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A REVIEW ON DEVELOPMENTS OF THERMOELECTRIC REFRIGERATION AND AIR CONDITIONING SYSTEMS: A NOVEL POTENTIAL GREEN REFRIGERATION AND AIR CONDITIONING TECHNOLOGY

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ABSTRACT

In recent years, with the increase awareness towards environmental degradation due to the production, use and disposal of ChloroFluoro Carbons (CFCs) and Hydro Chlorofluorocarbons (HCFCs) as heat carrier fluids in conventional refrigeration and air conditioning systems has become a subject of great concern and resulted in extensive research into development of novel refrigeration and space conditioning technologies. Thermoelectric cooling provides a promising alternative R&AC technology due to their distinct advantages. A brief introduction of thermoelectricity, principal of thermoelectric cooling and thermoelectric materials has been presented in this paper. The research and development work carried out by different researchers on development of novel thermoelectric R&AC system has been thoroughly reviewed in this paper. The cost-effectiveness of this technology has been also discussed in this paper. The authors are also conducting research for development of renewable energy based TER system and they have been designed and developed an experimental thermoelectric refrigeration system having a refrigeration space of 1 liter is cooling by four numbers of thermoelectric cooling module (Q_{max}=19W) and a heat sink fan assembly (R_{th}=0.50 $^oC/W$) for each thermoelectric module used to increase heat dissipation rate. A temperature reduction of 11^{o}C without any heat load and 9^{o}C with 100 ml of water in refrigeration space with respect to 23^{o}C ambient temperature has been experimentally found in first 30 minutes at optimized operating conditions. The calculated COP of thermoelectric refrigeration cabinet was 0.1.

Keywords: Thermoelectric module; Peltier effect; Figure of merit; Coefficient of Performance (COP).

1. INTRODUCTION

The first important discovery relating to thermoelectricity occurred in 1823 when a German scientist, Thomas Seebeck, found that an electric current would flow continuously in a closed circuit made up of two dissimilar metals provided that the junctions of the metals were maintained at two different temperatures. Some 12 years later French watchmaker, Jean Charles Athanase Peltier, discovered thermoelectric cooling effect, also known as Peltier cooling effect, Peltier discovered that the passage of a current through a junction formed by two dissimilar conductors caused a temperature change. The true nature of Peltier effect was made clear by Emil Lenz in 1838, Lenz demonstrated that water could be frozen when placed on a bismuth-antimony junction by passage of an electric current through the junction.

He also observed that if the current was reversed the ice could be melted. In 1909 and 1911 Altenkirch give the basic theory of thermoelectrics. His work explained those thermoelectric cooling materials needed to have high Seebeck coefficients, good electrical conductivity to minimize Joule heating, and low thermal conductivity to reduce heat transfer from junctions to junctions. In 1949 Ioffe developed theory of semiconductors thermoelements and in 1954 Goldsmid and Douglas demonstrated that cooling from ordinary ambient temperatures down to below 0^{o}C was possible Rowe [1]. Shortly after the development of practical semiconductors in 1950's, Bismuth Telluride began to be the primary material used in the thermoelectric cooling.

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Thermoelectric cooling works on the principle of Peltier effect, when a direct current is passed between two electrically dissimilar materials heat is absorbed or liberated at the junction. The direction of the heat flow depends on the direction of applied electric current and the relative Seebeck coefficient of the two materials. A Peltier module or thermoelectric module (Fig.1.) is a solid-state active heat pump which consist a number of p- and n- type semiconductor couples connected electrically in series and thermally in parallel are sandwiched between two thermally conductive and electrically insulated substrate. The performances of a thermoelectric cooler are expressed as follows and are described in many handbooks and papers [2-3]

$$Q_c = \alpha_{pn} T_c I - \frac{1}{2}(I^2 R) - K(T_h - T_c) \tag{1}$$

The overall rate of expenditure of electrical energy is given by

$$W = \alpha_{pn} I (T_h - T_c) + I^2 R \tag{2}$$

The Coefficient of Performance is defined as

$$COP = \frac{Q_c}{W} \tag{3}$$

The refrigeration capability of a semiconductor material is depend on a combined effect of the material's Seebeck coefficient, thermal conductivity and electrical resistivity over the operational temperature range of hot and cold side named as figure of merit and expressed as

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

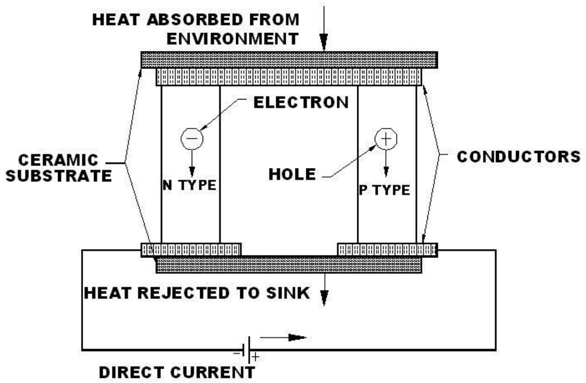

Fig.1. Schematic Diagram of a Thermoelectric Cooler

The commonly material employed for commercially available thermoelectric cooler is based on Bismuth Telluride mixed crystal and modification of Bi_2Te_3, have the highest figure-of-merit and most suitable in refrigeration.

In addition to Bismuth Telluride, there are other thermoelectric materials including Lead Telluride (PbTe), Silicon Germanium (SiGe), and Bismuth-Antimony (Bi-Sb) alloys that may be used in specific situations.

The thermoelectric cooling systems having advantages of lightweight, reliable, noiseless, portable and uses electrons rather than refrigerant as a heat carrier, and is feasible for outdoor purpose in cooperation with solar PV cells. Thermoelectric coolers will either heat or cool depending upon the polarity of the applied DC power. This feature eliminates the necessity of providing separate heating and cooling functions for a given enclosed space. Xi et al. [4] presented in their study that thermoelectric refrigeration emerges as alternative green refrigeration technology due to their distinct advantages as noiseless and wearless due to no moving parts, reliable, portable and compatible with Solar PV cell generated DC power, making them complete environment friendly.

2. DEVELOPMENTS IN THERMOELECTRIC REFRIGERATION AND AIR CONDITIONING SYSTEMS

Dai et al. [5] have designed and developed a thermoelectric refrigeration system powered by solar cells generated DC voltage and carried out experimental investigation and analysis. They developed a prototype which consists of a thermoelectric module, array of solar cell, controller, storage battery and rectifier. The system with solar cells and thermoelectric refrigerator is used for outside purpose in daytime and system with storage battery, AC rectifier and TER is used in night time when AC power is available. Experimental analysis on the unit was conducted mainly under sunshine conditions. The studied refrigerator can maintain the temperature in refrigerated space at 5–10^{o}C, and has a COP about 0.3 under given conditions. Min et al. [6] developed a number of prototype thermoelectric domestic-refrigerators with different heat exchanger combination and evaluated their cooling performances in terms of the COP, heat pumping capacity, cooling down rate and temperature stability. The COP of a thermoelectric refrigerator is found to be 0.3-0.5 for a typical operating temperature of 5^{o}C with ambient at 25^{o}C. The potential improvement in the cooling performance of a thermoelectric refrigerator is also investigated employing a realistic model, with experimental data obtained from this work. The results show that an increase in its COP is possible through improvements in module contact resistances, thermal interfaces and the effectiveness of heat exchangers. Wahab et al. [7] designed and developed an affordable thermoelectric refrigerator powered by solar cells generated DC voltage for the desert people living in Oman where electricity is not available. In this study the researchers used 10 nos. of thermoelectric module in design of refrigerator.

The finned surface (heat sink) was used to enhance and increase the rate of heat transfer from the hot surface of thermoelectric module. Cooling fan was used to reject the heat from the hot side of module to ambient surroundings. The experimental data collected from running one thermoelectric module indicate that it is possible to achieve temperature difference upto 26.6^{o}C at current 2.5 A and voltage 3.7 V. The coefficient of performance of the refrigerator was calculated and found to be about 0.16.

An experimental study on cooling performance of a developed combined Solar Thermoelectric- Adsorption cooling system has been carried out by Abdullah et al. [8]. They developed a novel solar thermoelectric-adsorption cooling system and tested at eight different days. Cooling is produced via the Peltier effect during the day, by means of thermoelectric elements, and through adsorption process at night. They evaluate the coefficient of performance values by using derived equations, the average COP values of the overall system were found ~ 0.131 (adsorption) and ~ 0.152 (thermoelectric), respectively. Putra [9] designed, manufactured and tested a portable vaccine carrier box employing thermoelectric module and heat pipe. The position of heat pipe as a heat sink on the hot side of the TEM enhanced the cooling performance. The minimum temperature in the vaccine carrier cabin reached -10^{o}C, which shows that vaccine carrier can store the vaccine at desired temperature. Adeyanju et al. [10] carried out a theoretical and experimental analysis of a thermoelectric beverage chiller. Comparison were also made between the thermoelectric beverage chiller's cooling time with cooling times obtained from the freezer space and cold space of a household refrigerator. The result shows that for the refrigerator freezer space, the temperature of the water decreased linearly with increasing time and for thermoelectric beverage chiller the temperature of the water decreased exponentially with increasing time.

Lertsatitthanakorn et al. [11] evaluated the cooling performance and thermal comfort of a thermoelectric ceiling cooling panel (TE-CCP) system composed of 36 TEM. The cold side of the TEM was fixed to an aluminum ceiling panel to cool a test chamber of 4.5 m^3 volume, while a copper heat exchanger with circulating cooling water at the hot side of the TE modules was used for heat release. Thermal acceptability assessment was performed to find out whether the indoor environment met the ASHRAE Standard-55's 80% acceptability criteria. The standard was met with the TE-CCP system operating at 1 A of current flow with a corresponding cooling capacity of 201.6 W, which gives the COP of 0.82 with an average indoor temperature of 27^{o}C and 0.8 m/s indoor air velocity.

Gillott et al. [12] conducted an experimental investigation of thermoelectric cooling devices for small-scale space conditioning applications in buildings. They performed a theoretical study to find the optimum operating conditions, which were then applied in the laboratory testing work. A TEC unit was assembled and tested under laboratory conditions. Eight pieces of Ultra TEC were shown to generate up to 220W of cooling effect with a COP of 0.46 under the input current of 4.8A for each module.

Bansal et al. [13] conducted a detail study on energy efficiency and cost-effectiveness for vapour compression, thermoelectric and absorption refrigeration of similar capacity (about 50 liter). The investigated result show that vapour compression refrigerator was the most energy efficient (with a COP of 2.59) followed by thermoelectric (COP of 0.69) and absorption refrigerator (COP of 0.47). The Cost analysis results show that the total purchasing and operating costs over the life of the systems was the lowest for the vapour-compression unit at NZ$506, followed by the thermoelectric ($1381.2) and the absorption refrigerator ($1387.4). The researchers finally concluded that the VC refrigerator was the most energy efficient and cheaper unit followed by the thermoelectric and the absorption refrigeration.

3. CASE STUDY

Authors designed and developed an experimental thermoelectric refrigerator (Fig.2.) with a refrigeration space of 1Liter capacity with outer casing of MS sheet and for thermal insulation a polyurethane foam sheet has been provided inside the box to prevent reversal of heat flow. A thin cupper sheet (0.4mm) has been fixed inside the box for uniform distribution of temperature.

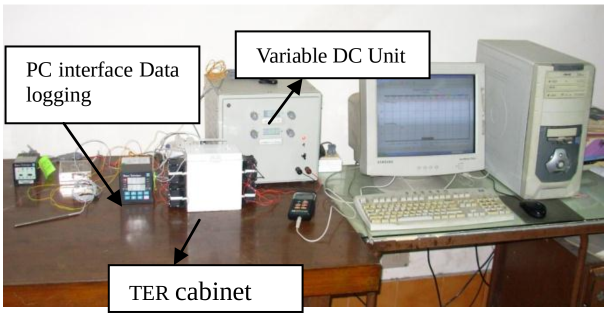

Fig.2. Photograph of developed thermoelectric refrigeration cabinet with computer interface data logging system

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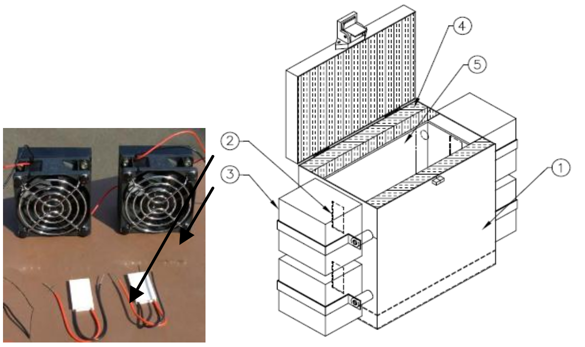

Fig.3. Schematic Diagram of developed thermoelectric refrigeration cabinet (1) Outer casing (2) Peltier Module (3) Heat sink fan assembly (4) PUF Insulation sheet (5) Cupper lining

Four numbers of Supercool make thermoelectric cooling modules (I_{max}=3.9A, V_{max}= 7.8V & Q_{max}=19W) (Fig.3.) were selected on the basis of active heat and passive heat removal from thermoelectric refrigeration cabinet. Active heat load is the heat dissipated by the mass being cooled and calculated by using equation (5).

The passive heat load is the heat loss due to convection & conduction of enclosed thermoelectric cabinet and calculated by using equation (6).

$$Q_{active} = \frac{mC_p \Delta T}{dt} \quad (5)$$

$$Q_{passive} = \frac{A\Delta T}{\left(\frac{X}{k} + \frac{1}{h}\right)} \quad (6)$$

Cold side of TEM mounted on refrigeration cabinet and hot side of module was fixed with heat sink. A black anodized heat sink fan assembly (Fig.3.) with thermal resistance of 0.50 ^{o}C/W has been used for each module to enhance the heat removal rate.

The heat sink has been selected on the basis of experimentally evaluated thermal resistance. The thermal resistance has been calculated as.

$$R_{th} = \frac{T_h - T_a}{Q_h} \quad (7)$$

$$Q_h = Q_a + Q_p + Q_{TEM} \quad (8)$$

A variable DC power supply unit has been used for precise control of DC voltage supplied to TEM. For online performance measurement of developed thermoelectric refrigeration system an 8-Channel data acquisition system (Make: Nippon Technologies, Model No: UNSC-08µ) with PT-100 temperature sensors and humidity sensor has been used.

The performance of single TEM has been evaluated at variable input electrical current conditions ($0.25I_{maxi}$, $0.5I_{maxi}$ & $0.75I_{maxi}$) and at forced air convection condition for heat dissipation from hot side of TEM.

The experimental result (Fig.4.) shows that at input electrical current condition $0.5I_{maxi}$ and at forced air convection condition the temperature reduction at cold side of module with respect to ambient at 30^{o}C was maximum.

With these optimized operating condition ($I=0.5I_{maxi}$ and at forced air convection) experiments were conducted for performance evaluation of developed experimental thermoelectric refrigeration cabinet without any heat load inside cabinet and with 50 ml, 75 ml & 100 ml of water inside refrigeration space and results (Fig.5.) shows a temperature reduction of 11^{o}C without any heat load and 9^{o}C with 100 ml of water in refrigeration space at 23^{o}C ambient temperature in first 30 minutes. The COP of thermoelectric refrigeration cabinet has been calculated for given operating conditions and it has been found 0.1 for 100 ml heat load condition.

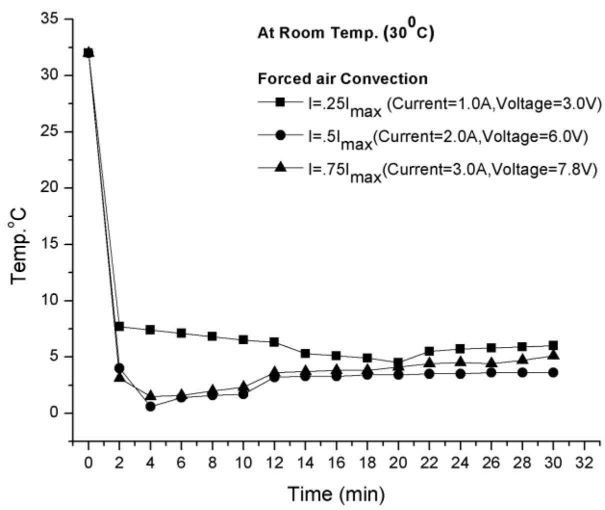

Fig.4. Cooling performances of single thermoelectric module

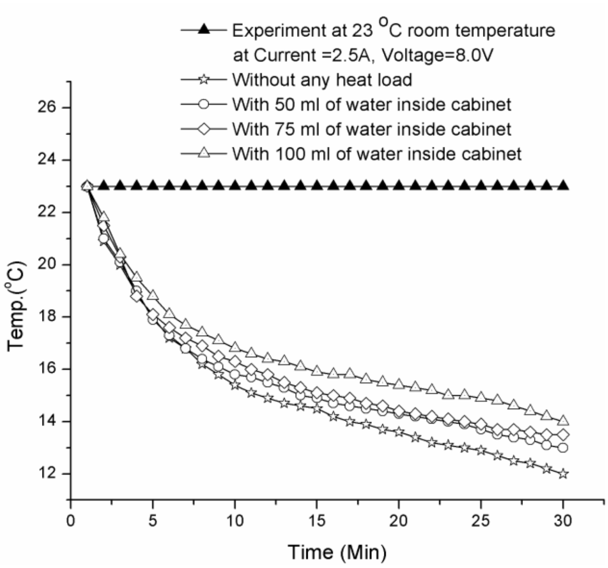

Fig.5. Experimental result of developed thermoelectric TER system

4. CONCLUSION

The research effort made by different researchers for design and development of novel thermoelectric refrigeration and space conditioning systems has been thoroughly reviewed in this paper. Also the advantages and cost-effectiveness offered by thermoelectric cooling system over conventional cooling system have been explained. A temperature reduction of 11°C without any heat load and 9°C with 100 ml of water in refrigeration space at 23°C ambient temperature in first 30 minutes has been experimentally found at optimized operating conditions. The calculated COP of developed experimental thermoelectric refrigeration cabinet was 0.1. The available literature shows that thermoelectric cooling systems are generally only around 5–15% as efficient compared to 40–60% achieved by conventional compression cooling system. This is basically limited by figure of merit of thermoelectric material and efficiency of heat exchange system. Continuous efforts are given by researchers for development of higher figure of merit thermoelectric materials may provide a potential commercial use of thermoelectric refrigeration and space conditioning system. Also compatibility of thermoelectric cooling systems with solar energy made them more useful and appropriate for environment protection.

5. ACKNOWLEDGEMENTS

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NOMENCLATURE

A Area of refrigeration cabinet exposed to air (m^2)
COP Coefficient of performance
C_p Heat capacity at constant pressure ($J/kg.k$)
DC Direct Current
h Overall heat transfer coefficient ($w/m^2\ ^o k$)
I Electric Current (Ampere)
I_{maxi} Maximum Electric Current (Ampere)
K Device thermal conductance (W/K)
k Thermal conductivity of insulation ($w/m\ ^o k$)
m Mass of liquid (Kg)
PV Photo voltaic
Q_c Rate of heat absorbed at cold junction (W)
Q_h Total heat to be removed by TEM (W)
Q_{TEM} Heat generated by TEM (W)
R Device Electrical Resistance (Ω)
R_{th} Thermal resistance of heat sink ($^\circ C/w$)
R&AC Refrigeration and Air Conditioning

TEC Thermoelectric cooler
TEM Thermoelectric Module
TER Thermoelectric refrigerator
T_h Hot Junction temperature, Kelvin (^oC)
T_c Cold Junction temperature, Kelvin (^oC)
T_a Ambient temperature (^oC)
V Voltage (V)
VC Vapour compression
W Electrical Power (W)
X Thickness of insulation (m)
Z Figure of merit (1/K)
ΔT Temperature difference (^oC)
α_{pn} The difference between the absolute Seebeck coefficient of p and n material (V/K)
ρ Thermoelectric material Electrical Resistivity (Ω.m)
λ Thermoelectric material Thermal conductivity W/(m.K)
α Thermoelectric material Seebeck coefficient, (V/K)

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