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Full Length Research Paper

Performance of Calcium Chloride- Ammonia Adsorption Refrigeration System

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ABSTRACT

An experimental study on the performance of calcium chloride-ammonia adsorption system is described. A single bed water cooled condenser adsorption refrigerator prototype, which utilises calcium chloride-ammonia pair has been developed and tested in the laboratory. Experiments have been conducted for desorption temperatures of 100 ℃ with desorption time varying from 1 to 4 hours. An electric tape heater and a timer were used to perform the experiments. The adsorption temperature profile, adsorption rate and prototype performance have been analysed and discussed. The tested heating and desorption temperature of 100 ℃ and heating and desorption time of 1 to 4 hours was able to create a cooling effect of the cold chamber of the prototype of between -0.8 to 8.3 °C, which is adequate for vaccine storage requirement of 2 to 8 ℃. The estimated Coefficient of Performance of the system ranges between 0.025 and 0. 076.

Keywords: *Adsorption, Ammonia, Calcium chloride, Refrigeration.*

INTRODUCTION

Significant implications to the environment such as ozone layer depletion, global warming and huge electrical energy consumption associated with the use of conventional halogen-based refrigeration systems have made scientists search for environmental friendly refrigerating technologies (Anupam *et al.*, 2016). Many rural areas of developing countries lack access to grid electricity. The International Energy Agency (IEA, 2020) reported that more than 15% of the world's population lacked access to electricity in the year 2015. Among them 57% live in Sub-Saharan Africa (Allouhi *et al.*, 2016). Among the important applications of refrigeration systems are preservation of food products and preservation of vaccines and medicines. The United Nations Food and Agriculture Organisation (FAO) estimated that 32 % of all food produced in the world was wasted in the year 2009 (Lipinski *et al.*, 2013). To keep vaccines at appropriate temperatures of +2 °C to +8 °C is main problem in the rural areas that are without grid electricity (WHO, 2006). Water-ammonia kerosene and gas-driven absorption refrigerators have been used to store vaccines. However, they do not meet the standards established by WHO on performance, quality and safety of the system (McCarney *et al.*, 2013). Batteries are needed to power photovoltaic (PV) cooling systems (Tina and Grasso, 2014).

Batteries live shorter than refrigerators, implying extra costs. Also, PV system have low possibility of being manufactured in most developing countries (Anyanwu and Ezekwe, 2003, Axaopoulos and Theodoridis, 2009).

Adsorption refrigeration systems can utilize low temperature waste heat or renewable energy sources like solar thermal energy to produce cooling effect (El-Sharkawy *et al*., 2008). Also, the use of heat generated by burning agricultural waste or biomass in general is possible, in the remote parts of developing countries or islands, where conventional cooling is difficult (Tamainot-Telto *et al*., 2009, Ullah *et al*., 2013). Adsorption refrigerators use clean and renewable energy resource, operate with environmentally harmless refrigerants and can be manufactured with locally available resources (Ullah *et al*., 2013, Allouhi *et al*., 2015). Several adsorption refrigeration prototypes have been reported for different application ranging from ice making, cooling of food products and vaccines, air conditioning and for hybrid systems of hot water and ice making. On ice making application, activated carbon-methanol pair (Boubakri *et al*., 1992, Li *et al*., 2002), monolithic carbon-ammonia pair (Tamainot-Telto and Critoph, 1997) and compound adsorbent of activated carbon and $CaCl_2$- ammonia pair (Lu *et al*., 2006) have been reported. Silica gel-water (Hildbrand *et al*., 2004, Bouzeffour and Khelidj, 2016, Brites *et al*., 2016), activated carbon-ethanol (Frazzica *et al*., 2016) and activated carbon-methanol (Anyanwu and Ezekwe, 2003, Lemmini and Errougani, 2005, Allouhi *et al*., 2016) were among the reported adsorption pairs in food products and vaccines storage applications. The AQSOA-FAM-Z02-water (Vasta *et al*., 2012), Silica gel-water (Kubota *et al*., 2008, Xia *et al*., 2009, Magnetto *et al*., 2011, Alahmer *et al*., 2016) and carbon-ammonia (Critoph *et al*., 2000) were used in air conditioning applications. Wang *et al*. (2000) used activated carbon-methanol pair for a hybrid system to produce ice hot water supply for domestic use.

The performance of adsorption refrigeration systems is measured by the Coefficient of Performance (COP). The highest cycle COP of 0.83 was reported on a system employing composites of silica gel and chloride-water pair (Askalany *et al*., 2013). Boubakri *et al*. (1992) reported a solar COP from 0.08 to 0.12 for activated carbon-methanol pair, ice makers with the production of 5.2 kg of ice of temperature between -15°C and -5°C a day. The COP of 0.120 and Specific Cooling Power (SCP) of 60 W/kg-carbon were reported for improved, monolithic carbon-ammonia ice making machine by Tamainot-Telto and Critoph (1997). Lu *et al*. (2006) reported improved performance from 161.2 W/kg and 0.12 to 770.4 W/kg and 0.39 for SCP and COP, respectively, by using compound adsorbent of activated carbon and $CaCl_2$-ammonia for ice maker for fishing boat driven by waste heat from exhaust and solar ice maker driven by a solar water heater. Gross solar cooling COPs of 0.10-0.25 were reported for silica gel-water pair using cylindrical tubes adsorbed and a 2 m^2 double glazed flat-plate solar collector with air-cooled condenser (Hildbrand *et al*., 2004). Frazzica *et al*. (2016) reported activated carbon-ethanol pair SCP of 95 W/kg and 50 W/kg and COPs of 0.09 to 0.11 for air conditioning and refrigeration cycles, respectively. Bouzeffour and Khelidj (2016) presented results of solar COP of 0.083 to 0.09 for silica gel-water pair, with a global irradiance of 773-837 W/m^2/day, maximum adsorbent bed temperatures of 95-117°C from total energy received by solar collector of 18 MJ/m^2/day to provide +5°C to +8°C as evaporator temperatures.

Anyanwu and Ezekwe (2003) presented results for activated carbon-methanol adsorption cycle with overall COPs ranging between 0.056-0.093 for the cycle and 0.007-0.015 including the solar systems respectively for evaporator temperatures 1.0-8.5°C. This temperature range is recommended for drugs, fruits and vegetables with preservation temperatures in the ranges of 4-16°C. Lemmini and Errougani (2005) presented performance of a solar powered adsorption refrigerator using activated carbon AC35-methanol pair, which produced cold air of 0 to -5°C with COP of 0.05-0.08 for an irradiation of 12,000-27,000 kJ/m^2/day and a daily mean ambient temperature of 14-18 °C. Magnetto *et al*. (2011) demonstrated the concept of a waste heat driven adsorption cooling system using silica gel-water pair for comfort cooling purposes in vehicles. The unit produced 2 kW of chilling power with a COP of 0.4. Xia *et al*. (2009) presented silica gel-water adsorption chiller driven by hot water of 60-90 °C, which produced a cooling power of 8.70 kW and COP of 0.39 for a heat source of 82.5°C, cooling water of 30.4 °C and chilled water outlet temperature of 12 °C. Critoph *et al*. (2000) presented a laboratory carbon-ammonia adsorption prototype refrigerator with heating power input of 1.130 kW, cooling power of 0.5 kW, COP of 0.44 and SCP of 0.180 kW/kg-carbon.

In this study performance of adsorption refrigeration system of $CaCl_2$-ammonia pair has been investigated experimentally. Calcium chloride is among the metal chlorides adsorbents, which features large adsorption capacity with ammonia adsorbate, 1 mol of calcium chloride can adsorb 8 mol of ammonia (N'Tsoukpoe *et al*., 2015). The boiling point of ammonia is lower than -34°C so that it can be used for sub-zero temperature applications. The resulting refrigerator works under conditions of positive pressure which is a feature of the simpler manufacturing techniques required for the system (Critoph, 1989). Therefore, the main objective of the study is to investigate the performance characteristics of the adsorption refrigeration prototype using $CaCl_2$-ammonia pair for possible use in vaccine storage in off grid location. The laboratory prototype has been manufactured at the Department of Mechanical and Industrial Engineering, University of Dar es Salaam. The experiment was conducted to measure the cold temperature attained by the adsorption system, energy consumption and hence the evaluation of the coefficient of performance of the prototype.

MATERIALS AND METHODS

The Basic Adsorption Refrigeration Cycle

The basic adsorption refrigeration cycle is shown in Figure 1. It involves four basic steps; a, b, c and d as follows (Zhong, 2006).

(a) Heating and pressurizing: At this stage the adsorbent contains a large concentration of refrigerant. The adsorbent bed receives heat, which causes an increase of temperature and pressure as well. The mass in the generator is considered to remain constant until the condensing pressure is reached.

(b) Heating and desorption: The adsorbent bed continues receiving heat while it is connected to the condenser, thus the condenser pressure prevails within the system. Further increase in the adsorbent temperature induces desorption of the refrigerant vapour and the vapour condenses in the condenser. The concentration of refrigerant decrease as the temperature increases from the lower to the upper generating temperatures.

(c) Cooling and depressurisation: The adsorbent bed is cooled, which induces a change in pressure from condensing to evaporation pressure. The mass in the generator is considered to remain constant until the evaporating pressure is reached.

(d) Cooling and adsorption: The adsorption bed is cooled while connected to the evaporator, thus the evaporator pressure prevails within the system. The adsorbent temperature continues decreasing, which induces adsorption of the refrigerant vapour that is adsorbed in the adsorption bed. This adsorbed vapour is vaporised in the evaporator with the evaporator heat being supplied by the heat source at lower temperature. The concentration increases as the temperature decreases from initial adsorption to final adsorption temperature.

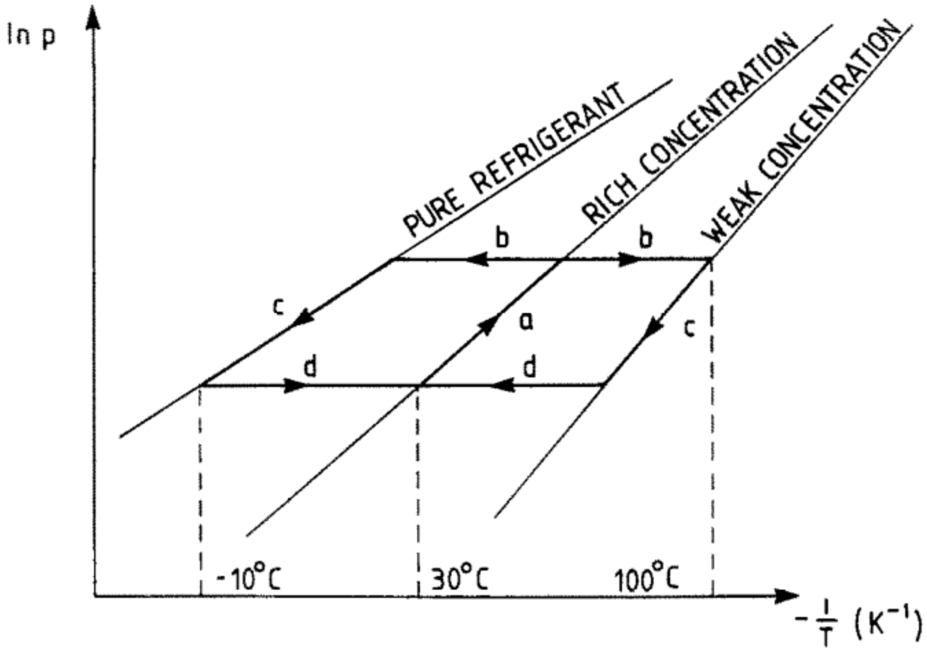
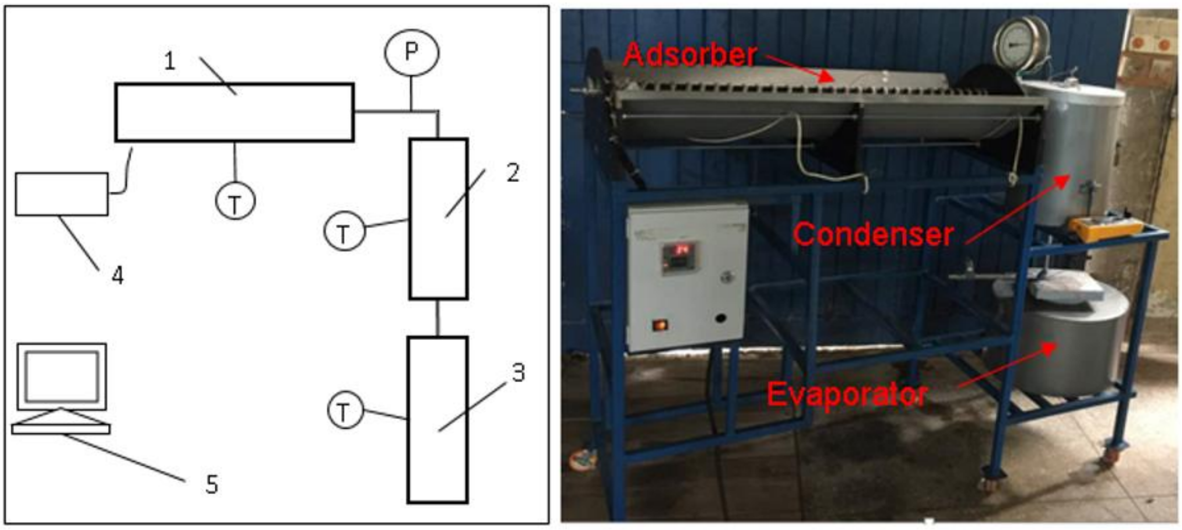


Figure 1: The Basic Adsorption Refrigeration Cycle (Critoph, 1989)

The Prototype Description

The adsorption refrigerator laboratory prototype (Figure 2) consists of the adsorber, which contains the adsorbent-adsorbate pair of calcium chloride-ammonia; the water-cooled condenser; and the evaporator, which contains the cold chamber; an electric tape heater and controller; connecting pipeline and affiliated parts. The adsorbent bed was heated by a temperature controlled electric tape heater thermocoax isopad IT-20. A water-cooled condenser with capacity of 36 litre of water was used, while the cold chamber was filled up with 0.5 litre of water. The thermocouple wires K-type were installed to record adsorber temperature, condenser water temperature, cold chamber water temperature and ambient temperature.

The adsorption refrigeration cycle is made up of two processes, adsorption refrigeration process and heating desorption process (Wang *et al.*, 2009). At low temperatures, adsorbent adsorbs refrigerant evaporating in the evaporator. Liquid refrigerant evaporates by absorbing heat from the refrigerator cold box. Thus, the refrigeration occurs until the adsorbent is saturated. The adsorber rich with adsorbed refrigerant is heated and temperature and pressure increase. When the system pressure increases to condensation pressure, the desorbed refrigerant gas condenses in the condenser. The adsorbent will cool down by natural convection, which will also decrease the pressure. The next adsorption refrigeration cycle begins when the pressure is reduced to evaporation pressure.



(a) Schematic (b) Photograph

Key: 1 - Adsorber, 2 - Condenser, 3 - Evaporator, 4 - Temperature Control System, 5 - Data Collection System, P - Pressure Gauge and T - Thermocouples

Figure 2: Experimental Adsorption Refrigeration Unit

Laboratory Testing

The adsorption refrigeration rate was tested at the selected desorption temperature and varying desorption time. Experiments were conducted by varying the desorption time from 1 to 4 hours for the fixed desorption temperature of 100 °C. Adsorber temperature, condenser water temperature, cold chamber water temperature and ambient temperature have been recorded using Pico TC-08 USB Thermocouple Data Logger with Pico Log Data Logging Software. Heat energy supplied by electric tape heater have been measured by using Energy meter PM498 with accuracy of +/- 3% of the measured values. The programmable timer switch AX300 was used to switch the electric heater.

The Coefficient of Performance, COP was estimated by the equation (1).

$$COP = \frac{qev}{qs} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

Where, qs is measured heat energy supplied by electric tape heater, qev is cooling energy attained at the evaporator cold chamber which estimated by using equation (2).

$$qev = mw.c.\Delta Tw + mi.L + mi.ci.\Delta Ti \quad \ldots\ldots\ldots \quad (2)$$

Where, mw is mass of water in cold chamber in kg, c is specific heat capacity of water, 4.187 kJ/kg.K, ΔTw is water temperature change in K, mi is mass of ice in kg, L is latent heat of fusion of water, 334 kJ/kg, ci is the specific heat capacity of ice, 2.108 kJ/kg.K and ΔTi is temperature change on ice in K (Engineering ToolBox, 2003).

RESULTS AND DISCUSSIONS

Adsorption Temperature Profile and Adsorption Rate

Figure 3 shows the adsorption refrigeration temperature profile for adsorber, condenser, evaporator cold chamber and the ambient temperature. In the heating desorption zone, the adsorber temperature was increased from the ambient temperature to the desorption temperature of around 100 °C. The condenser temperature increases as it condenses the desorbed ammonia vapour. This temperature is maintained for 3 hours and the heater is switched off to allow the cooling of the adsorber.

In the cooling adsorption zone, the adsorber is being cooled by natural convection and the temperature drop as well as the pressure. When adsorber temperature cools to around 65 °C, the adsorption begins, the liquid ammonia evaporates in the evaporator, which causes a temperature drop in the cold chamber. This process will continue until the adsorbent is saturated with the ammonia or all the liquid ammonia is evaporated.

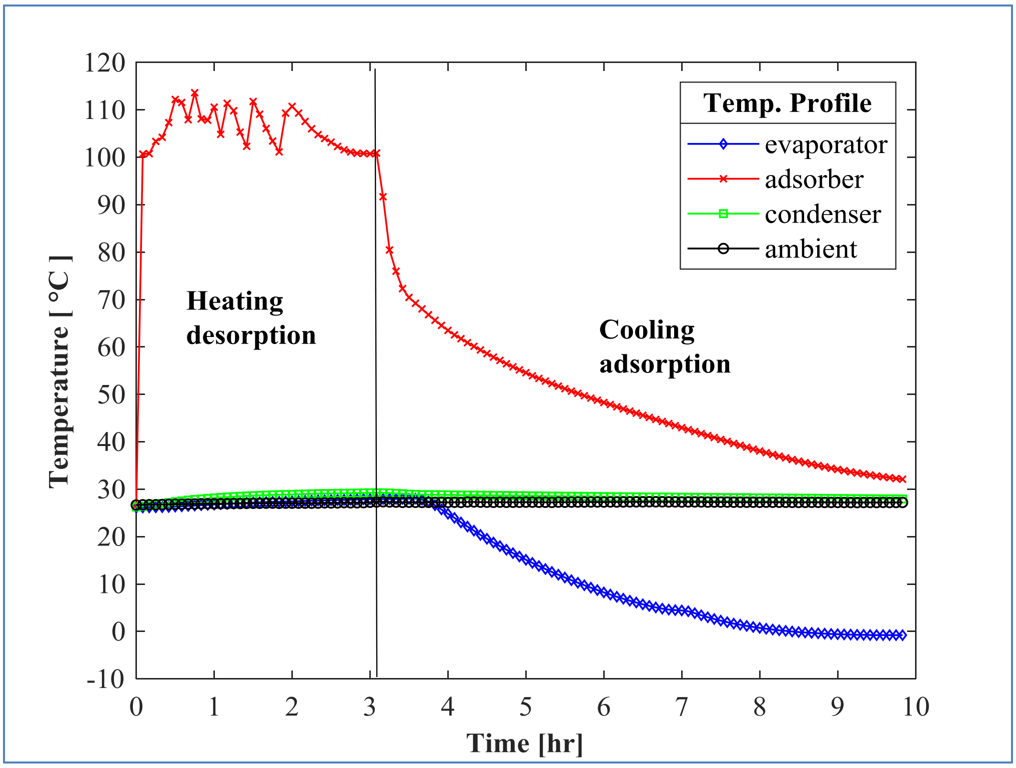


Figure 3: Temperature Profile of the Adsorption Refrigeration Prototype

Figure 4 shows the variation of temperature of the cold chamber with adsorption time for heating desorption times ranging from 1 to 4 hour of $CaCl_2$ and the ammonia pair. The evaporation temperature decreases rapidly at the beginning of the adsorption refrigeration process and then the rate decreases steadily. Lower temperatures of the cold chamber were attained with longer desorption time. Desorption time of three hours seems to be the optimum for this case.

Performance of the Adsorption Refrigerator Prototype

Figure 5 shows the variation of heat energy supplied with heating desorption time. The energy supplied has increased constantly from 1 hour to 3 hours, and thereafter decreased as the amount of the ammonia being adsorbed decreased.

Figure 6 show the variation of cooling effect obtained at the cold chamber of the evaporator with desorption time, estimated by using equation (2). Maximum cooling effect was obtained at the heating desorption time of 3 hours. Increasing heating beyond 3 hours caused an increase of condenser temperature and pressure. As a result, less amount of ammonia was desorbed and therefore less ammonia was available for evaporation during adsorption.

Figure 7 shows the variation of minimum attained cold chamber temperatures and COP with heating desorption time for the same heating desorption temperature. For the tested heating desorption temperature of 100 °C and heating desorption times ranging from 1 to 4 hours, the cold chamber of the prototype obtained temperatures ranging from -0.8 to 8.3 °C, which is within the recommended vaccine storage requirement of 2 to 8 °C (WHO, 2006). By using equation (1), the COP of the system ranges was calculated and found to range from 0.025 to 0.076. The low values of COP may be attributed by agglomeration and swelling phenomena, which lead to problems of low permeability and poor mass-transfer performance of adsorbents (Wang *et al.*, 2014). Wang *et al.* (2016) suggested the use of composite adsorbent of $CaCl_2$ with a porous medium like activated carbon (AC) and expanded natural graphite as solution for the agglomeration and swelling phenomena.

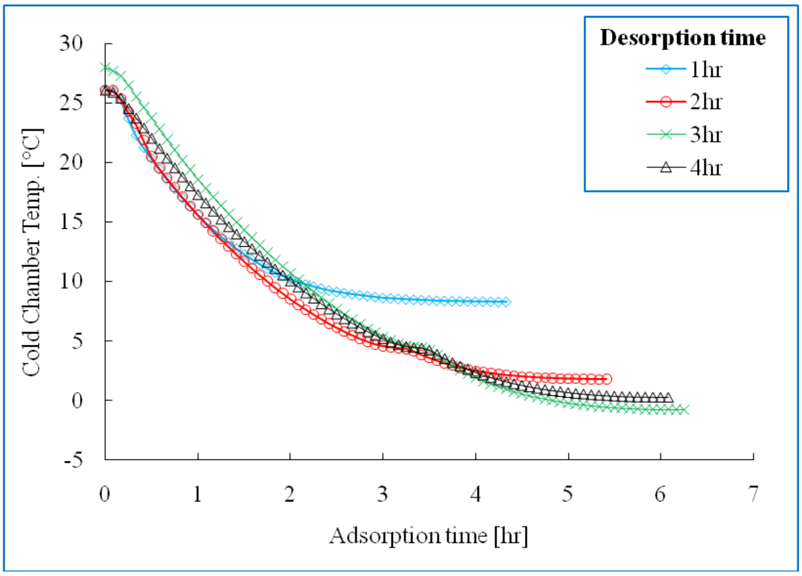


Figure 4: Adsorption Refrigeration Rate for Heating Desorption Temperature of 100 °C

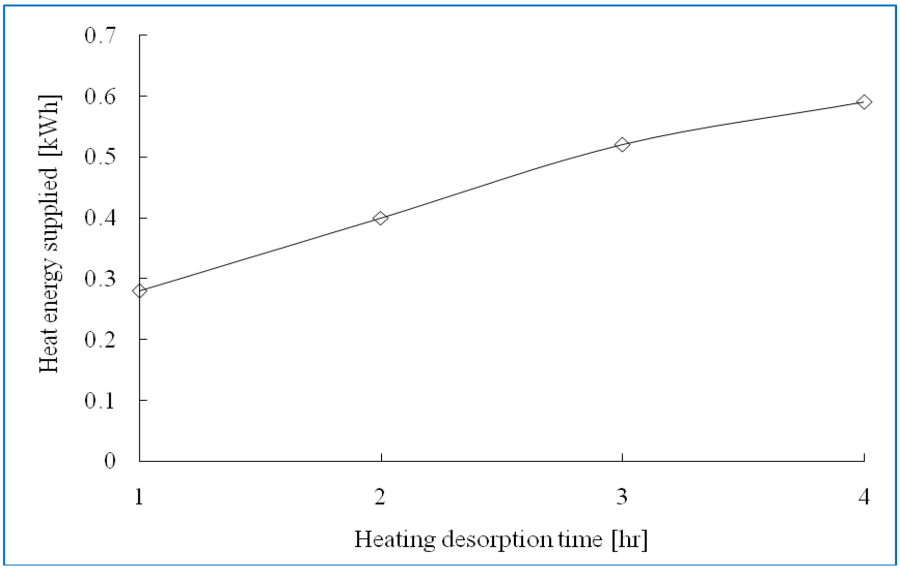


Figure 5: Heat Energy Supplied to Adsorption Refrigeration Prototype

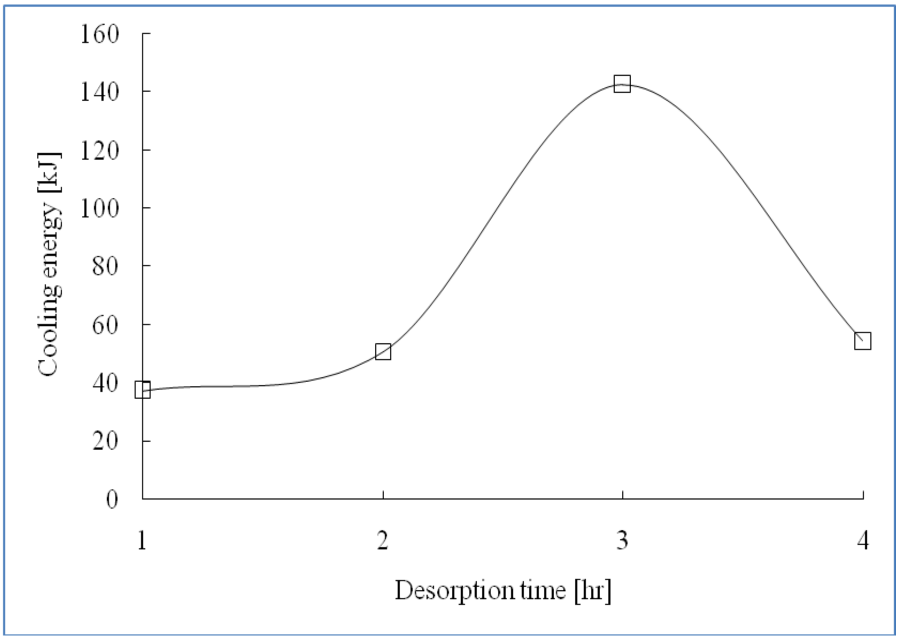


Figure 6: Cooling Energy Obtained at Cold Chamber of Evaporator

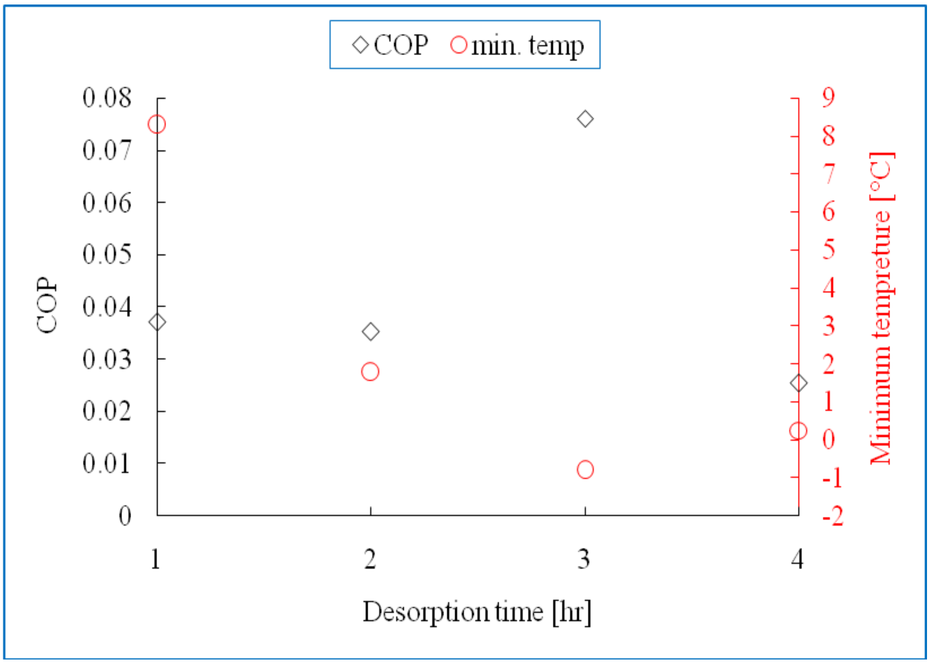


Figure 7: COP and Minimum Attained Temperature of the Cold Chamber

CONCLUSION

Adsorption refrigeration systems have shown great potential to meet cooling needs in off grid areas. The tested laboratory adsorption prototype attained temperatures ranging from -0.8 to 8.3 °C, which are within the recommended range for storage of vaccines. Such low temperatures could be attained by using low temperature heat sources of less than 100 °C, which can be obtained by using flat plate solar thermal collectors. Also, the use of heat generated by burning agricultural waste or biomass in general is possible, in the remote parts of developing countries or islands where conventional cooling is difficult. The COP of the adsorption system is very low compared with that of conventional vapour compression refrigeration system. However, adsorption refrigerators use clean and renewable energy resource that comes at little or no costs, operate with environmentally harmless refrigerants and can be manufactured with locally available resources.

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