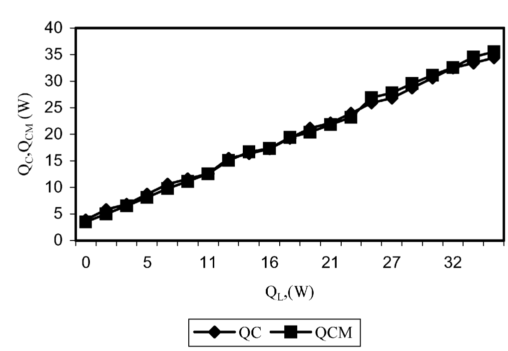

Fig. 8. Thermal load over module obtained using two different methods.

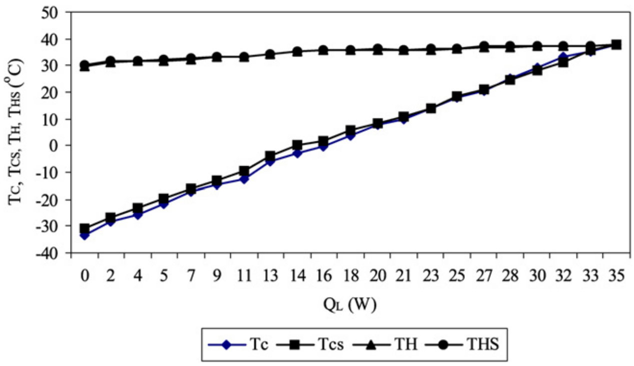

Fig. 9. Temperature measurement calibration results for various thermal load conditions.

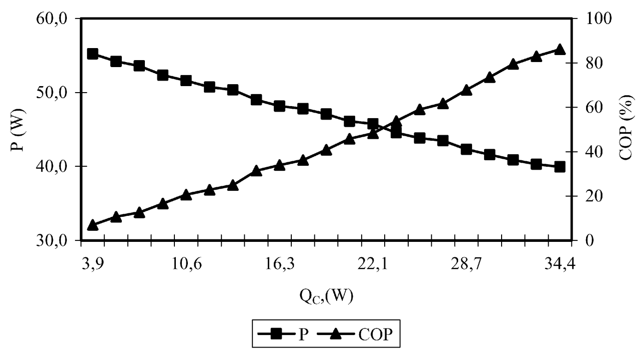

Fig. 10. Measurement of P and COP parameters of a module using microcontroller test system.

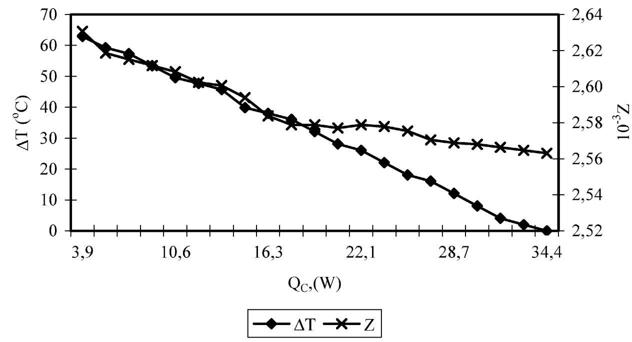

Fig. 11. Measurement of ΔT and Z parameters of a module using microcontroller test system.

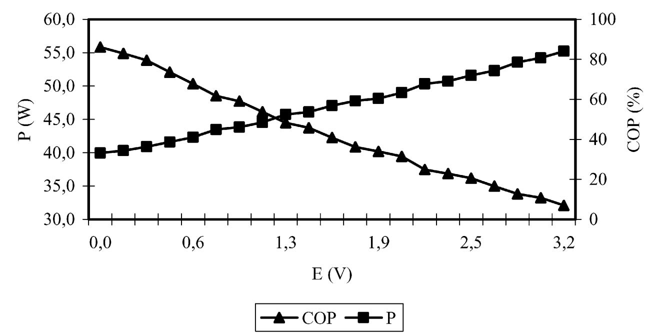

Fig. 12. The graph showing the effect of emf on the power and COP parameters of an operational module.

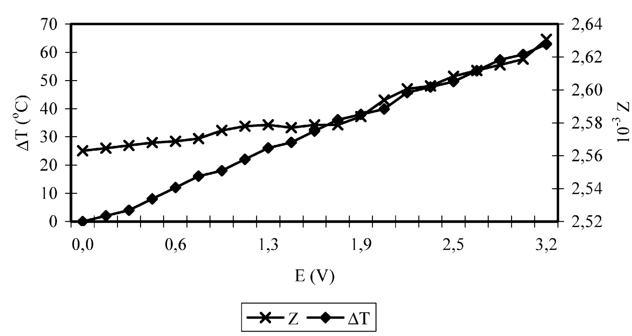

Fig. 13. The graph showing the effect of emf on the ΔT and Z parameters of an operational module.

reason is the thermal losses arising from non-ideal thermal isolation. Its value is around 3.46 W for the realized system, thus it is understood that thermal losses in the measurement apparatus is 3.46 W. The isolation can be approached to ideal by using a vacuum chamber [6]. However, the system can calculate the exact value of this thermal loss which cannot be avoided in many circumstances, like the active testing of a module installed in an appliance. So, this proves another useful utility in which the test system can be used to predict the thermal losses of the appliance if the test system is calibrated and the appliance under test is in a thermal balance.

The hot and cold side temperatures being measured by the system have also been measured and recorded by Hewlett-Packard Agilent 34 970 A data acquisition system and these recorded values are represented in Fig. 9. Here, T_{HS} and T_{CS} are the measured hot and cold side temperature values respectively by the data acquisition system, while T_H is the measured hot side temperature and T_C is the cold side temperature calculated by the test system. As it is seen from the graph, both systems have measured these parameters very close to each other.

In Figs. 10 and 11, all the parametric measurement results of an operational module using microcontroller test system has been represented as a graph. It shows that the realized microcontroller test system has the capability to measure indirectly all the parameters of a module for different Q_C values.

In Fig. 12, a graph, which represents the effect of emf on the power and COP parameters of a module, is seen, while its effect on the ΔT and Z parameters of an operational module is presented in Fig. 13. The emf of a module is the main input parameter in the operation of the microcontroller test system. These graphs (Figs. 10–13) show that the actual parameters of the module changes dynamically as the operating point is changed, yet it is possible to determine most of them by simply measuring module's emf, current and hot side temperature.

6. Conclusion

Thermoelectric systems are being used in a wide range of applications including aerospace and medical sciences. It is clear that the number of applications that utilize thermoelectric modules will increase in the future, if their advantages are considered. So it is imperative to develop a microcontroller thermoelectric module test system which can test modules effectively, practically and accurately in a short time (5–10 min). Such a test system must reliable accurate and portable. The designed and realized microcontroller based thermoelectric module test system has proven itself as a reliable and accurate measurement system according to the results of experiments.

Microcontroller test system depends on the measurement of the emf of the thermoelectric module. The calculated output parameters of a module according to these principals are its real dynamic values. As a result, the problem of testing of a thermoelectric module is solved in a practical and convenient way by using this new method.

Investigation of parameters of a standard thermoelectric module manufactured by Melcor using this newly developed system yielded very similar results to that have been obtained using classic methods, as it is seen in Figs. 8–9. For instance, the difference between the measured thermal load value of microcontroller system and the calculated value from datasheets of Melcor has not exceeded 0.7 W. Also the newly developed system has measured temperatures with a deviation from the calibration instrument 0.5 °C at most.

As it is seen from the graph in Fig. 11, the parameters of a standard module change linearly with generated emf. So, it is understood from above discussion that measurement systems based on the measurement of emf can be an alternative to present measurement systems based on classic methods. Also, this system has the capability to measure the dynamic parameter of a module installed in an appliance such as a refrigerator. So, it is possible to use the principles of the system to diagnose a module at work, reporting useful information such as the actual thermal load, health of the module (by monitoring the figure of merit of the module). Thus, it is possible to alarm the user when the health of the cooling process is in danger and when the module's performance begins to degrade or the module become overloaded.

Supplementary material

Supplementary material for this article may be found on ScienceDirect, in the online version.

Please visit DOI: 10.1016/j.ijthermalsci.2006.10.008.

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