Journal of Engineering and Applied Sciences 5 (3): 221-225, 2010
ISSN: 1816-949X

Experimental Comparison of Thermoelectric Refrigeration and Vapour Power Compression Refrigeration

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Abstract: The study shows the comparison between thermoelectric refrigeration and vapor compression refrigeration. Three tests were carried out on 325 mL of water in a glass jar. The result shows that for the refrigerator freezer space, the temperature of the water decreased linearly with increasing time. However, for the thermoelectric refrigeration, the water temperature decreased exponentially with increasing time. In other words, cooling rate for the refrigerator was constant while for the thermoelectric it decreased exponentially. The study also shows that the freezer of a vapor compression refrigeration took 61 min to cool the water to 6°C while the thermoelectric 69 min. It can be seen that for the majority of the cooling time, the thermoelectric was cooling at a faster rate than the freezer. But by virtue of the exponential cooling versus linear cooling, cooling rate for the thermoelectric decreasing while the freezer cooling rate was constant throughout the cooling process.

Key words: Thermoelectric, refrigeration, vapour power compression, exponential, cooling

INTRODUCTION

A thermoelectric device is one that operates on a circuit that incorporates both thermal and electrical effects to convert heat energy into electrical energy or electrical energy to a temperature gradient. Thermoelectric elements perform the same cooling function as freon-based vapor compression or absorption refrigerators. Energy is taken from a region thereby reducing its temperature. The energy is then rejected to a heat sink region with a higher temperature.

Thermoelectric elements are in a totally solid state while vapor cycle devices have moving mechanical parts that require a working fluid. Thermoelectric modules shown in Fig. 1 are small, sturdy and quiet heat pumps operated by a DC power source.

They usually last about 200,000 h in heating mode or about 20 h if left on cooling mode. When power is supplied, the surface where heat energy is absorbed becomes cold; the opposite surface where heat energy is released becomes hot. If the polarity of current flow through the module is reversed, the cold side will become the hot side and vice-versa.

Thermoelectric devices can also be used as refrigerators on the bases of the Peltier effect (Cengal and Michael, 1998). To create a thermoelectric refrigerator (Fig. 2), heat is absorbed from a refrigerated space and than rejected to a warmer environment. The difference between these two quantities is the net electrical work that needs to be supplied. These refrigerators are not

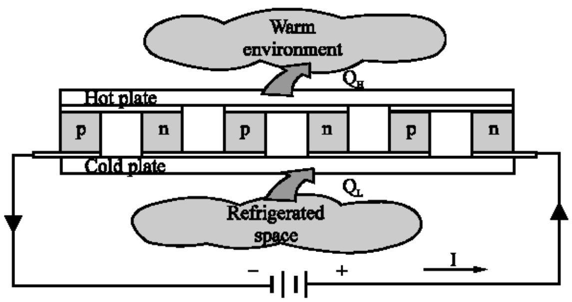

Fig. 1: A thermoelectric refrigerator based on the peltier effect

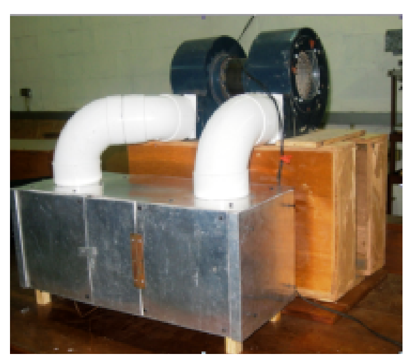

Fig. 2: Thermoelectric refrigeration

overly popular because they have a low coefficient of performance. Thermoelectric modules can be used as thermocouples for temperature measurement or as generators to supply power to spacecrafts and electrical equipment. Thermo electronic devices are used in a variety of applications. They are used by the military for night vision equipment, electronic equipment cooling, portable refrigerators and inertial guidance systems.

These products are useful to the military during war and training because they are reliable, small and quiet. Another advantage to these thermoelectric products is that they can be run on batteries or out of a car lighter. The medical community uses thermoelectric applications for hypothermia blankets, blood analyzers and tissue preparation and storage. The main advantage of thermoelectric devices to the medical community is that the devices allow doctors precise temperature control which is useful in handling tissue samples. Hypothermia blankets are pads that patients rest on during surgery to keep their body at a certain temperature. Thermoelectric devices are probably most well known for their contribution to powering spacecrafts like the Voyager.

Radioisotope Thermoelectric Generators provided all of the on-board electrical power for NASA's Voyager. The Thermoelectric devices proved reliable since they were still performing to specification 14 years after launch. The power system provided the equivalent of 100-300 watts electrical power and multiples thereof. NASA is now requiring higher efficiency rates out of smaller units.

The interaction between thermal and electric phenomena; Seebeck effect (1821), Peltier effect (1834), Joule effect (1841) and Thomson effect (1857) was known since the 19th century (Rowe and Bhandari, 1983). In 1885, the English physicist J.W. Rayleigh outlined the possibility of using thermoelectric devices as electricity generators but his development was totally stopped because of the low efficiency achieved. However, the major advance was made in the 1950s with the introduction of semiconductors as thermoelectric materials. It was observed that they had a high Seebeck coefficient, good electrical conductivity and low thermal conductivity.

In those moments thermoelectric refrigeration began to look more promising and Peltier devices were developed for refrigeration applications mostly for the military field. Work on semiconductor thermocouples also led to the construction of thermoelectric generators with a high enough efficiency for special applications.

There was little improvement in thermoelectric materials from the time of the introduction of semiconductor thermo-elements until the end of the 20th century. However, in recent years, several new ideas for the improvement of materials have been put forward and significant advances are being made (Goldsmid, 2009). Now-a-days, in the civil market, thermoelectric refrigeration has a place in medical applications and scientific mechanisms and devices where accurate temperature control is needed. Nevertheless, there are other applications with great potential, in which companies are starting to show interest, e.g., dehumidifiers (Vian *et al*., 2002), domestic and automobile air conditioning systems, portable iceboxes, domestic refrigerators, devices to transport perishable products, computer processor coolers, etc. For these applications, thermoelectric refrigeration competes with conventional refrigeration systems like Vapor compression refrigeration. For a typical conventional refrigeration system, a temperature difference between the ambient and the cabinet of about 25-30 K at T_h = 300 K is usually required to achieve satisfactory cooling performance.

This indicates that the maximum COP of a thermoelectric refrigerator comprised of a commercially available module is around 0.9-1.2. However, the practical COP of a thermoelectric refrigerator is much lower than this because the temperature difference between the hot and cold side of the thermoelectric module is larger than the temperature difference between the ambient and the cabinet. In other words, the hot side temperature is higher than the ambient and the cold side temperature is lower than the cabinet temperature. For a practical thermoelectric cooling system, the hot side heat exchanger rejects the heat produced on the hot side of the thermoelectric module to the ambient and so reduces the hot side temperature.

The cold side heat exchanger removes the heat from the cold region to the cold side of thermoelectric module and so increases the temperature of the cold side. Because the thermoelectric module is very high heat intensity equipment, the high efficiency thermoelectric heat exchangers is necessity. Use of a heat pipe will not be of benefit for natural convection, because the dominant thermal resistance in this case is the convection resistance (Webb, 1998). Water-cooled forced convection heat exchangers have excellent performance.

The main drawback of a water-cooled heat exchanger is that it needs a convenient source of cooling water. Without a source of cooling water, a forced convection water heat exchanger would require a pump and radiator and associated fittings and tubing. The added resistance of the radiator would increase the overall resistance. Air-cooled systems are therefore often more desirable. Many heat exchange systems based on the afore-mentioned forced air convection exchangers and the use of heat pipes have been reported. Sofrata (1996) reported that using a double fan in an appropriate position could significantly increase the efficiency of the forced air exchanger compared to using the single fan in a refrigerator. A long chimney for a natural-convection heat exchanger may also improve the performance of the refrigerator without the need to use fans that of course, require the electrical power input. A novel, air-cooled thermosyphon reboiler-condenser system has been reported (Webb, 1998) and has been used as a heat exchanger of a thermoelectric refrigerator (Gilley and

Webb, 1999). This system is capable of providing very low heat sink resistance values with air cooling and a thermal resistance as low as 0.0194-0.0505KW^{-1} was obtained for cooling a 45 mm^2 module. The system promises significantly higher COP for thermoelectric coolers than is possible using existing heat exchange technology.

Riffat *et al*. (2001) have reported a thermoelectric refrigeration system which employs a Phase Change Material (PCM) as a cold side heat exchanger for cooling storage and improvement of the COP. The refrigeration system was first fabricated and tested using a conventional heat sink system (bonded fin heat sink system) at the cold heat sink. In order to improve the performance and storage capability, the system was reconstructed and tested using an encapsulated Phase Change Material (PCM) as a cold sink.

Both configurations used heat pipe embedded fins as the heat sink on the hot side. Results of tests on the latter system showed an increased performance. This was because the PCM had a large storage capacity allowing most of the cooling energy to be absorbed by the PCM and therefore, the cold side temperature fell more slowly than when the PCM was not used. During the phase change process, the temperature of the refrigeration system was almost constant until the phase change process was complete. This helped to keep the temperature difference across the thermoelectric module to a minimum, thus improving its performance. In general, thermoelectric modules are very high heat intensity equipment which need high efficiency heat exchangers to lower the hot side temperature and increase the cold side temperature in order to improve the COP. Use of a greater number of modules would also improve the COP of the system. Use of more modules would reduce the heat load on each module and so lower the heat flux densities of both the hot and cold side of each module.

MATERIALS AND METHODS

The following tests were carried out on the thermoelectric refrigeration as shown in Fig. 2. Two of the TEC modules were connected to two 12 V computer power supplies and the other two were connected to a variable voltage Lab power supply. The blower was connected to 110 Vac. The readings for the voltage and current are shown in Table 1. The airflow rate through the two warm compartments were also measured and the readings were shown in Table 2. There mocouples were installed at various points in the thermoelectric refrigeration to take the temperatures at these points. The placement of the thermocouples is shown in Fig 3. Where, T1 indicates temperature at hot side heat sink base, $T_{base\ hot}$; T2 measures temperature at cold side heat sink base, $T_{base\ cold}$; T3 measures cold compartment Temperature, T_{cold} and T4 measures Water Temperature, T_{water}. Table 3 and 4 show the experimental results for the thermoelectric refrigeration when allowed to reach operating temperature with nothing in the cold compartment. The same quantity of water in the same glass jar was then placed in the freez compartment of vapour compression refrigeration, the cold space of vapour compression refrigeration and readings were taken until the desired temperature of 6°C was obtained.

The results of this experiment inside the freezer compartment and cold space are shown in Table 5. Table 5 shows the performance of the thermoelectric refrigeration.

Table 1: The voltage and current readings

TEC module	Voltage/V	Current/A	Power (Watts)
TEC 1	9.85	7.5	73.88
TEC 2	9.85	7.5	73.88
TEC 3	11.69	8.4	98.20
TEC 4	11.03	8.5	93.76

Table 2: The air flow-rate through the two warm compartments

	Left side warm compartment		Right side warm compartment	
Position	Air flow (CFM)	Air speed (ft min^{-1})	Air flow (CFM)	Air speed (ft min^{-1})
Before heat sinks	530	1879	880	3114
After first heat sink	160	587	450	1593
After second heat sink	120	452	361	1278

Table 3: Temperature readings for the cold and hot compartment

Time (min)	$T_{base\ hot}$/°C	$T_{base\ cold}$/°C	T_{cold}/°C
0	32.7	32.7	32.7
5	61.7	21.6	20.6
10	60.9	14.3	12.8
15	60.4	11.4	10.1
20	59.7	8.4	6.9
25	58.9	6.1	4.8
30	59.0	5.2	3.8
35	58.8	4.4	2.9
40	58.8	3.8	2.3
45	58.7	3.2	1.7

Table 4: Temperature readings for the cold and hot compartment when water was tested

Time after water is placed inside (min)	Total time chiller is on /min^{-1}	$T_{base\ hot}$/°C	$T_{base\ cold}$/°C	T_{cold}/°C	T_{water}/°C
0	46	59.0	4.0	5.7	31.5
5	51	59.2	5.5	5.6	25.9
10	56	59.4	6.0	5.6	22.4
15	61	59.4	6.0	5.5	19.4
20	66	59.5	5.9	5.3	17.0
25	71	59.4	5.7	4.8	14.8
30	76	59.5	5.5	4.6	13.2
35	81	59.5	5.2	4.1	11.7
40	86	59.5	5.0	3.9	10.4
45	91	59.5	4.8	3.7	9.4
50	96	59.4	4.6	3.4	8.3
55	101	59.4	4.5	3.2	7.7
60	106	59.3	4.3	3.0	7.0
65	111	59.5	4.2	2.9	6.2
69	115	59.4	4.1	2.7	6.0

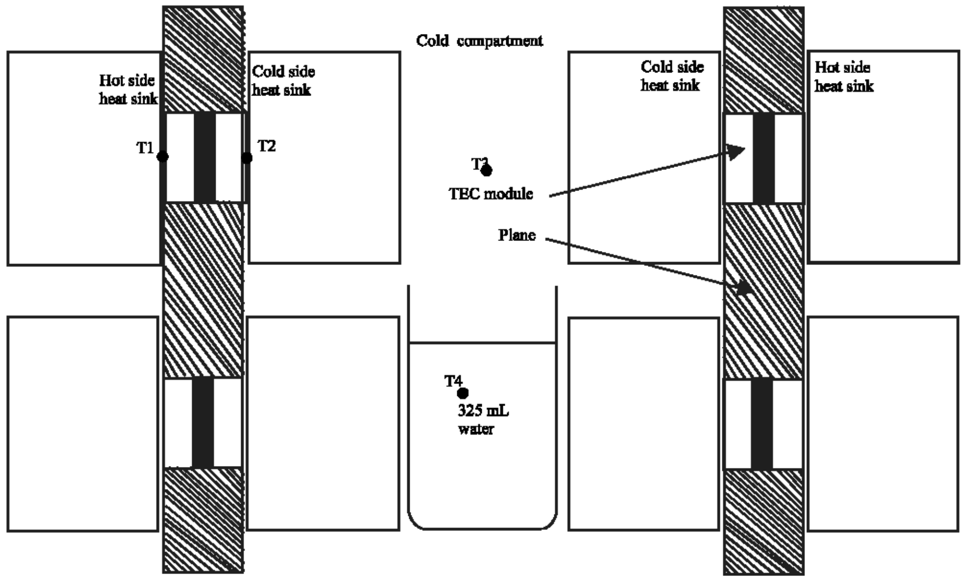

Fig. 3: Diagram showing the placement of thermocouples (T1, T2, T3 and T4)

Table 5: Variation of temperature with time for 325 mL water placed in freezer and cold space of refrigerator

Freezer		Cold space	
Time (min)	Temperature (°C)	Time (min)	Temperature (°C)
0	31.7	0	31.70
10	26.3	15	28.10
20	21.2	30	24.30
30	16.8	45	21.20
40	13.0	60	19.50
50	10.1	75	19.00
60	6.3	90	17.50
61	5.9	105	16.15
-	-	120	14.78
-	-	135	13.20
-	-	150	12.45
-	-	165	11.70
-	-	180	11.03
-	-	195	10.50
-	-	210	9.83
-	-	225	9.25
-	-	240	8.50
-	-	255	7.30

RESULTS AND DISCUSSION

The design power input obtained in the calculations for the TEC modules used was 98W. Figure 4 shows the performance of a TEC module variation with input power: performance in this case refers to the cooling rate Q_c. The Figure shows that as the input power increases, performance also increases. Operating at close to the maximum is inefficient; most applications do operate at 40-80% of input maximum power of TEC modules. For the selected TEC modules 40% input power max is 160.16 Watt. Therefore the cooling rate of the beverage chiller would have been improved if the design requirement of 98

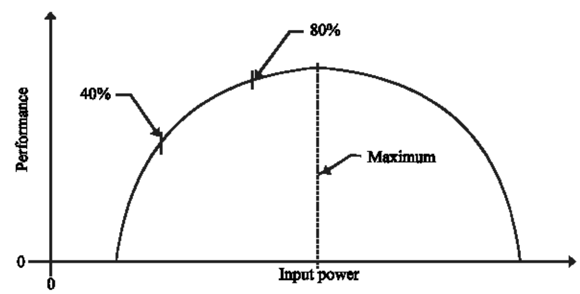

Fig. 4: Variation of performance with input power for a TEC module

Watt for each TEC module was met. If the available power supplies supported supplying 160 Watt, this would have increased the cooling rate even more. Inefficient forced convective heat transfer within the cold compartment also adversely affected the cooling rate of the thermoelectric refrigeration as shown in Fig. 5. A small fan was used to circulate air within the cold compartment. The fan had small cubic feet per minute (cfm) rating and its positioning also was not optimal. Having a fan set-up where the fans circulate air through the fins of all the cold side heat sinks and then directing a blast of cold air over the jar containing the water to be cooled would have resulted in better cooling times.

Figure 6 compares the thermoelectric refrigeration's cooling time with cooling times obtained from the freezer space and cold space of a vapour compression refrigerator. All three tests were carried out on 325 mL of water in a glass jar. The result shows that for the refrigerator freezer space, the temperature of the water

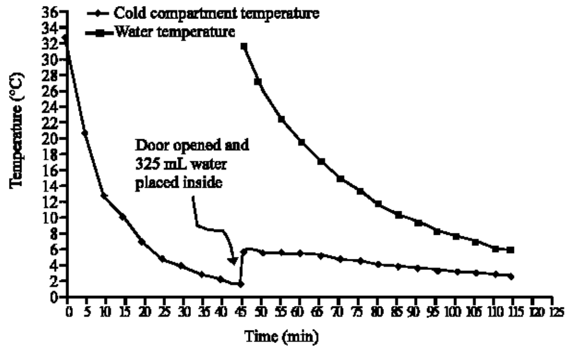

Fig. 5: Variation of temperature with time of the cold compartment of the Thermoelectric Refrigeration and of 325 mL water placed inside the cold compartment

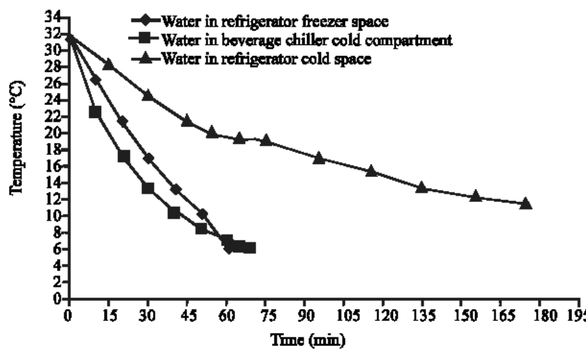

Fig. 6: Variation of temperature with time of 325 mL of water placed inside various cold spaces

decreased linearly with increasing time. However, for the thermoelectric refrigeration, the water temperature decreased exponentially with increasing time. In other words, cooling rate for the refrigerator was constant while for the thermoelectric refrigeration it decreased exponentially. Figure 6 also shows that the freezer took 61 min to cool the water to 6°C while the thermoelectric refrigeration took 69 min.

It can be seen that for the majority of the cooling time, the thermoelectric refrigeration was cooling at a faster rate than the freezer. But by virtue of the exponential cooling versus linear cooling, cooling rate for the vapour compression refrigerator was decreasing while the freezer cooling rate was constant throughout the cooling process. This caused the thermoelectric refrigeration's cooling rate to eventually reach a point where it was lower than the freezer's cooling rate. This happened at around 7°C as shown in the Fig. 6, where the lines crossed. It must also be noted that the temperature within the freezer space was measured at -17.4°C while that of the thermoelectric refrigeration's cold compartment was on average around 3.9°C (it started at 5.7°C and dropped to 2.7°C during the water cooling process). Therefore, at the point in time at which the required water temperature of 6°C was attained, the temperature difference between water and cold space was 23.4°C for the freezer and only 3.30°C for the thermoelectric refrigeration.

CONCLUSION

It can be stated that although, the thermoelectric refrigeration took more time to cool the water, the heat transfer process from the water to the cold compartment was more efficient than in the freezer of vapour compression refrigerator. The cold space of the refrigerator was measured at 5.1°C and took over 2 h to cool to 7.2 degrees which was very much slower than the thermoelectric refrigeration.

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