Construction and characterization of a solar refrigeration system based on nano-graphene

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Abstract. In this present work, we designed and fabricated a solar refrigeration system with increase in its performance compared to present refrigeration system by using different components (solar cell and Peltier module). The construction of the Peltier module was done using nano- graphene composite and its thermoelectric property was utilized for making the hot and cold junctions. A graphene composite material monolith was synthesized using solid state fabrication techniques and this constituted the junction of the Peltier module. A maximum coefficient of performance (COP) of 8.86 was achieved. ZT factor of graphene composite thermoelectric material can be further increased through modification in processing techniques and defect engineering. This will in turn increase the refrigeration COP further.

Keywords: graphene; Peltier; composite; hot junction; cold junction, coefficient of performance.

1. Introduction
Refrigeration is a process in which work is done on a system to transfer heat from cold body to hot body to generate cooling effect. It helps to maintain the temperature of certain space at a sub-ambient temperature. Heat is rejected from the system to the surroundings and is driven by a mechanical device. Refrigeration helps in storing of food products and preservation of medicine. Another variation is air conditioning employed in hot and humid places. Solar refrigeration system \([1,2]\) uses electricity directly produced from solar radiation using photovoltaic cell or solar collectors. Use of this will be more widespread with the decrease of fossil fuels and higher pollution levels.

The most widely used refrigerators and systems employ the conventional vapor compression cycle due to its high COP (~3-4). These systems use a liquefiable vapor as the refrigerant and require mechanical power for driving the compressor, which is usually provided electrically. However, these systems are now less attractive because the chlorofluorocarbons (CFCs) refrigerants have a high ozone depletion potential (ODP), high global warming potential (GWP), high consumption of electrical energy, producing greenhouse gases and other pollutants. Thermoelectric devices can be used for cooling purposes and this is called thermoelectric refrigeration. Thermoelectric Refrigeration (TER) or Thermoelectric cooler provides cooling effect by Peltier effect as opposed to ‘vapor compression cycle’ or the ‘gas compression cycle’. The applications for thermoelectric cooler can span different areas and industries. A thermoelectric cooler (TEC) is a semiconductor composed of an electronic component which transforms electrical energy into a temperature gradient. The TEC consists of one or more thermoelectric couples.

The coefficient of performance (COP) of compression refrigerators decreases with the decrease in its capacity. Therefore, when it is necessary to design a low-capacity refrigerator, TER is always
preferable. Also, better control over the space temperature is the major advantage of the Thermoelectric refrigerator. Researchers over the world are constantly striving for new materials for advanced thermoelectric energy conversion applications and to make existing thermoelements/materials perform better. S.B. Rifat [3] has studied thermoelectric refrigeration with use of bismuth telluride.

Large temperature differentials (up to 130 °C) can be achieved by multistage (cascade) series with the lowest temperature about -100 °C. Lifetime of this system is about 100,000 hours and can withstand harsh environments. Manoj Kumar Rawat [4], designed and developed 1 litre thermoelectric refrigeration system. Cooling is achieved by using four thermoelectric cooling modules (Q_{max}=19 W) and a heat sink fan assembly (R_{th}=0.50 °C/W) for each thermoelectric module. A no-load temperature reduction of 11 °C and reduction of 9 °C with load has been realized. The COP was 0.1. Sabah A. Abdulwahab [5], developed thermoelectric system using fins for use in arid conditions. The design uses 10 thermoelectric modules. John C. Bass [6] has studied the low COP of 1-D thermoelectric modules using “multilayer quantum wells” which increased the COP by four to five times.

Materials such as Bi₂Te₃ and Bi₂Se₃ have ZT, between 0.8 and 1.0. Nanostructuring these materials to produce a layered doped superlattice structure of alternating Bi₂Te₃ and Sb₂Te₃ layers results in ZT of 2.4 at room temperature [7,8]. Heremans [9] (2008) studied ZT of thallium-doped lead telluride alloy (PbTe) with a value of 1.5 at 773 K. Snyder [10] reported ZT~1.4 at 750 K in sodium-doped PbTe, and ZT~1.8 at 850 K in sodium-doped PbTe_{1-x}Se_{x} alloy. A heat to electricity conversion ratio of 15 to 20 percent was shown in PbTe, with a ZT of 2.2 [11]. Layered Ca₃Co₄O₉ demonstrated ZT values of 1.4–2.7 at 900 K. Recently, oxide thermoelectrics such as ZnO, MnO₂, and NbO₂ showed higher ZT values [12,13,14,15].CNT’s (carbon nanotubes) have proven to be good thermoelectric materials. Hick showed that 1-D conductors or quantum wires have high performance. The ZT value for 1-D Bi₂Te₃ nanomaterials is 2.6, which is much higher than that of the 2-D (ZT = 2.5) and 3-D (ZT = 0.5) materials [16]. Graphene has high electrical conductivity but its thermal conductivity is high, limiting its ZT. Using oxygen plasma treatment, ZT of graphene doubled twice to 2.6 corresponding to increase in defect density from 0.04 to 2.5 [2,17].

In this present work, we designed and fabricated a solar refrigeration system with increase in its performance compared to present refrigeration system by using different components (solar cell and Peltier module). The construction of the Peltier module was done using nano-graphene composite and its thermoelectric property was utilized for making the hot and cold junctions. A graphene composite material monolith was synthesized using solid state fabrication techniques and this constituted the junction of the Peltier module. A maximum coefficient of performance (COP) of 8.86 was achieved.

2. Materials and Methods

Graphene nano-powder was procured from Ad-Nano Technologies, Shimoga, India. The graphene was mixed with other constituents to gather in the fixed proportions [i.e graphene -7% (0.54 g) + graphite powder (Alfa Aesar) - 30% (2.4 g) + polyvinyl alcohol powder (Fisher Scientific) - 63% (5.04 g) + ferric chloride powder (Fisher Scientific) - 0.1M (16.22 g) + pyrrole (Fisher Scientific) 0.1M (2.24 ml) + water (7 ml)]. After mixing, the obtained mixture was poured into the cylindrical mould made up of galvanized iron (GI) sheet which has a diameter of 22 mm and length of 40 mm. Then it was pressed gently by applying small amount of pressure and the mould was left to set for 2-3 hours. Then the mould was opened and the solid-state composites of graphene were ready (Refer Figure 1).

The graphene powder was subjected to Raman spectra analysis at MNCF (Micro and Nano characterization facility), Indian Institute of Science Bangalore. The temperature of hot junction and cold junction was measured with the help of standard thermocouple and solar power output was measured using voltage-current meter.

Two identical sized pellets were prepared and kept back-to-back with a 5 mm gap in between. A Nichrome coil was inserted in the gap and connected to a voltage source. This constituted the hot junction. The rear side of the pellets was kept in proximity to a water-cooled jacket and this constituted the cold junction. The positive and negative voltage outputs of a typical poly-Si solar module was connected to the hot and cold junctions respectively.
3. Results and Discussion
Figure 2 shows the Raman spectra of the nano-graphene. The G band, D band and 2D band are observed at wavenumbers 1590, 1367 and 2762 cm\(^{-1}\) respectively. The presence of a strong D band allows for suitable defect engineering of the nano-graphene such that the ZT factor can be modulated. Figure 3 shows the guarded plate setup for arrangement of the hot and cold Peltier junctions.

In Figure 3, the specimen mentioned is the Peltier module. In place of guarded hot plate, Nichrome wire was used. Nichrome wire was firmly anchored between the two specimens i.e. Peltier modules, which constituted the hot junction (Figure 4). The Nichrome wire was connected to the 12-volt battery for power source to make the hot junction. The two opposite sides of that specimen constituted the cold junction. To maintain the cold junction, cold water was circulated through pipes, which was fixed with the cold junction and pump was used to inject the cold water into the pipes. Insulation was provided to this system to restrict the heat transfer with the help of polystyrene. The Peltier module in this system was then connected to the solar panels of different output power to perform refrigeration process. The positive terminal of solar panel was connected to the hot junction and negative terminal to the cold junction (Figure 5).
Figure 3. Guarded plate setup.

Figure 4. Arrangement of the hot and cold junctions
Three solar panels of different output power (10 W, 20 W and 30 W) were used as a power source to the Peltier module to perform the refrigeration process. At a time, one solar panel was connected to the Peltier module and readings of temperature of hot junction and cold junction was measured with the help of thermocouple and noted (Table 1). The corresponding power input by solar panel was also measured.

Table 1. Observation table for hot and cold junction.

| POWER (Watts) | HOT JUNCTION TEMPERATURE \( (T_h) \) | COLD JUNCTION TEMPERATURE \( (T_c) \) |
|---------------|----------------------------------|-------------------------------|
| 10            | 57                               | 24.2                          |
| 20            | 58.3                             | 25.4                          |
| 30            | 59.3                             | 26.7                          |

It is known that:

\[
\text{COP} = \frac{Q}{W} \tag{1}
\]

Or \( \text{COP}_{\text{cooling}} = \frac{Q_C}{Q_H - Q_C} = \frac{T_C}{T_H - T_C} \) \tag{2}

where \( Q \) and \( W \) are heat rejected and work done. \( T_c \) and \( T_h \) are temperature of cold and hot junction respectively.

By substituting the value of \( T_H \) and \( T_C \) in the above COP equation, the COP of Peltier module at different input power was determined which is listed below in the table 2.
Table 2. Variation of COP and input power (from the solar panel).

| POWER (Watts) | COP   |
|--------------|-------|
| 10           | 8.79  |
| 20           | 8.82  |
| 30           | 8.86  |

The COP obtained using Peltier module made up of composites of graphene is around 8 to 9 (Figure 6) which is very efficient compared to present refrigeration systems (COP of 3-4). So if we increase the proportion of graphene in the composites of graphene and perform defect engineering of graphene, then COP of thermoelectric refrigeration system can be further improved.

Figure 6. Variation of COP versus input power.

4. Conclusions
The graphene composite junction electrodes were prepared using standard powder compaction techniques. The graphene was mixed with other conducting constituents such as polyvinyl alcohol and polypyrrole (in-situ polymerized with ferric chloride) so as to improve the thermophysical properties. The graphene electrodes were characterized for their Raman signature and defect peaks. The G band, D band and 2D band are observed at wavenumbers 1590, 1367 and 2762 cm\(^{-1}\) respectively. They were subsequently assembled into a Peltier device using hot and cold junction setups. Junction measurements showed that they have good potential to form an efficient Peltier device. When connected to polysilicon solar panels, this system displayed reasonably high coefficient of performance (8.86), which can be further optimized by adjusting proportion of graphene in the composites as well as defect engineering of the graphene. Such a system has the potential to replace the present refrigeration system since it would be compact, pollution free and more efficient with less cost.

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