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Experimental Analysis of a Thermoelectric-(Vapor Compression) Hybrid Domestic Refrigerator

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Abstract

This work presents an experimental analysis for a hybrid domestic refrigerator that comprises thermoelectric and vapor-compression technologies. The hybrid refrigerator consists of three compartments; one of them is operated by a thermoelectric cooling system, which is based on the Peltier module. Two fan-cooled heat sinks are attached to both sides of the Peltier module. The hybrid refrigerator is constructed and tested under local operating conditions. The performance of the thermoelectric refrigerator is evaluated at different voltage values (5, 8.5, and 11 V) that are supplied to the Peltier module and two fans at both sides. For validation purpose, the experimental results are compared with another published study and the discrepancy was acceptable regarding to the difference between the two cases. Moreover, the effect of using different configurations of heat sinks is analyzed by testing the refrigerator performance. These configurations include: *(i)* a finned heat sink, *(ii)* a finned heat sink supported with heat pipe; with and without a fan.

The results show that use of the heat sink supported with heat pipes, on the hot side of the Peltier module, leads to (11.5 to 18.37) % increase in COP of the thermoelectric refrigerator and a reduction in power consumption by about of 8.5 % in comparison to the case of using regular finned heat sink. Consequently, this leads to an overall improvement in COP of the whole hybrid domestic refrigerator.

Keywords: Hybrid domestic refrigerator, Vapor compression cooling, Thermoelectric cooling, Heat sink.

1. INTRODUCTION

Refrigeration process is achieved by absorbing heat from one side or space in order to decrease its temperature to be less than that of the environment by using one of the known refrigeration systems. Vapor-compression refrigeration system (VCRS) is the most commonly used for refrigeration in industrial, commercial, and domestic applications. Following the VCRS are: absorption refrigeration systems (ARS), gas refrigeration systems (GRS), and thermoelectric refrigeration systems (TERS). Each refrigeration system is characterized by certain properties [1,2]. The main components of VCRS (compressor, evaporator, condenser, and expansion valve) are connected into a closed cycle. In the closed cycle, the phase of the refrigerant changes during its pass through the components for the purpose of absorbing the heat from a cooled space and rejecting it to the environment. VCRS can work in widely range of temperatures. In household refrigerator, the range can reach (-10 to -30) ^{0}C [3]. However, VCRS uses Freon and ammonia, which have negative effects on the global climate by destroying the ozone layer. For that, many protocols as Montreal (Canda1987) and Kyoto (Japan 1997) were established and signed by the delegates of many counties of the world to minimize use of the bad refrigerants that have high value for global warming potential (GWP) and ozone depletion potential (ODP) [4,5]. Moreover, the coefficient of performance (COP) of VCRS decreases significantly when VCRS are used with applications of low-cooling capacities. When VCRS is used in household refrigerators, the oscillation in the interior temperature of refrigerator may reach higher than 8 ^{0}C [6] because of nature of on/off compressor work. This is very bad for preservation of perishable products such as food and medicines. Using VCR equipped with electronic expansion valve and variable speed compressor reduces the temperature fluctuations. However, this makes the refrigerator more complex and more expensive [4,7]. Thermoelectric refrigeration systems (TERS) are represented as the best environment-friendly alternative for VCRS. They have become the field of research for many of the scientific centers around the world. TERS have many good characteristics such as: no use of refrigerant, high temperature control, compact, and there are no moving parts, consequently, they have less noise and vibrations [8, 9]. TERS (sometimes named as Peltier refrigerators) are defined as the devices which convert the electrical energy to temperature difference when a DC current is allowed to flow in closed cycle that contains two junctions of different materials based on the Peltier effect [10]. TERS have 10% of Carnot refrigeration efficiency in comparison to VCRS, which have 30% of the Carnot refrigeration efficiency [11]. TERS that is made of a Peltier module (PM) with single stage can produce a temperature difference of 70 ^{0}C between its both sides (cold and hot sides).

and it can transfer heat with a rate of 125 W [12]. PM consists of thermoelectric pairs connected electrically in series and thermally in parallel and are sandwiched between two ceramic substrates. Each thermoelectric pair is made of two types of thermoelectric materials, named as N-type and P-type [13], Fig. 1.

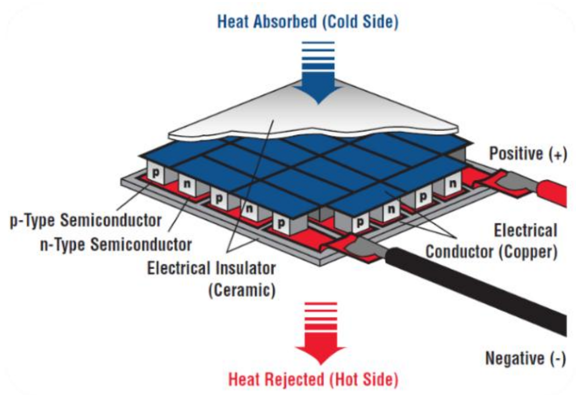

Fig. 1. Components of Peltier module [14]

When a low-voltage DC power source is applied to the cycle of the thermoelectric refrigerator, the temperature of one junction (side) decreases and the temperature of the other junction increases. This happens due to the Peltier effect. The main drawback of TERS is its low coefficient of performance. Currently, there are constant efforts to improve the performance of TERS by developing new thermoelectric materials with high value of figure of merit (Z). In general, the thermoelectric material has a higher value of Z if it has a low thermal conductivity (k), high electrical conductivity (σ), and high Seebeck coefficient (S) ($Z= S^2 / (k. \lambda) =S^2.\sigma/k$), where $\sigma = 1/\lambda$, and λ is the electrical resistivity. The parameter ($S^2.\sigma$) can be called as electrical power factor [15]. Sometimes, figure of merit is used as a dimensionless figure of merit (ZT_{ave}) when multiplied by the temperature (T_{ave}), where ($T_{ave} = (T_h +T_c) / 2$) is the mean temperature between the two sides of Peltier module. The most commonly used thermoelectric materials in thermoelectric refrigerator are Bismuth Telluride (Bi_2Te_3) and Lead Telluride (PbTe) [16]. Thermoelectric materials that have higher values to (ZT_{ave}) are more convenient materials to carry out higher cooling capacity and producing higher temperature drop. Another way to increase the COP of the TERS is by enhancing the heat transfer mechanism between both the cold and hot sides of the TERS and their surroundings [17]. The heat flux that passes through the Peltier module may reach 40,600 W/m^2, which makes a big problem due to the difficulty of transferring such a heat flux from the small surface area of a typical Peltier module (40 mm × 40 mm) with a reasonable rise of its temperature. Experimentally, it is found that the COP of thermoelectric refrigerator increases by 2.7% per 1^{0}C drop in the heat dissipater [8]. An experimental study was carried out by [18] to design a thermoelectric refrigerator and check its performance. Their results showed that COP of TER can reach a value from 0.3 to 0.5 at ambient temperature of 25 ^{0}C and operating temperature of 5 ^{0}C. Another investigation was carried out by [19], which included TER design, testing under transient state, and developing a computational model for the whole refrigerator. Performance of TERS used in a small-capacity portable cooler in comparison to other refrigeration systems was investigated by [20]. They compared between the vapor compression, Stirling, and thermoelectric refrigerator systems from the point of view of thermodynamic performance. Their results showed that vapor compression system and Stirling were the best with efficiency reaching 14%, but thermoelectric refrigerator efficiency was 1%. Another performance comparison between the three household refrigerators (thermoelectric, absorption, and vapor compression) was conducted by [21]. Their study showed that the vapor compression refrigerator had the highest COP (2.59) followed by the TER (0.69), then the absorption refrigerator (0.47). Effect of using different temperature control systems on COP and energy consumption for TER was tested experimentally by [22] by studying three systems: operating system based on idling voltage, on/off controller system, and proportional integral derivative controller. Their results showed that the idling voltage system was the best where an increase of 64% in COP and a decrease of 32 % in the energy consumption were achieved. On the other hand, experimental study for TER system equipped with heat pipes and phase change materials was carried out by [23] by building two different TER designs. The first was equipped by heat pipe and bonded-fin heat sink at the cold side. The second design was equipped by heat pipe and an encapsulated phase-change material instead of the heat sink. Their results showed that the use of a phase-change material resulted in an improvement in the performance of the TER. Application of the thermoelectric technology on domestic refrigerators were carried out by numerous researchers [24,4,6,25]. Combining thermoelectric and vapor-compression technologies in hybrid refrigerator can benefit from the advantages of each technology. Hybrid household refrigerator (HHR) was designed and tested experimentally by [4] where the hybrid refrigerator was tested under different ambient temperatures, loading, and operating conditions. CFD analysis and experimental measurements for hybrid household refrigerator was carried out by [24] to get the optimal position of the Peltier module inside the hybrid refrigerator. Similar studies were performed by [6, 25], where they developed a computational model based on the finite-difference technique to study the performance of a hybrid household refrigerator. Their hybrid system was operated in a cascade mode; each compartment has its independent cooling vapor compression system and the different positions of TEC on the walls of HHR were investigated. Based on the above literature review, it is found that there is a lack in the experimental studies that focus on performance analysis of hybrid household refrigerator that combines the vapor-compression and thermoelectric technologies. Thus, this paper focuses on developing a hybrid household refrigerator that combines the vapor-compression and thermoelectric technologies. Present investigation covers the use of different configurations of the heat sinks that are in contact with the Peltier module. Also, the effect of changing the supplied voltage to the Peltier module on the performance is studied.

2. EXPERIMENTAL SETUP

2.1. Specifications of the household refrigerator

The present household refrigerator is a top-freezer type with energy consumption efficiency of class B. It has two doors and two compartments: freezer compartment (FC), and cooler compartment (CC) as shown in Fig. 2a. It operates with a single vapor-compression cooling circuit; including a one fixed-speed tropical compressor for two compartments, coil condenser in the back wall, and an evaporator. The temperature control mode is manual. Its specifications are shown in Table (1). The refrigerator uses R134a as refrigerant, which has the properties: ODP = 0, and GWP =1200. To carry out the present investigation, the cooler compartment is divided into two divisions. The upper-division is prepared to be driven by TER, named as thermoelectric compartment (TEC), and the lower division named as fresh food compartment (FFC) as shown in Fig. 2b. The dimensions of compartments and thickness of walls of the hybrid household refrigerator (HHR) are shown in Table (2). The size of the thermoelectric compartment is (300 mm × 450 mm × 420 mm) for (H × W × D) with inner volume 57×10^{-3} m^3. To provide the cooling effect, a Peltier module of type TEC1-12706 with dimensions (40 mm × 40 mm × 3.8 mm), as shown in Fig. 3b, is used.

Table (1). Specifications of the household refrigerator

Specification	Value
Total Capacity	330 Liters
Freezer Capacity	82 Liters
Cooler Capacity	248Liters
Refrigerant	R 134a
Refrigerant Charge	0.160 kg
Energy consumption	2.3 kw.h /day
Climate Classes	T
Defrosting Type	Defrost
Indoor Dimensions (W × D × H)	620 × 630 × 1645 mm

Table (2). Dimensions and wall thickness of the compartments of HHR

	Compartments of the hybrid household refrigerator		
	Freezer compart.	Thermoelectric compart.	Fresh food compart.
Depth (m)	0.470	0.420	0.490
Width (m)	0.490	0.450	0.540
Height(m)	0.360	0.300	0.695
Interior vol. (m^3)	0.083	0.057	0.190
	Walls thicknesses		
	Freezer compart.	Thermoelectric compart.	Fresh food compart.
Ceiling wall (m)	0.050	0.060	0.040
Bottom wall (m)	0.060	0.040	0.050
Back wall (m)	0.075	0.085	0.055
Front door (m)	0.075	0.080	0.045
Side walls (m)	0.055	0.075	0.035

More specifications of the Peltier module are shown in Table (3) [26]. Where $Q_{c,max}$ is the cooling capacity at cold side of the module at ΔT= 0 ºC, ΔT_{max} is the temperature difference between the hot and cold sides of the module when cooling capacity is zero at cold side, I_{max} and V_{max} are the DC current and voltage applied to the modules at ΔT_{max}, respectively. The resistance of the Peltier module is tested under AC. On the cold side of the Peltier module, a heat sink with a fan (Heat sink-I) with dimeter 72 mm, is mounted, produced by Cooler Master [28]. It has 20 fins; each fin has dimensions (30 mm × 78 mm × 2 mm) for (Length (L) × width (W) × thick (δ)), respectively, as shown in Fig. 3a. On the hot side of the Peltier module, two heat sinks (made of aluminum) are used interchangeably. The first heat sinks (Heat sink-II) has dimensions (120 mm × 100 mm × 3 mm) for (Length (L) × width (W) × thick (δ)), respectively, with 23 fins; each fin has dimensions (100 mm × 20 mm × 1 mm) for (Width (W) × Height (H) × thick (δ)), respectively. As shown in Fig. 4a. the heat sinks and the fins are made of aluminum. The second heat sink (Heat sink-III) is a heat sink supported with heat pipes. It is produced by Cooler Master type HYPER H411R [27] and has dimensions (90 mm × 63.5 mm × 136 mm) with four heat pipes of 6 mm and a fan of dimensions 92 mm × 92 mm × 25 mm as shown in Fig. 4b, respectively.

Fig. 2. Household refrigerator before (a), and after adding TEC compartment (b).

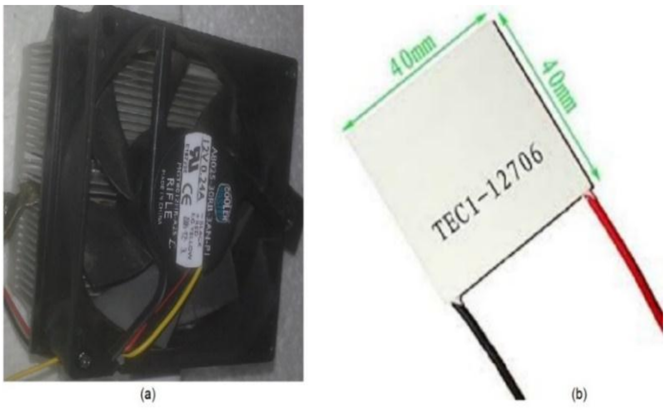

Fig. 3. Heat sink–I with a fan at the cold side (a) [28], and a Peltier module (b) [26].

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Table (3). Performance specifications of the Peltier module [26]

Specification	Value at T_h of 25 [^{0}C]	Value at T_h of 50 [^{0}C]
$Q_{c,max}$, (W)	50	57
ΔT_{max} (^{0}C)	66	75
$I_{max,}$, (A)	6.4	6.4
V_{max} ,(V)	14.4	16.4
Resistance of module, (Ω)	1.98	2.30

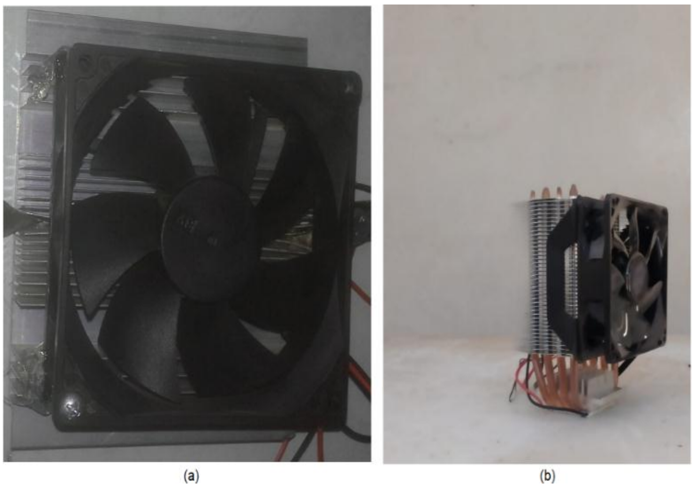

Fig. 4. Configurations of outside heat sink-II (a), and heat sink–III with heat pipes (b) [27].

The coefficient of performance of TER is estimated from:

$$COP = \frac{Q_c}{W_{te}} = \frac{(m_a.c_p.\Delta T)_{cs} / \Delta t}{W_{f,in} + W_{f.out} + W_p} \tag{1}$$

where,Q_c,W_{te}, ΔT_{cs}, Δt are the absorbed heat at cold side of Peltier module, and the total power consumption of the thermoelectric refrigerator, the difference temperature of the inside air (the average of the three temperature measurements) in the TER compartment (sc: cooled space), time to reach steady state, respectively. While the flow of the air m_a is calculated by:

$$m_a = \rho_a.V \tag{2}$$

where, ρ_a,V are the density of the inside air and volume of the TER compartment, respectively.

However, the electrical power consumed for the two fans ($W_{f,in}$,$W_{f,out}$) and Peltier module (W_p) is calculated as:

$$W = I.V \tag{3}$$

where, I, V are the supplied electrical current and voltage for each one.

2.2. Measuring instruments

RXN Linear DC Stabilized Voltage Power Supply [28] is used to deliver the DC current to the Peltier module and to the two fans. It is of type RXN-3010D with input voltage 220V± 10 % and 50 Hz, AC. It has output voltage range from 0 to 30 Volt with accuracy less than 0.05 %, and output current range from 0 to 10 Amperes with accuracy less than 0.2 %, as shown in Fig. 5a. The temperature of the cold and hot sides of the Peltier module as well as the temperature of TEC compartment is measured by a Digital Temperature Panel Meters of type TPM-30 with temperature measuring range from -50 to +110 ^{o}C, with a measurement uncertainty of ±0.5 ^{o}C, as shown in Fig. 5b. During the tests, the time interval between two consecutive readings is taken as one minute. Fig. 6, shows the studied hybrid household refrigerator and configurations of TER in the case of attaching two heat sinks on both sides of the TER. The numbers (1), (2), (3), (4), (5) , (6) and (7) indicate the positions at which (T_h), (T_c), (T_{ter}), (T_{frez}), and (T_{ffc}) are measured, respectively. Where T_{ter} is average of the T_3, T_4, and T_5.

Fig. 5. Power supply (a) and Digital temperature meters (b) [28].

3. EXPERIMENTAL PROCEDURE

The used hybrid domestic refrigerator with the three compartments, as shown in Fig. 6, where one of them is driven by a thermoelectric system, is facilitated with measuring devices and prepared to start the experimental tests. The refrigerator is maintained in an operation mode for 24 hours to reach the steady-state operational temperature. The time of each test was about 275 minutes. Four-series experimental tests are carried out. The first three tests examine the effect of changing the input voltage and the heat sink type on the cooling performance of the TER compartment.

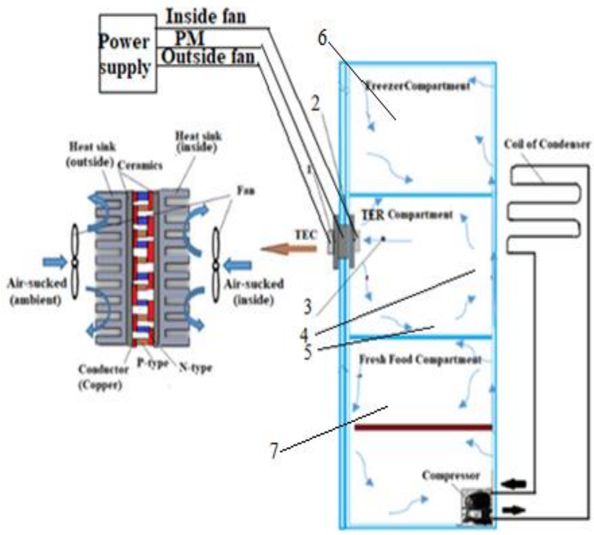

Fig. 6. Present hybrid household refrigerator.

Table (4). Four-Series experimental tests.

Test Type	Configurations of heat sink of TER		Input voltage
	Inside	Outside	V_{sup},(V)
Test 1			
Test 1-1	Heat sink-I with fan	Heat sink-III with fan	11 V
Test 1-2	Heat sink-I with fan	Heat sink-III with fan	8.5 V
Test 1-3	Heat sink-I with fan	Heat sink-III with fan	5 V
Test 2			
Test 2-1	Heat sink-I with fan	Heat sink-II with fan	11 V
Test 2-2	Heat sink-I with fan	Heat sink-II with fan	8.5 V
Test 2-3	Heat sink-I with fan	Heat sink-II with fan	5 V
Test 3			
Test 3-1	Heat sink-I without fan	Heat sink-III with fan	11 V
Test 3-2	Heat sink-I without fan	Heat sink-II with fan	11 V
Test 4			
(Test of measurement of the temperature of the 3 compartments)			
Test 4-1	Heat sink-I with fan	Heat sink-III with fan	11 V

In the fourth test, the temperatures of the three compartments (freezer compartment (T_{frez}), thermoelectric compartment (T_{ter}), and fresh food compartment (T_{ffc}) at input voltage 11 V for PM and both fans, when using the heat sink-I and heat sink-III, are measured. These test arrangements are shown in Table (4).

4. RESULTS AND DISCUSION

In each test shown in Table (4), the temperature at the three locations inside the TEC shown in Fig. 6 is measured. These locations are hot and cold sides of the Peltier module (T_c and T_h) as well as the temperature of the inside air of the TER compartment (T_{ter}) is the average of the T_3, T_4, and T_5. Fig. 7, shows the variation of temperature at the three locations with time for Test-1 when the input voltage to the Peltier module and to the two fans at both sides of TER changes from 5 to 11 Volt. It can be noted that the temperature of the hot side increases above the ambient temperature gradually with time while the temperatures of the cold side and the internal of the TER compartment decrease with higher rates. This is due to the absorption of heat from the TER compartment and rejecting it by means of the heat sink-III to the hot side and then to the environment. It is noted that the rate of increase or decrease of the temperature in all studied cases depends strongly on the value of the supplied voltage to the Peltier module. The temperature reached steady-state condition after nearly 200-230 minutes during the experimental tests. For Test 1-1, the interior temperature reached a steady-state of 6.5 ºC after cooling time 206 min. For Test 1-2 and Test 1-3, the steady-state temperatures were 7.4 ºC and 8 ºC after cooling time 214 min and 220 min, respectively. This means that when the input voltage to Peltier module and the two fans decreases, the cooling time to reach steady-state condition and the interior temperature of the thermoelectric compartment increase, as shown in Table (5). Also, COP of TER (calculated using equation (1)) and the energy consumption for TER (W_{te}) are shown in table (5), where W_{te} is the product of the input voltage and the electrical current. On the other hand, The energy consumption for the vapor-compression refrigerator ($W_{e,\,vcr}$) is calculated based on the equation:

$$W_{e,vcr} = \text{energy consumption of compressor/day} \times \text{No. of operating hours}/24 \quad (4)$$

While, the total energy consumption of the HHR is calculated by using the equation:

$$W_{HHR,tot} = W_{te} + W_{e,vcr} \quad (5)$$

Table (5) shows the results of Tests 1-1 to 1-3, which include the use of heat sink-I and heat sink-III on both sides of the TER at the steady-state condition. It can be noted that the power supplied to the Peltier module (W_{te}) decreases with the decrease in the input voltage to the Peltier module and the two fans, which increases COP_{TER} Compared to W_{te}. Value of the energy consumption of VCR is the highest compared with W_{te}, and it decreases from 70.3 W for Test 1-1 to 59.8 W for Test 1-3. Also, it can be seen that the total energy consumption of the hybrid household refrigerator decreases with small rate according to each test type because it has its independent cooling vapor compression system and it is based on the operating time of the compressor.

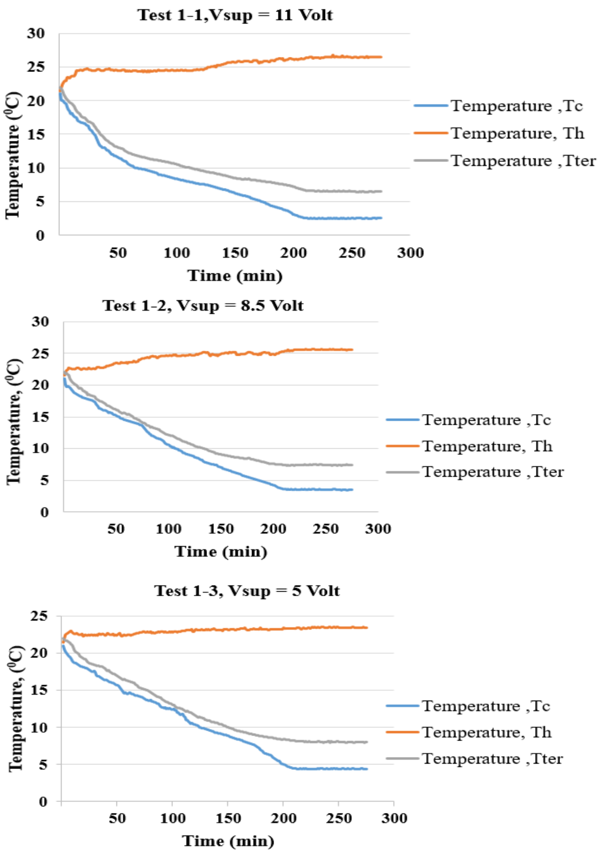

Fig. 7. Comparison of the results of temperatures for Test 1-1, Test 1-2, and Test 1-3

Table (5). Results of Types Test 1-1 to Test 1-3

Type Test	Input	Output					
	V_{sup} [V]	T_c [K]	T_h [K]	COP_{TER} -	W_{te} [W]	$W_{e,vcr}$ [W]	$W_{HHR,tot}$ [W]
Test 1-1	11	275.5	299.5	0.196	37.4	70.3	107.7
Test 1-2	8.5	276.5	298.7	0.334	20.4	65.2	86.6
Test 1-3	5	277.4	296.4	0.652	7.5	59.8	67.3

Table (6). Results of Types Test 2-1 to Test 2-3

Type Test	Input	Output					
	V_{sup} [V]	T_c [K]	T_h [K]	COP_{TER} -	W_{te} [W]	$W_{e,vcr}$ [W]	$W_{HHR,tot}$ [W]
Test 2-1	11	276.4	303.2	0.160	38.5	80.4	118.9
Test 2-2	8.5	277.2	301.4	0.283	21.25	67.5	88.75
Test 2-3	5	278.1	299.5	0.577	8	62.5	70.5

The results of measurements of Test 2-1, Test 2-2, and Test 2-3, where heat sink-I and heat sink-II are used on both sides of the Peltier module, are presented in Fig. 8. It is clear from Fig.8 that there is a more increase of (T_h) for the three studied cases (Test 2-1, Test 2-2, and Test 2-3) in comparison to the three cases studied in Test 1. This is due to the lower efficiency of heat sink-II in comparison to the heat sink-III, which is supported by heat pipes. Accordingly, the values of (T_c) and (T_{ter}) for Test 2-1, Test 2-2, and Test 2-3 are higher and taking a longer time to reach steady-state condition than the corresponding values of Test 1-1 to Test 1-3, as shown in Fig. 8. The interior temperature of the thermoelectric compartment in Test 2-2 reaches the steady-state condition of 8.5 °C after cooling time 220 min, and in test 2-3 it reaches the steady-state after 228 min with a value of 9.3 °C.

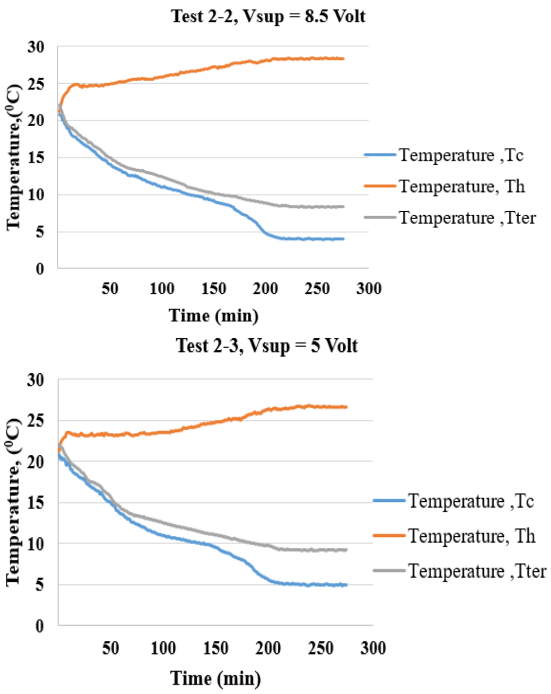

Fig. 8. Comparison of the results of temperatures for Test 2-2, and Test 2-3.

Table (6) shows the results of the steady-state condition. It can be seen that the use of regular heat sink on the hot side results in a decrease in COP in comparison to the case of using heat sink that is supported by heat pipes (Test-1) by about 18.37 % (type test 1) ,15.27% (type test 2), and 11.5 % for (type test 3). Also, it can be shown increase in W_{te} of TER and the energy consumption of VCR in all cases of Test 2, in comparison to the cases of Test 1. To validate of the results of the experimental measurements, the results are compared with another experimental study [29] of a TER with inner volume 55 x 10^{-3} m^3, outer finned heat sink with a fan, inner finned heat sink without a fan, and powered with 12V in an ambient temperature of 296 K, as shown in Fig. 9. The curves of the dashed line $T_{h,ref}$ and $T_{ter,ref}$ belong to the case study of reference [29], which represents the temperature of the hot side of TER, and the inner temperature of TER compartment, respectively. The curves of the continuous line belong to the present study. An acceptable agreement can be noticed in regarding to the differences between the current cases and those of [29] that are manifested in the inner volume for the two thermoelectric compartments, input voltage, working conditions, and configurations of heat sink at both sides of TER. In Fig.9, it can be seen that the difference between T_h and $T_{h,ref}$ when reaching steady-state condition is about 3.8 °C (10 %), while the difference between T_{ter} and $T_{ter,ref}$ is about 1.4 °C.

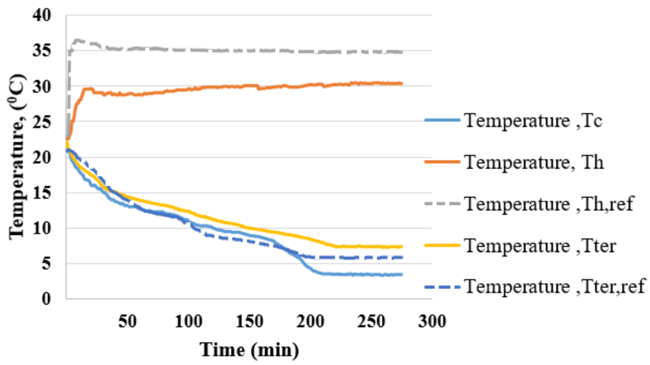

Fig. 9. Comparison of the results of Test 2-1 with the results of case studied of refe. [29]

As shown in Fig. 10, shows varying the electrical current with supplied voltage to the Peltier module for the studied cases during the experimental tests. It can be noted that electrical current increase with increase the supplied voltage to Peltier module (PM) at all studied cases of the cases Type Test1 and Type Test 2. However, values of the electrical current in the type test 2 were higher comparison with its in the type test1, as shown in the table (7).

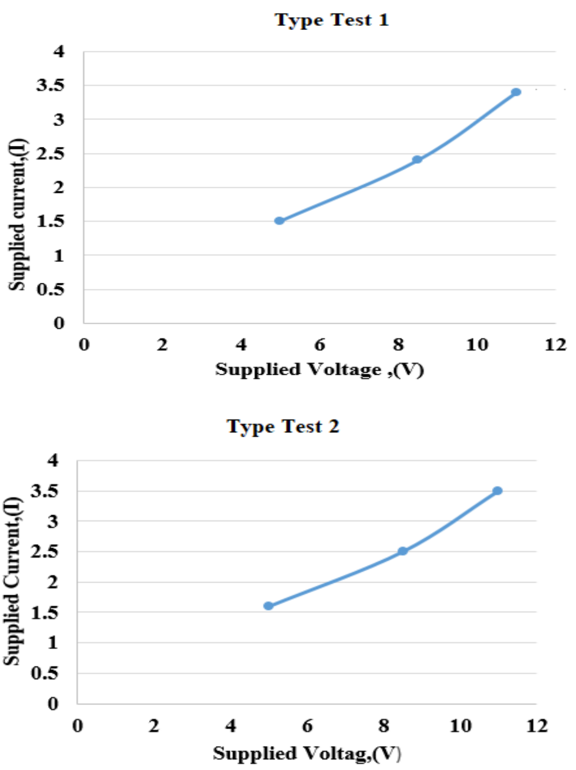

Fig. 10. Varying of the current with the supplied voltage for TER each type test.

Table (7). Varying the electrical current with supplied voltage for TER of Types Test 1, 2

Test	Input	Output	
		Type Test1	Type Test2
	V_{sup}, (V)	I for TER , [A]	I for TER, [A]
Test 1	11	3.4	3.5
Test 2	8.5	2.4	2.5
Test 3	5	1.5	1.6

Test 3-1 and Test 3-2 are carried out to study the effect of using a fan inside the TER compartment to produce a forced convection air motion. In these two test cases, the inside fan, which is attached to heat sink-I is turned off. Heat sink-III and Heat sink-II are attached on the hot side of the Peltier module for Test 3-1 and Test 3-2. The fan attached to the hot side heat sink is kept on. Fig. 11 shows the temperature variation with time for Test 3-1 and Test 3-2. In Test 3-1, the fast decrease of the temperature of the cold side (T_c), which reaches about -2 ^{0}C can be noted. This test is stopped after about 90 minutes due to ice formation on the surfaces of heat sink-I. The ice formation causes the interior temperature of the TER compartment to rise due to the insulation effect of the ice, which reduces the heat exchange between the inner heat sink surface and the inside air of the TER compartment. This emphasizes the importance of the forced-convection motion of the air in absorbing heat from the TER compartment. In Test 3-2, it can be seen that the interior temperature of the TER compartment reaches a steady-state temperature of 7.3 ^{o}C after cooling time 134 min.

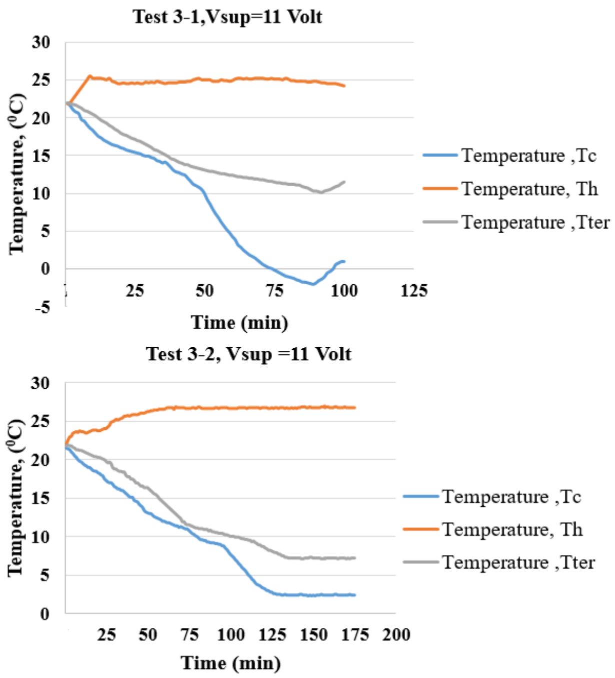

Fig. 11. Comparison of the results of temperatures for Test 3-1 and Test 3-2

Due to the high efficiency of the outside heat sink (Heat sink-III, Test 3-1) and the lower heat transfer rates associated with this test, the temperature of the hot side did not increase above 25^{0}C. Using heat sink-II on the hot side on test 3-2 results in the increase of T_h with time and it reaches a steady-state temperature of 27 ^{0}C after about 90 minutes of the test. This is due to the lower thermal efficiency of heat sink-II in comparison to heat sink-III. The above-mentioned results show the advantage of using low thermal resistance heat sink on the performance of the TER system. The thermal resistance of a heat sink can be reduced either by using a fan to produce convection air motion or by supporting the heat sink with heat pipes.

Test 4 is conducted to measure the variations of the inner temperature of TER compartment (T_{ter}) in addition to the temperature of the freezer compartment (T_{frez}) and the fresh food compartment (T_{ffc}), as shown in Fig. 13. This test is carried out for just one configuration: heat sink-III with fan on the hot side, heat sink-I with the fan on the cold side, and the input voltage for the Peltier module and two fans equals 11 Volts.

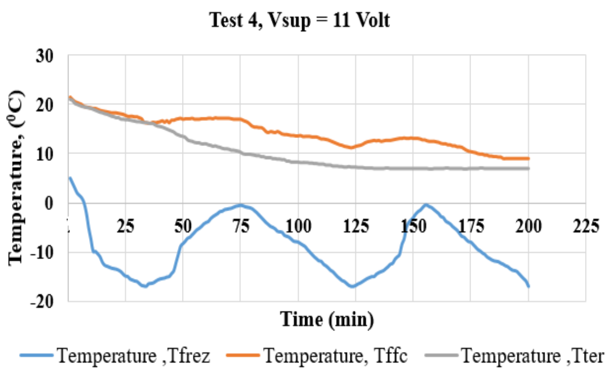

Fig. 12. Comparison of the results of temperatures of Test 4.

Fig. 12 shows the big oscillation in the temperature of the freezer compartment (T_{frez}), which ranges between -0.5 and -18 ^{0}C whereas the temperature of the fresh food compartment (T_{ffc}) oscillates more than 5 ^{0}C. These compartments are driven by a vapor-compression system, and the oscillation is due to the nature of the compressor on/off operation. However, it is noted that the fluctuations of the temperature in the freezer and FFC compartments do not affect the temperature inside the TER compartment. The temperature of the TER compartment decreases gradually till reaching the steady-state temperature after about 180 minutes. This is attributed to the nature of TER operation, which works continuously by the input DC voltage to the Peltier module.

5. CONCLUSIONS AND FURTHER WORK

A hybrid household refrigerator, which combines the vapor-compression and thermoelectric technologies, is developed by adding a new compartment that is driven by the thermoelectric refrigerator (TER) to the original commercial VCR refrigerator. Performance of The TER refrigerator is tested for different values of the input voltage for Peltier module and fans with using different configurations for the heat sinks, which are mounted on both sides of the Peltier module.

The results show that the increase of the input voltage to the TER system decreases its coefficient of performance (COP). However, in some cases, the increase of the input voltage is crucial to get the desired reduction in the temperature and the desired cooling capacity on the TER compartment. Also, the results demonstrate that decreasing the thermal resistance of the heat sink mounted on the hot side by using a heat sink supported with heat pipes leads to an increase of the value of COP of TER by about (11.5 to 18.37 %) and a decrease in power consumption of about 8.5% in comparison to the use of a regular heat sink, respectively. Where the maximum error in the power consumption is less than 5%. In addition, the use of a fan to push the air over the heat sink, which is mounted on the cold side, proves to be of high importance in improving the TER performance. For validation of the experimental results, a comparison with another published study is performed. The discrepancy was about 10%, which is acceptable regarding to the difference in the design and operating conditions. Monitoring the temperature on the three compartments of the hybrid refrigerator shows that, despite the high oscillations in the freezer temperature, the TER system is able to keep the stability of the temperature in the TER compartment. This is of high importance, particularly in preserving food and other perishable products. Moreover, in all the tests that have been carried out, the results show that the current hybrid refrigerator is capable of obtaining an inner temperature of the TER compartment ranging from 6.5 to 9.3 ^{0}C, with temperature oscillation of about ± 0.5 ºC, while the fresh food compartment with temperature oscillation of about 5 ºC, and the freezer compartment with temperature oscillation of about -18 ºC. The results of this work will be the basis for further investigation, which will include more improvements to the developed design, and developing a computational model based on the produced data of the present experimental tests.

NOMENCLATURE

H: Height of the compartment	mm
I : Electric current	A
I_{max}: DC current through the PM at ΔT_{max}	A
k : Thermal conductivity	W/m. K
L: Length of the compartment	mm
Q_c: Heat absorbed at cold side of TER	W
$Q_{c,max}$: Cooling capacity at cold side of PM at ΔT= 0 ºC	W
S : Seebeck coefficient	V/m
ΔT: Temperature difference between both sides of PM	^{0}C
ΔT_{max}: Temperature difference of PM at Q_c = 0	^{0}C
T_{ave} : Average temperature	^{0}C
T_c : Temperature of cold side of PM	^{0}C
T_{ffc}: Temperature of fresh food compartment	^{0}C
T_{frez} : Temperature of freezer compartment	^{0}C
T_h : Temperature of hot side of PM	^{0}C
$T_{h,ref}$: Temperature of hot side of PM of ref [29]	^{0}C
T_{ter} : Temperature of TER compartment	^{0}C
$T_{ter,ref}$: Temperature of TER compartment of ref [29]	^{0}C
V_{max} : Voltage applied to the Peltier modules at ΔT_{max}	V
V_{sup} : Supply voltage to PM	V
W: Width of the compartment	mm
W_{te}: Power consumption of TER	W
$W_{e,vcr}$: Power consumption for VCR	W
$W_{HHR,tot,}$: Power consumption for HHR	W
Z: Figure of merit	1/ K
Greek symbols	
λ: Electrical resistivity	Ω.m
σ : Electrical conductivity	S/m
δ: Thick	mm

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