EXPERIMENTAL AND LIFE CYCLE ANALYSIS OF A SOLAR THERMAL ADSORPTION REFRIGERATION (STAR) USING ETHANOL - ACTIVATED CARBON

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EXPERIMENTAL AND LIFE CYCLE ANALYSIS OF A SOLAR THERMAL ADSORPTION REFRIGERATION (STAR) USING ETHANOL - ACTIVATED CARBON

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ABSTRACT

EXPERIMENTAL AND LIFE CYCLE ANALYSIS OF A SOLAR THERMAL ADSORPTION REFRIGERATION (STAR) USING ETHANOL - ACTIVATED CARBON

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The off-grid location and unreliable electricity supply to medical clinics in remote parts of India make it difficult to safely store vaccines and other medications using traditional refrigeration systems. The Engineers in Technical Humanitarian Opportunities of Service-learning (ETHOS) program at the University of Dayton, in collaboration with Solar Alternative and Associated Programmes (SAAP) of Patna India, are developing a novel refrigeration system which works on the principle of solar thermal adsorption. This refrigeration system does not require electricity for operation and uses safe, environmentally benign and locally available adsorption pair of ethanol-activated carbon. A bench-scale prototype was developed at the University of Dayton using ethanol-activated carbon as working pair which can generate evaporative temperatures between 2°C and 8°C.
The existing horizontally oriented system can achieve targeted refrigeration temperatures (2-8°C) during the adsorption cycle and ethanol can be desorbed from the activated carbon during desorption. However, the horizontal geometry inhibited the return of liquid ethanol to the evaporation chamber. A new vertical oriented bench scale system was built to addresses the limitation of the original prototype. The effects of desorption heating temperature, desorption time duration, double activation of activated carbon on evaporative cooling, and possible decomposition of ethanol during desorption were analyzed. Experimental results suggested better desorption happens at elevated temperature (90-125°C) and most of the desorption happens in the first 1-2 hours of heating the adsorbent bed. The high pressure on the evaporator side for multiple adsorption-desorption process, and analysis of GC/MS of desorbed ethanol obtained from the analytical chemist showed possible decomposition of ethanol. The ethanol decomposition prevented multiple cycle operation of the system. The use of double activation technique of the activated carbon helped to achieve as low as -12.7°C evaporator temperature in the first adsorption process. However, no adsorptive cooling was obtained in multiple cycle. However, activated carbon prepared at high temperature 800°C on inert condition showed initial pressure condition on evaporator and activated carbon side after first cycle of adsorption-desorption. This suggest multiple adsorptive cooling can be achieved on multiple cycle operation by using activated carbon prepared at high temperature on inert condition.
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<tr>
<td>STAR</td>
<td>Solar Thermal Adsorption Refrigeration</td>
</tr>
<tr>
<td>GWG</td>
<td>Green House Gas</td>
</tr>
<tr>
<td>GWP</td>
<td>Global Warming Potential</td>
</tr>
<tr>
<td>CFC</td>
<td>Chlorofluorocarbon</td>
</tr>
<tr>
<td>HCFC</td>
<td>Hydrochlorofluorocarbon</td>
</tr>
<tr>
<td>HFC</td>
<td>Hydrofluorocarbon</td>
</tr>
<tr>
<td>COP</td>
<td>Coefficient of Performance</td>
</tr>
<tr>
<td>P</td>
<td>Pressure</td>
</tr>
<tr>
<td>T. O</td>
<td>Toaster Oven</td>
</tr>
<tr>
<td>GC</td>
<td>Gas Chromatography</td>
</tr>
<tr>
<td>MS</td>
<td>Mass Spectroscopy</td>
</tr>
<tr>
<td>LCA</td>
<td>Life Cycle Analysis</td>
</tr>
<tr>
<td>LCI</td>
<td>Life Cycle Inventory</td>
</tr>
<tr>
<td>BOM</td>
<td>Bills of Material</td>
</tr>
<tr>
<td>TRACI</td>
<td>Tools for Reduction and Assessment of Chemicals and other Environmental Impacts</td>
</tr>
</tbody>
</table>
CHAPTER 1
INTRODUCTION

1.1 Introduction to Refrigeration

Refrigeration and air conditioning have grown from a luxury to necessity and have contributed in many ways to the quality of life. Refrigeration has made it possible to process, preserve, transport fresh food longer and to keep medications from spoiling. The vapor compression refrigeration system is most commonly used in domestic and commercial refrigerators, large-scale warehouses for chilled or frozen storage, industrial services, and plants.

Vapor compression refrigeration uses a circulating refrigerant fluid to absorb and remove heat from refrigerator and freezer compartments. Vapor compression refrigerating systems have four components: a compressor, a condenser, an expansion valve (or a throttle valve) and an evaporator. The refrigerant at low pressure and low-temperature liquid is converted to vapor in the evaporator by absorbing heat from the refrigerated space. The refrigerant fluid is driven by the compressor, which compresses the low pressure and low-temperature vapor coming from the evaporator into a high temperature and high-pressure vapor. The compressor uses electrical power for operation. The vapor is condensed in the condenser by giving off heat to surrounding environment, typically with cooling water or cooling air. The condensed liquid refrigerant is reduced in pressure by passing through as the expansion valve. This provides the input to the
evaporator and completes the refrigeration cycle. The cycle is called as vapor compression cycle because the vapors of refrigerant are compressed in the compressor. The refrigerant flows continuously through vapor compression cycle, extracting heat from the refrigerated space and making refrigeration possible.

Different refrigerants are used for different conditions and applications. The early or first generation (1830-1930’s) refrigerants include carbon dioxide, ammonia, sulfur dioxide, diethyl ether and methyl chloride (Pearson 2003). The second generation (1931-1990’s) refrigerants include chlorofluorocarbons (CFCs) hydrochlorofluorocarbons (HCFCs), hydrofluorocarbons (HFCs), ammonia and water. The third generation (1991-2010’s) refrigerants include HCFCs, HFCs, hydrocarbons, ammonia, and water (James M. Clam 2016). The fourth generation (2010 - ) refrigerants currently in use include difluoromethane, tetrafluoroethene, ammonia, carbon dioxide, isobutane, propane, propylene, and others (Pavkovic 2013). For decades, vapor compression refrigerators typically used refrigerants such as chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), or hydrofluorocarbons (HFCs) for refrigeration. In the 1980s, it was discovered that the emission of CFCs and HCFCs from refrigerators (during operation or after their useful life) were depleting the ozone layer (W. Goetzler et al. 2014).

The atmosphere of earth is divided into layers called troposphere, stratosphere, mesosphere, and thermosphere. The ozone layer is a region of earth’s stratosphere with high concentrations of ozone (O$_3$). The ozone layer absorbs most of the biologically harmful sun’s ultraviolet (UV) rays coming to earth’s surface. The depletion of the ozone layer allows harmful UV rays to come into the earth surface. The UV rays can cause skin
diseases and cataract in human beings, affects physiological and developmental processes of plants, effects marine ecosystem, naturally occurring biopolymers and biogeochemical cycles (United States Environmental Protection Agency [EPA] 2016b). The ozone layer can be depleted by free radical catalyst like nitric oxide (NO), nitrous oxide (N\textsubscript{2}O), hydroxyl (OH), atomic chlorine (Cl), and atomic bromine (Br). There are natural resources for such free radicals, but the concentration of chlorine and bromine has increased significantly in recent years (U.S Energy Information Administration 2011). Scientific evidence has shown that human-produced chemicals are responsible for accelerating depletion of the ozone layer (Basics 2008). The ozone-depleting substances (ODS) that release chlorine and bromine include CFCs, HCFCs, carbon tetrachloride, methyl chloroform, halons and methyl bromide (United States Environmental Protection Agency [EPA] 2016a).

The Vienna Convention for the Protection of Ozone Layer (1985) and several protocols like the Montreal Protocol (1987) and the Kyoto Protocol (1997) were established to phase out or reduce the emission of such refrigerants (Fernandes et al. 2014a),(Ullah, Saidur, Ping, and Akikur 2013). The use of CFCs and HCFCs were phased out, although their replacement HFCs are currently in use.

HFCs do not attack ozone layer, but they have high global warming potential (GWP). The earth gets warm due to continuous sun’s energy coming in the form of high-frequency radiation. A delicate balance should be maintained between energy gained and returned to the outer space. Many gases such as CO\textsubscript{2}, methane (CH\textsubscript{4}), nitrous oxide (N\textsubscript{2}O), various hydrocarbons, CFCs, HCFCs, HFCs, etc., are released by mankind due to various agricultural and industrial activities (Venkataramathan and Murthy 2012). These
gases called, greenhouse gases (GHGs), increase the temperature of the earth by absorbing and slowing the rate at which the energy escapes to space. GWP is a measure of how much energy the emissions of one ton of greenhouse gas will absorb over a given time frame relative to the emissions of one ton of carbon dioxide. GWP provides a common unit for comparison of the global warming potential of different gases. HFCs can cause as much as 12,240 times more warming as an equivalent mass of carbon dioxide over a 100-year period (EPA 2010). Even though HFCs are safe from the ozone depletion point of view, they are contributing to the global warming.

The currently proposed phase-down of HFCs refrigerant presents a huge opportunity for non-vapor compression technologies (William Goetzler et al. 2014). Alternative technologies to vapor compression fall into three broad categories: solid-state, electro-mechanical, and thermally driven technologies (William Goetzler et al. 2014). Solid state cooling or thermoelectric cooling are solid state heat pumps that work on the Peltier effect. When an electric current is passed through a circuit consisting of two different conductor junctions, a cooling effect is produced in one junction and heating effect in another junction. Such a cooling effect produced is called the Peltier effect. A solid-state system consists of the semiconductor-based bi-metal junction, heat sink, and direct current power.

Electro-mechanical technologies are electrically driven technologies that alter the phase of a working fluid to pump the heat. The electrically driven heat pumps like Brayton-cycle heat pump, evaporative cooling, membrane heat pump fall into this category. Thermally driven technologies use thermal energy as the primary input to drive a heat pump. Technologies like absorption heat pump, adsorption heat pump, Stirling
heat pump and desiccant heat pump are primary thermally driven technologies. While there are uncertainties about ultimate potentials of such technologies, they offer the most promise in terms of environmental impact and future prospect.

The benefits of refrigeration are widely enjoyed in industrialized countries. However, despite its broad success, conventional refrigeration has not reached many developing and underdeveloped parts of the world, where the electric grid is unreliable, and the residents cannot afford a local photovoltaic system (Hu 1998b). Solar refrigeration has the potential to improve the quality of life living in such areas. There are two ways to achieve solar refrigeration by means of solar energy. The first way is to convert solar energy to electricity by means of photovoltaic cells and run the conventional refrigerator. This refrigerator uses environment unfriendly refrigerant and solar electric makes it expensive. The second is using solar thermal radiation directly for refrigeration with the help of a chemical adsorption pair. Solar thermal refrigeration technologies have advantages of removing harmful effects of a conventional refrigerator, coincides with the necessity for peak demand of cooling and maximum solar radiation availability (Fernandes et al. 2014a). This system helps to promote significant primary energy saving in comparison to mechanical vapor compression refrigeration, it has a simple control system, vibration less, noiseless, and with lower environmental impacts (Choudhury et al. 2013). Adsorptive refrigeration is a thermally driven system, in which the conventional mechanical compressor of the common vapor compression cycle used in most refrigerators is replaced by an adsorbent, which drives the flow of the working fluid.
1.1.1 Adsorption Process

Adsorption is a chemical or physical process involving two components: an adsorbate and an adsorbent. The adsorbate is a working fluid and the adsorbent is a porous solid with a large surface area. Physical adsorption or physisorption happens when the force of attraction existing between adsorbate and adsorbent are weak Van der Waal forces of attraction (Sumathy, Yeung, and Yong 2003). It has a low enthalpy of adsorption and takes place at low temperature. When the force of attraction between adsorbate and adsorbent are chemical forces of attraction, the process is called chemical adsorption or chemisorption. It has a high enthalpy of adsorption.

1.1.2 Desorption Process

An adsorbed species present on adsorbent after adsorption process at low temperature may remain almost indefinitely in that state. Desorption is a thermal process of applying heat to the adsorbent so that the adsorbate adsorbed on adsorbent may desorb from the surface and return to the gas phase.

1.1.3 Adsorptive Refrigerator

Adsorptive refrigerators work on a basic physical adsorption cycle which consists of two phases:

a) Adsorbent cooling with adsorption process, which results in refrigerant evaporation inside evaporator producing a cooling effect.

b) Adsorbent heating with desorption process, which results in refrigerant condensation at a heat exchanger.
1.1.4 Adsorptive Refrigerator Operation

Figure 1 shows the basic adsorption refrigeration cycle. The refrigerator usually consists of three main components; a solid adsorbent bed, a condenser and an evaporator. When valves connecting evaporator to adsorbent bed are opened, the working fluid vaporizes, producing a cooling effect. Initially, the valves are closed. Both the adsorbent bed and evaporator are at low vacuum pressures and temperatures and are filled with refrigerant.

Due to the latent heat of vaporization, the working fluid on liquid stage vaporizes into vapor stage. Latent heat of vaporization is a physical property of a substance and is defined as the heat required to change phase from liquid to vapor. The phase change during vaporization is an endothermic process, and so the working fluid absorbs energy to vaporize. Thus, vaporization of working fluid extracts the heat from evaporator producing a cooling effect.

The vaporized working fluid is adsorbed onto the adsorbent surface. Once the adsorbent bed is close to the saturation point, the valve between the evaporator and the absorber is closed and solar heat is applied to adsorbent bed, thus releasing the adsorbed working fluid vapor. The vapors are collected and condensed in the condenser before returning to the evaporator. Once this cycle is completed the heat on the adsorbent bed is removed until the adsorption conditions are established, then the valve between the evaporator and the adsorption bed is reopened. The daily cycling of this process is the basis of intermittent adsorption refrigeration which uses the natural cycling of temperature throughout a day.
1.1.5 Adsorption Pair

There are several adsorbent-adsorbate working pairs for adsorption refrigeration systems. The most commonly used working pairs are zeolite-water, silica gel-water, activated carbon-methanol, activated carbon-ammonia and activated carbon-ethanol (Sur and Das 2010). The selection of the adsorption pair depends upon certain desirable characteristics of their constituents: thermodynamic and chemical properties, affinity to each other, physical properties, costs, and availability. The choice of adsorbate depends upon properties:

1) Evaporation temperature below 0°C;
2) High latent heat of vaporization and low specific volume;
3) Thermally stable with an adsorbent at a various temperature range of operation;
4) Non-corrosive, non-toxic and non-flammable;
5) Low saturation pressure;
6) Low cost, easy to manufacture and widely available (Alghoul et al. 2007).
The important considerations for selection of adsorbent are:

1) Higher adsorption of adsorbate at low temperature to yield good coefficient of performance (COP);

2) Desorption of adsorbate when heated;

3) No deterioration with age or use;

4) Non-corrosive, non-toxic and non-flammable;

5) Low cost, easy to manufacture and widely available (Alghoul et al. 2007).

1.1.6 Selecting a Sustainable Adsorption Pair

The working fluids ammonia, methanol, and water are used with an absorbent like zeolite, silica gel, and activated carbon as adsorption pairs for the adsorptive refrigerator.

Table 1 shows different physical properties like the latent heat of vaporization, triple point, normal boiling point and molecular weight of working fluids.

<table>
<thead>
<tr>
<th>Working fluids</th>
<th>Latent heat of vaporization (kJ/kg)</th>
<th>Triple point (°C)</th>
<th>Normal boiling point (°C)</th>
<th>Molecular weight (g/mole)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ammonia</td>
<td>1368</td>
<td>-77.76</td>
<td>-34</td>
<td>17</td>
</tr>
<tr>
<td>Methanol</td>
<td>1160</td>
<td>-97.7</td>
<td>65</td>
<td>32</td>
</tr>
<tr>
<td>Water</td>
<td>2258</td>
<td>0.01</td>
<td>100</td>
<td>18</td>
</tr>
<tr>
<td>Ethanol</td>
<td>846</td>
<td>-123</td>
<td>79</td>
<td>46</td>
</tr>
</tbody>
</table>

Ammonia, methanol, and water have the relatively high latent heat of vaporization and low specific volume (10.3 m³/kg) (Fernandes et al. 2014b). The triple point for ammonia and methanol is low but ammonia is toxic and corrosive, methanol is toxic, and both are difficult to manufacture in impoverished and developing countries. Although water is non-toxic and has a high triple point, and it cannot be used for freezing
purposes because it solidifies at 0°C. Ethanol has very low triple point temperature, the average latent heat of vaporization, relatively nontoxic, and can be produced in developing countries. Activated carbon is cheaper than zeolite and silica gel, it can be produced with properties to suit specific applications by varying the activation time and temperature, and can be manufactured in developing countries of origin and use (Critoph 1988). So, adsorption pair of ethanol - activated carbon makes a good candidate for a sustainable adsorption-based refrigeration system.

1.1.7 Activated Carbon-Ethanol Adsorption Pair

Ethanol is environmentally friendly, non-toxic, has a relatively high vapor pressure even at low-temperature levels and its low freezing temperature makes it a better alternative as sustainable working fluid. The highest Coefficient of Performance (COP) value achieved by an adsorption cooling system using adsorption pair activated carbon-ethanol is 0.8 (Critoph 1988). Thus, activated carbon-ethanol adsorption pair makes a good choice of refrigerant in terms of environmental and system performance.

1.2 Literature Review

The earliest trace of the adsorption refrigeration phenomenon was found in the Faraday’s lab in 1848, where the cooling capacity could be generated when silver chloride adsorbed on ammonia (Goyal et al. 2016). Adsorption cycles for refrigeration were used in the early 1900s before the advent of mechanical compression refrigerators (Critoph 1989). Later, G. E. Hulse in 1920, proposed a refrigeration system using silica gel-sulfur dioxide as adsorption pair for storing food in a train (R. Z. Wang, Wang, and Wu 2014). In 1940-1945, the adsorption refrigeration system using calcium chloride and ammonia as working pair was used for food storage in the train from London to
Liverpool which was driven by steam at 100 °C (Goyal et al. 2016). The development of both the compressor and the absorption cycle led to the demise of these adsorption systems. In the 1970s, the energy crisis offered a great chance for the development of the alternative refrigeration technology as the adsorption refrigeration system is driven by a low-grade heat source such as waste heat and solar energy (Hodgson 2008). The interest in adsorption has resurfaced also by the need for environmentally friendly refrigeration systems. Since then, researchers worldwide are working to improve the performance of adsorption cooling systems to overcome its current technical and economic issues.

The adsorption refrigeration system differs in performance, specific cooling capacity, and COP with a different type of adsorption pairs, climatic condition of operation and system parameters (pressure, temperature, and quantity of refrigerants). Different research works related to the evaluation of adsorption and properties (physical and chemical) of the working pairs, development of predictive models of their behavior when working under different conditions and the study of different cycles have been performed. In this literature review, development of adsorptive refrigerator using different working pair are briefly covered.

1.2.1 Development of Zeolite-Water Adsorption Pair Refrigerator

Zeolites are crystalline microporous alumina silicate materials. Zeolite is widely used in industrial applications for hydration processes. Initially, Pons and Grenier (1981) used natural zeolite-water as adsorption pair to produce refrigerating effect, and the coefficient of performance for the system was 0.1 (Z. F. Li and Sumathy 1999). Zhu et al. (1992) used natural zeolite-water as adsorption pair in adsorption refrigerator for producing chilled water using exhaust gas from a diesel engine as a heat source. Ismail
Solmus et al. (2011) investigated a thermally driven adsorption cooling unit using natural zeolite-water as the adsorption pair at various evaporator temperatures. The COP of the system was 0.25, the maximum average volumetric cooling power density and mass-specific cooling power density per kg adsorbent of the cooling unit was 5.2 kW/m³ and 7 W/kg, respectively. Later on, (Myat et al. 2013) tested zeolite FAM Z01-water in the adsorption cooling system driven by low-grade waste heat source extracted from power plant’s exhaust. The result showed the coefficient of performance (COP) of the system could be as high as 0.48 while the waste heat source temperature was as low as 55°C. A. Li et al. (2014) presented an environment-friendly adsorption chiller using Zeolite FAM Z01-water adsorption pair. Experiments indicated that the cooling capacity increased with heat input over the supplied hot water temperatures and a peak cooling capacity was found at 65-85°C. The optimum hot water temperature for most efficient operation was 65°C.

The adsorption heat for the zeolite-water pair is about 3000-4000 kJ/kg. Due to large adsorption heat and high desorption temperature, the performance of zeolite-water is more energy intensive. For the same cooling capacity, high adsorption heat needs to be removed and high desorption temperature is required. The zeolite-water pair can have higher COP and specific cooling power (SCP) if the desorption temperature is higher than 200°C (Ramos et al. 2003). The disadvantage of zeolite-water pair is: water makes it impossible to produce evaporation temperature below 0°C and the high-temperature heat source is required for desorption.
1.2.2 Development of Activated Carbon-Methanol Adsorption Pair Refrigerator

Activated carbon can be produced from a large variety of raw materials like wood, coal, coconut shell, char and other. Normal carbon can be activated by physical or chemical activation or combination of both. The large internal surface area, pore volume, good chemical stability and wide availability makes it a good choice as an adsorbent (Ceyhan et al. 2013).

Activated carbon-methanol is one of the most common working pairs. (Bentayeb, Lemmini, and Guilleminot 1995) introduced an adsorptive refrigerator using activated carbon-methanol pairs as a function of climatic condition to Moroccan climate and were challenged with the problem of freezing in the winter. A study on a solar-powered adsorption refrigerator using activated carbon-methanol by (Anyanwu, Oteh, and Ogueke 2001) revealed solar refrigerator performances depend upon absorptivity of the collector surface, adsorbent thermal conductivity and heat transfer coefficient at adsorbent.

Various types of solar ice maker adsorption system were analyzed at Shanghai Jiao Tong University. The normal solar ice maker using activated carbon-methanol could produce 5-7 kg-ice/m² solar collector with solar COP from 0.11 to 0.13 (R. Wang 2000). An experimental analysis on the hybrid solar water heater and ice maker using same adsorption pair with 2 m² vacuum solar collector could produce 65 kg 85-100°C hot water and 5 kg of ice or keep 150-liter cold box with a temperature lower than 5°C for 50 hours (R. Wang 2000). (Khattab 2006) analyzed a simple structure, low cost solar powered adsorption refrigeration module with adsorption pair of local domestic type charcoal from Egypt and methanol. The system was able to produce 6.9-9.4 kg of ice per
m² solar collector and net solar COP was 0.136 and 0.159 for cold and hot climate respectively.

Later on, (Lemmini and Errougani 2007) built and experimented with a solar adsorption refrigerator using activated carbon-methanol adsorption pair. The results showed that the refrigerator could give good performance in Rabat, Morocco. The solar coefficient of performance (COP) (cooling energy/solar energy) was between 5% and 8% for an irradiation between 12,000 and 28,000 kJ/m² and a daily mean ambient temperature around 20°C. A similar experiment was carried by (Hamdih 2009) using activated carbon-methanol adsorption pair. The result showed minimum temperature for the refrigerator was 9°C while the ambient temperature was 26°C with the gross cycle coefficient of performance, \( \text{COP} = 0.688 \). (El-Sharkawy et al. 2009) investigated the adsorption of methanol on Maxsorb III activated carbon powder and Tsurumi activated charcoal by using Dubinin-Raduskevich (D-R) model. The experimental results showed adsorption equilibrium uptake of Maxsorb III/methanol pair (1.03 kg kg⁻¹) higher than that of Tsurumi activated charcoal/methanol pair (0.6 kg kg⁻¹) by about 72% at 15 °C evaporation temperature along with 30 °C adsorption temperature.

Large adsorption quantity and lower adsorption heat of 1800-2000 kJ/kg make activated carbon-methanol pair a good option for adsorptive refrigeration. Low adsorption heat and lower reproducing desorption temperature are beneficial to increase COP of an adsorptive refrigerator. The activated carbon-methanol pair is suitable for low heat application due to the low desorption temperature about 100°C. (Hu 1998a) investigated thermal decomposition of methanol in solar powered adsorption refrigerator. The result showed at desorption temperature of 110°C methanol was decomposing into
dimethyl ether, methoxymethyl methyl ether, and ethanol. Desorption temperature higher than 100°C should be avoided because decomposition of ethanol occurs at higher temperature.

Despite several advantages, toxic nature of methanol makes such system hazardous and decomposition of methanol questions the reliability of this adsorption pair at higher temperature operation.

1.2.3 Development of Silica Gel-Water Adsorption Pair Refrigerator

Silica gel is a granular and porous form of silicon dioxide made synthetically from sodium silicate. Silica gel is commonly used as a desiccant to control humidity and to avoid spoilage and degradation of goods. Silica gel is also paired with water in adsorptive refrigerators. (Boelman, Saha, and Kashiwagi 1995) studied a conventional two-bed silica gel-water adsorption chiller. Experiments were performed with the hot water of 50 °C and the cooling water of 20 °C. The highest experimental value of COP is more than 0.4. The adsorption characteristics of silica gel-water has been studied further by using type A and RD silica gel by (Chua et al. 2002). The adsorption capacity of water vapor with type A and RD silica gel was calculated to be about 0.4 and 0.45 kg/kg respectively. (Chen et al. 2010) experimentally studied a compact silica gel-water adsorption chiller without vacuum valves. The cooling power and COP for the chiller were 9.60 kW and 0.49 respectively, when the average hot water inlet temperature, cooling water inlet temperature, and chilled water outlet temperature were 82.0, 31.6 and 12.3°C, respectively. (Luo, Wang, and Dai 2010) optimized the key operation parameters, such as solar hot water temperature, heating/cooling time, mass recovery time, and chilled water temperature for silica gel-water adsorption refrigerator which was able to
produce a cooling capacity about 66-90 W per m² solar collector under the climatic conditions of daily solar radiation being about 16-21 MJ/m² with COP about 0.1-0.13. (Najeh et al. 2016) studied silica gel-water adsorption chiller experimentally and verified numerically using SIMULINK. COP and refrigeration power of the chiller was 0.62 and 5.64 kW respectively.

The experiments proved that the application of this adsorption system is successful, especially with low-grade heat sources. The adsorption heat for this pair is about 2500 kJ/kg. The performance of silica gel-water adsorption refrigerator is limited by desorption temperature and use of water makes it impossible for producing temperature below 0°C.

### 1.2.4 Development of Ethanol-Activated Carbon Adsorption Pair Refrigerator

Ethanol is used as a refrigerant as it is non-toxic and has a high vapor pressure at low temperature. There is limited research on ethanol-activated carbon adsorption pair refrigerators. (Bidyut Baran Saha et al. 2006) experimentally measured adsorption kinetics of ethanol on pitch-based activated carbon fibers (ACFs) of type A-20 at different adsorption temperatures ranging from 27 to 60 °C. The heat of adsorption was experimentally found to be 1006 kJkg⁻¹. The adsorption isotherms of the ACF (A-20)/ethanol pair for temperatures ranging from 20 to 80 °C and pressures from 0 to 15 kPa data were fitted with the Dubinin-Radushkevich (D-R) equation. The comparison of experimental data and predicted results showed satisfactory agreement. (B B Saha et al. 2007), (B B Saha, Chakraborty, and Koyama 2007) presented the transient modeling for a two-bed, activated carbon fiber (ACF)-ethanol adsorption chiller. The adsorbent utilized low-temperature waste heat sources (60-95°C) with a cooling source at ambient
temperature. The results showed that the system can achieve the optimum COP values for driving source temperature between 80 and 85°C and suitable for low-temperature waste heat recovery with relatively high performance (El-sharkawy et al. 2008) experimentally investigated on activated carbon (Maxsorb III)-ethanol pair for solar powered adsorption cooling using thermogravimetric analyzer (TGA) for adsorption temperature ranging from 20 to 60°C. Dubinin-Astakhov (D-A) was used to correlate experimental data, and the isoteric heat of adsorption was estimated by using the Clausius-Clapeyron equation. The experimental result showed Maxsorb III can adsorb up to 1.2 kg of ethanol per kg of adsorbent and theoretical calculations showed Maxsorb III-ethanol adsorption could achieve a specific cooling effect of about 420 kJ/kg, with an evaporator temperature of 7°C with heat source temperature 80°C. (Habib and Saha 2013) presented a theoretical analysis of the performance of a two bed solar driven activated carbon fiber-ethanol adsorption chiller designed for Malaysian climate. The result showed absorption cycle could achieve a cooling capacity of 12 kW when heat source temperature is 85°C (Uddin et al. 2014) investigated adsorption characteristics of ethanol with activated carbon powders namely parent Maxsorb III and surface treated Maxsorb III with controlled oxygen content. The experiments were conducted within an evaporator temperature range from 14 to 77°C and adsorption temperature between 20 and 80°C. The results showed adsorption capacity of H₂ treated Maxsorb III/ethanol was slightly higher than that of the parent Maxsorb III/ethanol pair, and the KOH-H₂ treated Maxsorb III had the lowest adsorption capacity. The average heat of adsorption of ethanol onto parent Maxsorb III, KOH-H₂ treated Maxsorb III and H₂ treated Maxsorb III was found to be
1002, 963 and 926 kJ/kg, respectively. (Mansouri, Shirazi, and Mclaury 2014) experimentally and numerically investigated adsorption characteristics of ethanol adsorption on pellet size Norit RX3 activated carbon. The adsorption isotherms and kinematics of pellet (length 3 to 12 mm) was measured by dynamic vapor sorption testing and simulated in COMSOL Multiphysics. The results showed that increasing the pellet size causes slower adsorption kinetics and increasing the adsorption temperature leads to a reduction in adsorption capacity.

(Brancato et al. 2015) tested activated carbon and synthesized porous composite of LiBr inside a silica gel as an adsorbent material with ethanol as a refrigerant. The COP was calculated under typical working boundary conditions for refrigeration and air conditioning applications. The composite material showed the highest thermodynamic performances of 0.64-0.72 and the best carbonaceous material reached comparable COP value with composite. (Frazzica et al. 2016) tested on novel small-scale adsorption refrigerator prototype based on activated carbon (SRD 1352/3)-ethanol working pair. The experimental performance analysis was carried out by means of the Gravimetric-Large Temperature Jump (G-LTJ) apparatus. The experimental results showed high specific cooling powers (SCPs) of 95 W/kg and 50 W/kg, for air conditioning and refrigeration respectively, while the COP ranged between 0.09 and 0.11

### 1.2.5 Comparison of Methanol-Activated Carbon with Ethanol-Activated Carbon Working Pairs

This section of literature review helps to compare system performance and environmental analysis of adsorption pairs methanol-activated carbon with ethanol-activated carbon for solar thermal adsorption refrigeration. There are a few research
papers which make head to head comparisons of such adsorption pair. (M. Li et al. 2004) carried out an experimental analysis using two different working pairs, one of them activated carbon-methanol and other activated carbon-ethanol in a solar ice maker to determine ice production and refrigerant criteria under similar radiation energy and environmental conditions. The result showed that the performance of an activated carbon-methanol refrigerator is 3-4 times higher than activated carbon-ethanol. Further experimental result showed that ice can be produced by activated carbon-methanol pair, however, no ice was produced with activated carbon-ethanol pair for same operating conditions. The study of intermittent refrigeration phenomenon for solar solid adsorption refrigeration by (M. Li et al. 2005) showed that the performance of ice maker was severely affected by sky cloudy cover, no ice would be obtained if cloudy conditions prevailed for an interval of 3 hours. The research highlighted challenges faced by intermittent refrigerator as unreliable for continuous refrigeration.

(Cui et al. 2005) used an environmentally benign working pair for adsorption refrigeration. The adsorption working pairs: water and ethanol were selected as refrigerants; 13x molecular sieve, silica gel, activated carbon, adsorbent NA and NB (adsorption isotherm of NA and NB were obtained by high vacuum gravimetric method) were selected as adsorbents, and the performance of adsorption working pairs in adsorption refrigeration cycle was studied. The results showed the maximum adsorption capacity of water on adsorbent NA to be 0.7 kg/kg, and the maximum adsorption capacity of ethanol on adsorbent NB to be 0.68 kg/kg, which is three times that of ethanol on activated carbon, the refrigeration capacity of NA-water working pair was 922 kJ/kg, the refrigeration capacity of NB-ethanol was 2.4 times that of activated carbon-methanol,
as environmentally friendly and no public hazard adsorption working pair, NA-H$_2$O and NB-ethanol could substitute activated carbon-methanol in adsorption refrigeration system using low-grade heat source.

Ethanol-activated carbon as a refrigerant is non-toxic, has no impact on the environment and easy to manufacture locally. The improvement in the performance of ethanol-activated carbon can be a good choice over methanol-activated carbon adsorption pair.

1.3 Problem Definition

The remote and off-grid parts of the world have low demand for refrigeration. There are few critical applications such as refrigerating vaccines where the need for the refrigeration is urgent and immediate. The storage of vaccines under proper temperature is very critical for preserving the medicinal value of vaccine. The recommended temperature for safe storage of vaccine is between 2°C and 8°C (Cdc 2016). Many rural health centers in developing countries completely lack electricity, or experience substantial blackouts, making it difficult to safely store vaccines at the recommended temperature. The remote location, the high cost of locally available photovoltaic electricity and lack of resources make conventional refrigeration unreliable.

In 2014, Government of India found only 39.8% of the children in Bihar, India are fully vaccinated (NITI Aayog/Planning Commission 2014). Later in 2015, a survey of 124 Primary Health Centers (PHCs) in Bihar showed only 15% had a one-week supply of vaccines and 60% had no vaccines on site. 25% of vaccine go wasted in India due to lack of cold chain (Sushmi Dey 2016). Lack of refrigeration was a major contributor: of the 124 PHCs, 42 facilities had no electricity and another 31 had no reliable electricity, and
in two facilities with electricity, the ice-lined refrigerator used to store vaccines was not working.

There is need of appropriate technology that uses locally available materials and expertise to implement sustainable, culturally acceptable solutions to engineering problems. Responding to this need, a team of undergraduate and graduate students from the University of Dayton is investigating solar thermal adsorption refrigeration (STAR) as an innovative alternative to conventional refrigeration. The STAR is collaborative efforts of the chemical engineering department, mechanical engineering department and Engineers in Technical Humanitarian Opportunities of Service-learning (ETHOS) program at University of Dayton and Solar Alternatives and Associated Programmes (SAAP), an Indian non-governmental organization, in Patna, India.

This collaborative effort helped in the development of a solar thermal adsorptive refrigerator that uses ethanol/activated carbon as adsorption pair. While there has been a minor success with a prototype in India, a fully working prototype has not been yet achieved. A bench-scale prototype was developed at the University of Dayton using ethanol-activated carbon as working pair. The previous team worked in design, material research, process control, and construction of STAR bench scale system with horizontal orientation. Figure 2 shows horizontal STAR bench-scale system. This system has several elements. The freezer compartment is a yeti cup with a vacuum chamber inside it. Tubing connects the vacuum chamber to the adsorbent bed, which contains activated carbon. The system can be evacuated with a vacuum pump, and a vacuum trap captures ethanol that would otherwise enter the vacuum pump. A series of valves allow the vacuum chamber, the adsorbent bed, and the vacuum trap to be isolated from the system.
When the horizontal prototype is operating, the vacuum chamber contains liquid ethanol under vacuum. At the start of the refrigeration cycle, the valves between the vacuum chamber and the adsorption bed are open. Ethanol vapor flows from the vacuum chamber to the adsorbent bed and adsorbs onto the activated carbon. The jelly jar is used as an adsorbent bed. Ethanol vapor evaporates off the liquid in the vacuum chamber, leading to evaporative cooling of the freezer compartment. During the second stage of the cycle, the valves connecting the vacuum chamber and the adsorption bed are closed, and the adsorption bed is heated by application of heat lamp (each of 200 Watt). The heat lamp acts as a simulation of solar thermal heat from the sun. The applied heat causes desorption of ethanol from the activated carbon, and the pressure inside adsorption bed rises. When this stage is complete, the valves are opened; the ethanol vapors cool and condense as they flow back to the vacuum chamber. This makes the STAR refrigeration...
cycle an intermittent cycle, with adsorption happening one half of day and desorption on another half of day.

The horizontal STAR system can generate evaporative temperatures between 2°C and 8°C. The horizontal system can achieve targeted refrigeration temperatures during adsorption cycle, and the ethanol can be desorbed from the activated carbon during desorption. However, the horizontal geometry inhibits the return of liquid ethanol to the evaporation chamber. No return or less return of ethanol limits the number of cycles that can be performed.

1.4 Objectives

A vertically oriented bench scale system was built to address the limitation of the horizontal prototype. The horizontal system used the jelly jar as an adsorbent bed. Experiments showed that the activated carbon inside the adsorbent bed (jelly jar) was not heated enough for proper desorption. A small test rig was designed for temperature profiling of jelly jar which helped to understand the rate of heat transfer from outer layer to inner layer and then to activated carbon. In previous work on the horizontal system, temperature from the outer layer of the jelly jar was recorded which did not show actual temperature of activated carbon during the adsorption-desorption process. A temperature probe was integrated into the adsorbent bed to record the actual temperature of activated carbon. The heat lamp was used as a source of solar thermal heat. The unregulated heat from heat lamp made it difficult to control desorption temperature. An Arduino based temperature control system was designed and coded to regulate desorption temperature. With the progress on experimental works and results obtained in the process were implemented on the system modification.
The major focus of this thesis is to understand the performance of STAR vertical system on multiple cycle operation. The second half of thesis is about life cycle analysis. The major objectives of this thesis are to:

- Identify effects of temperature, vacuum pressure and desorption time during the desorption process.
- Determine lower and upper limit temperature for desorption of ethanol from activated carbon during desorption.
- Detect possible decomposition of ethanol during desorption process at high desorption temperature.
- Analyze life cycle analysis and environmental impact of the vertically oriented STAR system and make a comparative analysis with the horizontal STAR system and conventional refrigerators.

1.5 Thesis Outline

This thesis consists of five chapters. Chapter one introduces the research topic covered by this thesis. It includes an introduction, literature review, problem definition, and objective of the thesis. The literature review provides reviews of up to date research progress on various adsorption pairs refrigerator.

Chapter two presents experimental design and procedures that is used to investigate the performance of vertical STAR bench-scale system. The detail information will be provided for temperature profiling setup, bench scale desorption test rig, Arduino Uno temperature control system, vertical STAR bench system setup, and current experimental setup.
Chapter three presents experimental results and discussions obtained from experimentation.

Chapter four presents general introduction on life cycle analysis (LCA), literature review on LCA of refrigeration systems, economic and environmental analysis of adsorption systems, and, environmental life cycle analysis, economic, social impact of conventional refrigeration vs STAR system.

Chapter five presents findings from the study on conclusion, and recommendation on the possible future research.
CHAPTER 2

EXPERIMENTAL SETUP AND PROCEDURES

This chapter explains the different types of experimental setups and procedures used in the experimentation. Initially, small sets of experiments were carried out and the results were implemented on the final assembly of the STAR vertical bench system. The experiments on temperature profiling of adsorbent bed were carried out to find an appropriate container. Bench-scale desorption were performed to with the aim of determining lower and upper bounds on the desorption temperature; however, the uncontrolled temperature on the bench scale desorption and initial experiments on vertical system made it difficult to understand effects of particular temperature on desorption process. An Arduino temperature control system was designed and fabricated to regulate the desorption temperature. The code was written in C/C++ format using open source Arduino software. The Arduino temperature control system helps to set the desired temperature of heat lamp, which in turn controls the temperature inside the activated carbon during desorption.

2.1 Temperature Profiling of Adsorbent Bed

A jelly jar is used as adsorption bed in the horizontal STAR system. During desorption, it is difficult to heat the activated carbon to high temperatures on jelly jar, as the jelly jar is made of glass, and poor rate of heat transfer from outer layer to inner layer of the jar was not able to heat activated carbon good enough.
The temperature profiling test setup was designed to run experiments to find an alternative container for the adsorbent bed. The jelly jar is made of glass, and the lid was built by the assembly of a copper flat plate and aluminum and rubber gasket as a sealant. The temperature profiling test setup consists of the following parts: adsorbent bed jelly jar (figure 3 left) or copper tube (figure 3 right), two heat lamps, temperature probes, activated carbon and wooden support structure. The copper tube has two caps at either end, with one a ¼ inch threaded connection and another a closed end. The ¼ inch threaded female type connector provides connection to the ¼ inch male type connector to the tubing system. The diameter of the copper tube is 1 inch, the wall thickness is 0.05 inch and it weighs 243.8 grams. The copper tube was assembled together by with a soldering joint. (See APPENDIX C) Later, a temperature probe was integrated into the copper tube to record the temperature of the activated carbon inside the copper tube.

**Figure 3:** Temperature profiling test setup; jelly jar setup (left) and copper tubing setup (right)

These experiments were carried for a short time duration of 10 to 15 minutes on the jelly jar, as the maximum safe operating temperature limit of the jelly jar was unknown, and prolonged heating of the jelly jar could cause hazards and safety issues. The adsorbent bed was filled with 20 grams of activated carbon (8×16 Mesh size
Charcoal House activated carbon). The temperature probe was attached to the outer layer and activated carbon for copper tube, and on the outer layer, inner layer, and in activated carbon for the jelly jar. The two heat lamps were turned on and temperature of the outer layer, the inner layer, and activated carbon was recorded using Omega HH 147U data logger thermometer into the computer to analyze heat transfer rate.

2.2 Bench Scale Desorption

Desorption is another important step of adsorption refrigeration. During desorption, the adsorbed ethanol on the activated carbon is regenerated by the application of thermal heat. Desorption of ethanol from adsorbed activated carbon makes the process cyclic. The right desorption temperature and time duration of desorption are very crucial to desorb ethanol to make adsorption-desorption cycle. The suitable temperature and time duration at which desorption of ethanol occurs were unknown for the STAR system.

The bench-scale desorption test rig was designed to perform experiments to determine the lower and upper bound desorption temperatures of ethanol from activated carbon, as well as time duration for desorption. The test rig consists of an evaporator, valves and pipe connection, a pressure gauge for vacuum pressure reading, two 200 W heat lamps, copper adsorbent bed with a temperature probe, stand to hold evaporator and wooden frame to support the setup. The glass chamber and copper adsorbent bed were filled with 10 milliliters of ethanol and a varying amount of activated carbon, respectively. The mass of ethanol was constant for all experiments. Dehydrated and undenatured Spectrum 200 proof (99.5% pure) ethanol was used for experimental analysis. Chemi glass 29/42 was used as evaporator and nylon tubing of diameter 10 mm was used as the piping connection. A Pittsburgh 2.5 cubic foot per minute (cfm) vacuum
pump was used to pull the vacuum on the system through the valve between ethanol chamber and pressure gauge. After pulling a vacuum, the adsorption cycle was carried out until all the ethanol has adsorbed to activated carbon. Heat lamps were turned on during desorption process. Desorption cycle was carried out for a limited time with different heating temperatures.

Figure 4: Experimental setup for bench scale desorption; adsorbent bed with lamp (left) and evaporator (right)

Figure 4 shows the experimental setup for bench scale desorption. The temperature of the outer layer of the adsorbent, the temperature of activated carbon inside the bed and the room temperature was recorded using an Omega HH 147U data logger thermometer. The volume of desorbed ethanol and mass of activated carbon after desorption was recorded for all experiments.

2.3 Arduino Based Temperature Control System

The solar heat source was simulated on STAR system by using two heat lamps, each with a capacity of 200W power. When the heat lamps were turned on, the temperature increased sharply to very high temperature. The uncontrolled heat made it difficult to get the desired temperature for heating adsorbent bed. An Arduino based
temperature control system was built to control the temperature of the activated carbon during desorption.

The Arduino based temperature control system was designed and assembled using an Arduino Uno board, thermocouple Type-K, thermocouple amplifier, Alternating Current (A.C) light dimmer module controller board, breadboard, and wires with sockets. The Arduino temperature control system regulates the temperature of the adsorption bed by adjusting the power to the heat lamp.

Arduino board design uses a variety of microprocessors and controllers. The board is equipped with sets of digital and analog input/output (I/O) pins that may be interfaced to various expansion boards and other circuits. The boards feature serial communications interfaces, including Universal Serial Bus (USB), which are used for loading programs from personal computers. The microcontrollers are typically programmed using a dialect of features from the programming languages C and C++. Thermocouple Type-K is a bare wire bead-probe which can measure air or surface temperatures. This thermocouple uses fiberglass braid, so it can be used in high-temperature measurements such as heaters and ovens. There's a small piece of heat shrink at the end to keep the fiberglass from fraying.
Figure 5 shows Arduino Uno R3 (left) and thermocouple K-type (right) used in temperature control system. Thermocouples are very sensitive and need a good amplifier to process the signal. The MAX31855K thermocouple amplifiers were used in this system to interface with a microcontroller. It has a breakout board, a 3.3V regulator with 10uF bypass capacitors and level shifting circuitry, all assembled together. It has a 2pin terminal block for connecting to the thermocouple and pin header to plug into any breadboard.

The A.C phase control circuit (dimming circuit) module contains two tracks with a zero-cross detector for programming the intensity of incandescent lamps, A.C LED dimmable bulbs, heating elements or fan speed controlled through a micro-controller. The triacs are three terminal semiconductor devices for controlling current. The A.C supply was directly connected to one channel and two channel provides regulated current to the heat lamps. The Arduino board was connected using jumper cables. When the temperature rises above the reference temperature Arduino gives the command to A.C light dimmer module board to cut off the supply of electricity; if the temperature is below reference
temperature it turns on the heat lamp. Figure 6 shows amplifier used for the thermocouple before soldering (right) and A.C light dimmer module controller board (left).

Figure 6: Thermocouple amplifier MAX31855 breakout board and A.C light dimmer module controller board (Adafruit)

A breadboard was used for temporary assembly for the circuit. A breadboard is a solderless device for a temporary prototype with electronics and test circuit designs. The board is solderless, so it can be reused. This makes it easier for temporary prototyping and experimenting with circuit design. The breadboard has strips of metal underneath the board and connects the holes on the top of the board. The breadboard consists of plastic with numerous tin-plated phosphor bronze or nickel silver alloy spring clips. The typical solderless breadboard consists of two areas called strips i.e. terminal and bus strips.

- **Terminal or Socket Strips:** This is the main area to hold the most of electronics. All the holes are internally connected in a column in terminal strips. It consists of two sections each with 5 rows and 64 columns.

- **Bus Strips:** This strip provides power to the electronics. All the holes are internally connected in rows in bus strips. It consists of two columns, one for power voltage and other for ground.
Jump wires or jumper are used for connection in-between the holes. Figure 7 shows physical breadboards (right) and holes definition in rows and columns.

**Figure 7:** Breadboard and holes definition (Adafruit & Wiring.org)

### 2.4 Assembly and Working

**Figure 8:** Arduino based temperature control system for heat lamps

Figure 8 shows heat lamps with thermocouples (right) and final assembly of components used in the temperature control system. In this system, the Arduino board is the central controller of every part. The power and commands to the Arduino board are
supplied through the USB of the computer. The Arduino board is controlled by codes which are written in Arduino 1.8.5, an open source C/C++ based software. The channels and points are defined on the codes (See APPENDIX A and B). A.C power is supplied to the two-channel A.C controller board.

The thermocouple type-K is a temperature sensor which is attached to the heat lamp. The real-time temperature of the heat lamp is displayed on the serial monitor on Arduino screen. The real-time temperature of heat lamp can be changed according to the reference temperature. The reference temperature in degree C is the temperature inputs given by the user. According to reference temperature the Arduino system controls the temperature of a heat lamp. This happens by the regulated power supply to the two-heat lamps and maintained by on/off control of the heat lamp. This Arduino based controller maintains the temperature to within 20⁰C of the reference temperature.

2.5 Vertical STAR System Setup

The results from these experiments were incorporated into a vertical prototype. The jelly jar was replaced with copper tube, and power to the heat lamps was controlled by the Arduino system. The vertical STAR system setup was designed and assembled to run adsorption-desorption experiments for the adsorption pair of ethanol with activated carbon.

The setup consists of following parts: glass tube, yeti cup, fabric, nylon tube, two vacuum pressure gauges, heat lamp, vacuum pump, vacuum trap, three ball type valves, elbows, straight and T-connectors, temperature probe and plywood board to support the system. A Chem glass 29/42 tube was used as the evaporator, which contains measured liquid ethanol under vacuum. The Chem glass cap was used as a lid for the glass tube.
DOW Corning high vacuum grease was used to make the connection vacuum proof. The cap has two extruded tube-like openings; both the openings were vacuum greased, and nylon tubes with 12 mm diameter were inserted into the opening and tightened with 12 mm ABA Sweden hose clamps. One of the openings was closed by 12mm nylon cap and another opening was connected to the tube using 12mm to 10mm connector.

Figure 9: Glass tube as ethanol chamber and adsorbent bed made of copper tube; evaporator (left) and adsorbent bed with a temperature probe (right)

Figure 9 (left) shows the assembly of the glass tube, a glass cap, nylon tubes, hose claps and connector as evaporator or ethanol chamber. The 10mm nylon tube was used to make the connection from the evaporator to the adsorbent bed. Three ball type valves, two nylon T’s, and an elbow was used for connecting tube from evaporator to adsorption bed. The adsorbent bed was built by soldering (See Appendix C) copper tube (5 inches long, 1-inch diameter and a wall thickness of 0.05 inch) with two copper caps (1-inch diameter), two brass females type National Pipe Thread Taper (NPT) threaded connector, and K-type temperature probe connection. Figure 9 (right) shows the assembly of copper tube, copper caps, threaded connector and probe as an adsorbent bed.
A vacuum trap was assembled to capture ethanol or activated carbon that would otherwise enter the vacuum pump. The trap consists of a Chem glass tube, Chem glass cap with openings, two 12mm to 10mm reducer connector, a valve, and a T connector. The two openings were vacuum greased, and nylon tubes with 12 mm diameter were inserted into the opening and tightened with 12 mm ABA Sweden hose clamps. The connector (12mm to 10mm) was connected to the tube with diameter 10 mm on either side. The T-connector further connected to the valve (as shown in figure 11) on the one side to release the vacuum and another side to the vertical system for pulling a vacuum. The vacuum trap was used to pull vacuum at the beginning of every experiment.

Figure 10: Vacuum trap

A plywood board was used as a frame to hold the system in a vertical way by using cable ties. Ashcroft analog vacuum pressure gauges were used to take vacuum pressure reading. The gauges can measure vacuum pressure up to -30 inHg with an accuracy of +/- negative 2-3 %. The setup was designed to simulate solar thermal heating using two heat lamps, each with 200-Watt capacity. During desorption, the required energy to adsorbent bed was supplied by heat lamps through heat radiation and
convection from heat lamp surface to the adsorbent bed. Figure 11 shows the final assembly of the vertical system. For the experimental procedure for adsorption-desorption process see Appendix D.

![Figure 11: Complete setup of the vertical system](image)

**2.6 Current Process for the Vertical STAR System**

The experimental setup on the vertical system was changed with the progress of research to make experimental works more effective. The process for the preparation of activated carbon for experimentation and collection of desorbed ethanol was altered. In the previous experiments, activated carbon was activated by heating in a toaster oven. Figure 12 (left) shows double activation process using a toaster oven. This activation process was not good enough to remove impurities and was exposed to air before placing
into the adsorbent bed. The STAR vertical system does not have a proper condenser to cool off desorbed ethanol vapor during desorption. There are chances of re-adsorption of desorbed ethanol vapor in absence of proper condenser. The need for a condenser was realized with progress on experimental works. The changed process includes additional activation of activated carbon under vacuum and ice cooled evaporator acting as a condenser during the desorption process.

The new procedure consists of an additional process for double activation of activated carbon. Initially, the activated carbon is prepared by heating at 150°C in Black Decker toaster oven for 30 minutes. After heating activated carbon for 30 minutes at 150°C in the toaster oven, it is weighed. The weighed activated carbon is placed on adsorbent bed using a funnel. The adsorbent bed is then connected to the tubing. In addition to the heating activated carbon in the toaster oven, changed the experimental setup for preparing activated carbon consists of an adsorbent bed, activated carbon, temperature-controlled heat lamp, vacuum pressure gauge and tubing assembly with valves as shown in figure 12 (right).

**Figure 12:** Experimental setup for double activation of activated carbon
With help of the vacuum trap and vacuum pump, the vacuum is pulled out until the pressure gauge reading shows -28 inHg towards the adsorbent bed. The valve toward vacuum trap is closed after pulling a vacuum. The adsorbent bed is heated at 300°C (heat lamp temperature) for 30 minutes, and then vacuum is pulled at end on the adsorption side of the apparatus. The adsorbent bed cools to room temperature. Then, the ethanol chamber was connected to the system. The vacuum is pulled on the ethanol side and valve toward the vacuum trap is closed. At this point, the bench scale system is ready to begin adsorptive cooling.

**Figure 13:** Ice cooled evaporator as condenser during desorption process

The adsorption process starts after opening the valve separating ethanol chamber with the activated carbon. The adsorption process is carried for different time duration. During desorption, all the valves connecting the evaporator to the adsorbent bed are opened. Ice is used on the yeti cup to condense the ethanol vapor which is desorbed from
activated carbon from the adsorbent bed (figure 13 shows ice cooled evaporator as condenser). The adsorption cycle was performed till all ethanol was adsorbed onto activated carbon which happened usually in a time interval of 18-20 hours. Desorption is carried for a different time interval. The pressure was recorded at the beginning, middle and end of each experiment cycle. After the final cycle, the volume of ethanol left in the ethanol chamber is measured with a graduated cylinder, and the mass of activated carbon from adsorbent bed is recorded.
CHAPTER 3

EXPERIMENTAL RESULTS AND DISCUSSIONS

This chapter explains experimental results and discussions obtained from the experimentation. The experiments were performed on a bench scale system and a vertical system setup. Temperature profiling helped to identify appropriate alternative container for the activated carbon. The bench-scale desorption experiments also helped to understand the effects of different desorption heating temperatures, system vacuum pressure, and time duration on the desorption of ethanol.

Experiments performed on the vertical system were used to study multiple cycle operation. The effects of system pressure, saturation pressure of ethanol, evaporator temperature during adsorption, desorption heating temperature, and time duration of adsorption-desorption were analyzed. Possible ethanol decomposition at high desorption heating temperatures was studied. Mass spectroscopy of desorbed ethanol samples was used to identify the species formed on ethanol decomposition. Integration of an Arduino Uno temperature controller enabled controlled desorption by controlling the desorption temperature. Experiments using activated carbon by double activation under vacuum and activated carbon prepared by high-temperature heating in a continuous flow of inert gas were also performed.
3.1 Selection of Activated Carbon Container

During the experiments performed by temperature profiling of the activated carbon container, the temperature of the outer layer, the inner layer and activated carbon present on container were recorded. This helped to analyze the heat flow from outer layer to inner layer and then to activated carbon in the container. Temperature profiling of the carbon container helped to analyze the difference on temperature from the outer layer of the adsorbent bed to the inner layer and then to activated carbon present in the container. The placement of heat lamps at various distances from the adsorbent bed helped to vary the temperature range during the experiments.

Figure 14 shows the temperature of outer and inner layer of a jelly jar used to hold activated carbon and temperature of activated carbon inside a jelly jar. Experiments done on the jelly jar showed that within 10 to 15 minutes of heating by the lamps, the temperature of the outer layer of jelly jar increases from room temperature (usually 21-23°C) to about 180°C. The differences in temperature between the outside and inside of the jelly jar surfaces was about 55°C, and between the inside surface of the jelly jar and the activated carbon was about 84°C. This shows that there was good heat transfer from the outer layer of the jelly jar to inner layer but no significant heat transfer from inner layer to the activated carbon in the jelly jar. The jelly jar was not capable of handling such temperature for a long time, and it was not possible to achieve such high solar thermal temperature within short time for actual application.
Figure 14: Temperature of outer, inner layer of the jelly jar and activated carbon inside a jelly jar

An alternative material having high thermal conductivity, such as copper, could solve the problem. Experiments were run on a soldered copper tube using the same bench-scale setup as the jelly jar. During the experiments, the copper tube was heated for a longer duration (1-2 hour) than the jelly jar (10-20 minutes). Figure 15 shows the temperature of the outer layer of the copper tube and the temperature of activated carbon inside the copper tube. Experiments on the copper tube showed a gradual rise in temperature with a greater rate of heat transfer from the outer wall to inner wall, and the temperature difference between the outer wall of the tube and the activated carbon inside the tube was only 1°C.
Figure 15: Temperature of the outer layer and activated carbon inside the copper tube

So, a copper tube was used as the activated carbon container for the remainder of the experiments, as it allowed for gradual rate of heat transfer, better thermal stability, ease of fabrication, and safe operation at high temperature.

3.2 Desorption on Bench Scale Setup

Five experiments were performed on the bench-scale system to understand the desorption process. Each experiment used 10ml of 200 proof anhydrous ethanol and about 20g of activated carbon. During the experiments, the evaporator with 10 ml of ethanol and the activated carbon container with 20g of activated carbon was connected to the experimental setup (Figure 4). A vacuum was pulled, and the adsorption process was carried out. Enough time (usually 18 - 20 hours) was allowed to adsorb all the ethanol
into the activated carbon. During the desorption process, the heat lamps were turned on and the desorbed ethanol was collected in the evaporator.

Table 2 shows five experiments with desorption time duration, desorption temperature, mass of desorbed ethanol, and the system pressure (initial, after desorption, and after system cools down). In experiments 1 and 5, desorption was carried out using low-temperature heating between 80°C to 90°C for 2 - 3 hours. In experiments 2 and 3, desorption was carried out at high temperature; the activated carbon was heated at 122°C for 4 hours in experiment 2, and at 126°C for 2 hours in experiment 3. Desorption in experiment 4 was performed at average temperature heating around 109°C for 2 hours.

<table>
<thead>
<tr>
<th>Experiments</th>
<th>Desorption Temperature (°C)</th>
<th>Initial gauge P before adsorption (in.Hg)</th>
<th>Gauge P after desorption (in.Hg)</th>
<th>Final gauge P after system cools (inHg)</th>
<th>Desorption time (hours)</th>
<th>Mass of desorbed ethanol (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exp 1</td>
<td>84</td>
<td>-28</td>
<td>-23</td>
<td>-27</td>
<td>3.2</td>
<td>0.9</td>
</tr>
<tr>
<td>Exp 2</td>
<td>122</td>
<td>-28</td>
<td>-17.5</td>
<td>-17.5</td>
<td>2.0</td>
<td>2.6</td>
</tr>
<tr>
<td>Exp 3</td>
<td>126</td>
<td>-28</td>
<td>-18</td>
<td>-18</td>
<td>2.0</td>
<td>2.8</td>
</tr>
<tr>
<td>Exp 4</td>
<td>109</td>
<td>-28</td>
<td>-21.5</td>
<td>-21.5</td>
<td>4.3</td>
<td>2.1</td>
</tr>
<tr>
<td>Exp 5</td>
<td>91</td>
<td>-28</td>
<td>-25.5</td>
<td>-27</td>
<td>2.0</td>
<td>1.7</td>
</tr>
</tbody>
</table>
**Figure 16**: Experiments with desorption temperature, the time duration of desorption and volume of ethanol desorbed

Figure 16 shows the various experiments with their desorption temperature, time duration, and volume of ethanol desorbed. Experiments (2, 3, and 4) using high and average desorption temperature showed high desorption of ethanol and experiments (1 and 5) using low desorption temperature showed less ethanol desorption. Experiments 2 and 3 shows that at high desorption temperatures, most of the desorption happens early in the desorption process. The difference of ethanol desorbed at high desorption temperature heat experiments for 4 hours and 2 hours of desorption was only 0.2g. The mass of desorbed ethanol was not significant as compared to the time duration. Thus, we can state that desorption is better at elevated desorption temperatures, and most of the desorption process happens in the early hours of desorption process. These bench scale desorption
experiments also showed the lower bound temperature at which desorption could happen is around 80°C and the upper bound temperature is around 125°C.

During the adsorption process, evaporative cooling and adsorption of ethanol onto activated carbon happens at vacuum pressures near -28 inHg. During desorption, the adsorbent bed is heated to a higher temperature, and so the application of heat increases the pressure of ethanol by ideal gas law effect. In every experiment (1-5) the gauge pressure of the system increased during the desorption process.

![Figure 17: Effects of desorption temperature on gauge pressure of the system](image)

**Figure 17:** Effects of desorption temperature on gauge pressure of the system

Figure 17 shows the effect of temperature on gauge pressure of the system. In the low desorption temperature heating experiments (experiments 1 and 5) heating the activated carbon increased the gauge pressure to -23 inHg and -25.5 inHg respectively; after desorption, the system cooled for 2 hours, and the gauge pressure dropped to -27 inHg in both experiments. The experiment 1 and 5 were carried out at low desorption heating temperature (80-90°C) and experiments 2, 3 and 4 were performed at high
desorption heating temperature (110-126°C). The gauge pressure increased to -17.5 inHg, -18 inHg and -21.5 inHg for experiment 2, 3, and 4 respectively, and the gauge pressure remained same when the system was cooled for 2 hours.

This suggests good desorption happens at high desorption temperatures, but the system pressure increases. Conversely, at low-temperature desorption, less ethanol desorbs, and the system pressure does not significantly increase.

3.3. Adsorption-Desorption on Vertical System

Adsorption-desorption experiments were performed on the vertical system to analyze adsorptive cooling, to understand pressure effects on the ethanol side and activated carbon side, and to determine the effect of desorption heating temperature on multiple cycle adsorptions - desorption operation.

Initially, three sets of experiments (3.3.1 normal process, 3.3.2. using same activated carbon, but replacing the used ethanol fresh ethanol, and pulling a vacuum on the ethanol and the activated carbon side after each adsorption-desorption cycle, and 3.3.3. using same ethanol but replacing the used activated carbon with freshly activated carbon and pulling vacuum on the ethanol and the activated carbon side after each adsorption-desorption cycle) were carried out in the vertical system using 50 ml of water in the freezer compartment, 10 ml of 200 proof undenatured anhydrous ethanol in the evaporator, and 20g of activated carbon.

3.3.1 Normal Process

The normal process involved three cycles of adsorption and desorption without changing the ethanol or activated carbon or pulling a vacuum between cycles. Figure 18 shows the temperature of the evaporator during the adsorption process for adsorptive
cooling obtained in the first, second, and third cycle of multiple cycle operation in the vertical system. The lowest evaporator temperature during the adsorption stage was 12.2°C, 19.5°C, and 20.5°C for first, second and third cycles. During the progressive adsorption stages, the increase in an evaporator temperature suggests a gradual decrease in adsorptive cooling with the progress in multiple cycles. No multiple adsorptive cooling was obtained when using the same initially charged ethanol and activated carbon, and without pulling a vacuum between cycles.

Figure 18: Evaporator temperature during first, second, and third adsorption process during multiple cycle operation.

For successful multiple cycle adsorption-desorption operation, the ethanol saturation pressure should be equal to the pressure inside the system during the adsorption stage. Figure 19 shows the ethanol temperature, absolute saturation pressure
of ethanol at the ethanol temperature, and initial and final absolute pressure of ethanol on
the evaporator side in the first, second and third adsorption-desorption cycles.

![Graph showing evaporator temperature, ethanol saturation pressure, and pressure of ethanol on the evaporator side in adsorption-desorption cycles.](image)

**Figure 19:** Evaporator temperature, ethanol saturation pressure and pressure of ethanol on the evaporator side in first, second and third adsorption-desorption cycle.

The absolute saturation pressure of ethanol for first cycle adsorption-desorption was 68 mbar, which was same as the initial pressure on the evaporator side of the system at 22.5°C ethanol temperature. After the first adsorption-desorption process, the absolute pressure on the evaporator side of the system went up. The pressure on the evaporator side remained high even after the system cooled. A similar trend could be noticed in the pressure reading on the evaporator side for multiple cycle adsorption-desorption processes.
The increase in the pressure on the evaporator side suggests the formation of other species during desorption, which are not condensing, and which increase the system pressure on the evaporator side. Alternatively, the increase in the pressure on the evaporator side could happen by loss on the vacuum. In either case, increase in the pressure on the evaporator side may be decreasing adsorptive cooling on the multiple cycle operations.

![Graph showing pressure changes](image)

**Figure 20**: Gauge pressure on the activated carbon side of apparatus in the first, second, and third adsorption-desorption cycle.

Figure 20 shows the pressure on the activated carbon side before and after each adsorption-desorption cycle. This graph shows the pressure on the activated carbon side at the initial stage of the experiment, final (after desorption), and after the system is cooled. During the adsorption step of the first cycle, the initial gauge pressure on the activated carbon side was -28 inHg, and at the end of desorption step of the same cycle,
the pressure increased to -23 inHg, then dropped to -27.5 inHg after the system cooled. This was the initial pressure on the activated carbon side of the apparatus during the second adsorption process. After the second adsorption-desorption process, the final gauge pressure at the end of desorption was -21.5 in Hg. The gauge pressure dropped to -27.5 inHg after the system cooled. This was initial pressure for the third adsorption process, and final gauge pressure toward activated carbon at the end of third desorption was -20.4 inHg. The gauge pressure when the system cooled was -27.5 inHg. The maximum temperature of activated carbon during desorption was 124°C, 129°C, and 131°C for first, second, and the third cycle respectively. The increase in the pressure with an increase in temperature and vice-versa for a constant volume of space on the activated carbon side, number of moles of ethanol vapor and gas constant can be explained by ideal gas law \((PV = nRT)\). Where, \(V\) is volume occupied by \(n\) moles of ethanol gas having pressure, \(P\) at temperature, \(T\) in Kelvin. Experiments showed that the pressure dropped to nearly the initial pressure on the activated carbon side during multiple cycle adsorption-desorption. This was only possible if vapor (right after desorption) present between adsorbent bed and ethanol side valve was re-adsorbed to activated carbon.

The decrease in adsorptive cooling capacity over multiple cycles could be due to a loss of vacuum, less desorption of the ethanol, formation of other species during desorption, or saturation of activated carbon after the first adsorption process. To assess these possibilities, the further experimental analysis was carried out, using different scenarios.
3.3.2 Using Same Activated Carbon, Fresh Ethanol and Pulling a Vacuum on Both Sides After Each Adsorption-Desorption Cycle

This set of experiments were carried out to understand whether adsorptive cooling was possible for multiple cycle adsorption using initially charged activated carbon. The experiments used the same activated carbon but with a fresh charge of ethanol for every cycle. The vacuum was pulled on the activated carbon side and evaporator side after each adsorption-desorption cycle. After each desorption process, the system was cooled, and pressure readings were recorded.

Figure 21 shows the evaporator temperature during the first, second, and third adsorption processes during multiple cycle operation of the vertical system using the same activated carbon, fresh ethanol, and pulling vacuum after each adsorption-desorption cycle. The lowest evaporator temperature was 12.9°C, 16.7°C, and 17.9°C for the first, second, and third cycles. There was a gradual decrease in adsorptive cooling, just like in the normal process. The desorption step was performed at high temperature to make sure enough ethanol was desorbed; the maximum temperature of the activated carbon during desorption was 152°C, 143°C, and 178°C during the first, second, and third cycles respectively.
Figure 21: Evaporator temperature during first, second, and third adsorption process during multiple cycle operation.

Figure 22 shows the gauge pressure towards the activated carbon side for multiple cycles of adsorption-desorption. The initial gauge pressure on the activated carbon side was -28 inHg for the first, second, and third cycle. After desorption and when the system cools down, the gauge pressure came near to the initial gauge pressure.
Figure 22: Gauge pressure towards the activated carbon side on first, second, third adsorption-desorption cycles.

These experiments suggest the formation of non-condensing species by possible ethanol decomposition and re-adsorption of such species into the activated carbon on the carbon side. This process of formation of non-condensing species and re-adsorption on activated carbon might be interfering multiple cycles of adsorptive cooling.

3.3.3 Using Same Ethanol, Fresh Activated Carbon and Pulling a Vacuum on Both Sides After Each Adsorption-Desorption Cycle

This set of experiments were carried out to understand adsorptive cooling of initially charged ethanol with fresh activated carbon after each adsorption-desorption. The vacuum was pulled on the activated carbon side and evaporator side after each adsorption-desorption cycle. Figure 23 shows the evaporator temperature during the first and second adsorption process during multiple cycle operations of the system using same
ethanol, freshly activated carbon and pulling a vacuum on both sides after each cycle of adsorption-desorption.

The lowest evaporator temperature was 11.8°C and 12.1°C for first and second cycle respectively. The initially charged ethanol was able to achieve near similar performance in the second adsorption cycle with fresh activated carbon and vacuum pulled on both sides in between the first-second cycles. The maximum temperature of activated carbon during desorption was 166°C and 188°C for the first and second cycles respectively.

![Figure 23: Evaporator temperature for the first and second adsorption process](image)

In the first set of experiments, which used the same charge of ethanol and activated carbon for several cycles, the adsorptive cooling declined after every cycle of
adsorption-desorption (figure 18). Initially, the pressure in the evaporator side of the system equaled the saturation pressure of ethanol, which indicates that only ethanol was present in the vapor phase. However, as the refrigerator cycled, the pressure on the evaporator side increased and did not return to the ethanol saturation pressure. On the activated carbon side, the pressure rose significantly while the activated carbon was heated but returned to near initial value after the activated carbon had cooled to room temperature (figure 19). This suggests the formation of volatile species during desorption at the high temperature which are not condensing and so increase pressure on the evaporator side. The pressure drop during cooling on the activated carbon side suggests these species are re-adsorbed by the activated carbon.

The experiments using the same activated carbon, using fresh ethanol and pulling a vacuum on both sides after each adsorption-desorption cycle showed a gradual decrease in the evaporative cooling after each cycle. The experimental analysis confirmed the formation of additional species during desorption which could be re-adsorbing onto to the activated carbon. The formation of such species and possible re-adsorption into the activated carbon could reduce adsorptive cooling during multiple cycle operation.

The experiments using the same ethanol, fresh activated carbon and pulling a vacuum on both sides after each adsorption-desorption cycle showed similar adsorptive cooling on a first and second cycle of adsorption. The use of fresh activated carbon and removal of third species formed during desorption by pulling a vacuum on ethanol side improved the adsorptive cooling.

This experimental analysis from 3.3 showed the formation of new species during or after desorption. These species were not condensing and increased the pressure toward
the ethanol side. And the same species were re-adsorbing on activated carbon on the activated carbon side. Thus, no adsorptive cooling was achieved in multiple cycles of adsorption and desorption.

3.4 Possible Ethanol Decomposition During Desorption

The experimental analysis suggested the formation of new species during the desorption process. For detection of ethanol decomposition, two experiments were performed, each with a single adsorption-desorption cycle, and desorbed ethanol liquid samples were collected and sent for analysis. The maximum desorption heating temperature was 150°C in the first experiment and 120°C in the second experiment. These samples were sent to an analytical chemist for Gas Chromatography (GC) / Mass Spectroscopy (MS) analysis. Table 3.1 shows the results of this analysis.

**Table 3:** Liquid ethanol samples with specifications and contents after the test (refer to APPENDIX F)

<table>
<thead>
<tr>
<th>Liquid Sample Number</th>
<th>Specifications</th>
<th>GC/MS Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>refrig. 1</td>
<td>200 proof ethanol (anhydrous an undenatured)</td>
<td>Ethanol and very small amount of water.</td>
</tr>
<tr>
<td>refrig.3</td>
<td>200 proof desorbed ethanol by temperature heating around 150°C</td>
<td>Ethanol, carbon dioxide, lots of water, acetaldehyde, formic acid ethyl ester, methyl isobutane ketone (MIBK).</td>
</tr>
<tr>
<td>refrig. 5b</td>
<td>200 proof desorbed ethanol by temperature heating around 120°C</td>
<td>Ethanol, carbon dioxide, lots of water, formic acid ethyl ester, caprolactam, butyl benzene sulfonamide.</td>
</tr>
</tbody>
</table>

The refrig.1 sample is 200 proof anhydrous and undenatured ethanol as purchased from the vendor. The GC/MS analysis of refrig.1 showed ethanol and presence of a very small amount of water. The presence of water on ethanol could be due to exposure of pure ethanol to room condition and atmospheric moisture. The refrig. 3 sample is ethanol
that desorbed from the activated carbon at temperatures around 150°C. The GC/MS analysis of refrig.3 showed ethanol and along with other species like carbon dioxide, lots of water, acetaldehyde, formic acid ethyl ester, and methyl isobutane ketone (MIBK). The refrig. 5b is desorbed ethanol by temperature heating around 120°C. The GC/MS analysis of refrig.5b showed ethanol and along with other species like carbon dioxide, lots of water, formic acid ethyl ester, caprolactam, and butyl benzene sulfonamide.

The possible decomposition of ethanol could happen in two ways i.e. by dehydrogenation and dehydration. Dehydrogenation of ethanol is a process of removal of hydrogen from ethanol and formation of acetaldehyde. Dehydration is a process of removal of hydrogen and formation of ethylene.

**Dehydrogenation**

\[
C_2H_5OH \text{ (ethanol)} \rightarrow C_2H_4O \text{ (acetaldehyde)} + H_2 \text{ (hydrogen)}
\]

**Dehydration**

\[
C_2H_5OH \text{ (ethanol)} \rightarrow C_2H_4 \text{ (ethylene)} + H_2O \text{ (water)}
\]

The ethanol might decompose at high temperature by dehydrogenation or dehydration. This might be the primary reaction happening during the desorption process in the vertical system. The formation of other species could happen due to secondary or tertiary reactions. The primary products may be reacting with possible contaminants like air and moisture present on the activated carbon to form such species. This suggests possible decomposition of the ethanol at temperatures around 120°C and above. The regulation of the desorption temperature is essential for proper desorption and to prevent decomposition of ethanol.
3.5 Integration of Temperature Control Arduino System

The bench-scale desorption and first three sets of vertical setup experiments were carried out by using a heat lamp. Different desorption temperatures were obtained by changing the distance from adsorbent bed to the heat lamp. This approach makes it difficult to control the desorption temperature. The construction of a temperature-controlled system with the help of Arduino Uno helped the user to control desorption temperature heating.

Two experiments with one cycle of the adsorption-desorption process were carried out to test the temperature control Arduino system. 6 ml of 200 proof anhydrous ethanol was used with about 20g of activated carbon for the experiment. For experiment 1 adsorption and desorption were carried out for a time duration of 1.5 hours. For experiment 2 adsorption and desorption was performed for 3.5 hours and 2 hours respectively.

**Figure 24:** Evaporator and activated carbon temperature during the adsorption-desorption process for experiment 1
Experiments 1 and 2 were able to achieve adsorptive cooling in the temperature range of 2-8°C. Figure 24 and 25 shows the temperature of the evaporator and activated carbon during adsorption and desorption process. Both experiments (exp 1 & exp 2) showed the consistency of heating temperature during desorption. The desorption temperature in experiment 1 was 105°C and 130°C in experiment 2. This shows that temperature control system can regulate the desorption temperature.

**Figure 25:** Evaporator and activated carbon temperature during the adsorption-desorption process for experiment 2
3.6 Double Activation of Activated Carbon

Activated carbon is activated chemically or physically by the manufacturer using various chemical and physical processes. During these processes, there might be some chemicals left on the activated carbon surface. The activated carbon is also exposed to the atmosphere during storage and preparation before an experiment. The contaminants on the activated carbon surface, like moisture and oxygen, may react with ethanol at high temperature to form unwanted species during desorption. The decomposition of ethanol showed the presence of such species in the activated carbon.

In this study, a double activation process was developed involving two successive heatings of the activated carbon. Initially, the activated carbon was heated at 150°C in the toaster oven for 30 minutes, weighed, and then placed into the vertical apparatus. Then, the activated carbon was heated a second time, under vacuum, at 300°C for 30 minutes. The initial gauge pressure on the activated carbon side was usually -28 inHg. The pressure increased during the heat application, by ideal gas law effect. The final gauge pressure on the activated carbon side at the end of heating was usually -27 inHg to -26 inHg. While the heat lamps were still turned on, the vacuum was pulled at end of the 30 minutes heating period. This process removes some contaminants from the activated carbon bed.

Several experiments were performed using 20 gm activated carbon prepared by this double activation method, as well as 10 ml of 200 proof anhydrous ethanol, using the temperature-controller system to regulate the desorption temperature. The adsorption process was carried out for 20 hours followed by desorption for 2 hours.
After complete adsorption of ethanol into activated carbon, the yeti cup (cooler) was filled with ice and desorbed ethanol vapor was condensed on the evaporator. (See APPENDIX E) The vertical system has no proper condenser to cool the desorbed ethanol vapor during the desorption. The main purpose of adding ice to the cooler is to cool the desorbed ethanol vapor and collect liquid ethanol on the evaporator.

Figure 26 shows evaporator temperature achieved during the first adsorption process using single activation on toaster over and double activation on toaster oven plus heating under vacuum. The lowest evaporator temperature for single activation on a toaster oven and double activation on toaster oven plus heating under vacuum are 2.8°C and -12.7°C. Thus, double activation helped in the removal of contaminants to some extent and helped to achieve lower adsorptive cooling during the first adsorption.

**Figure 26:** Evaporator temperature using different double activation method for preparing activated carbon
Figure 27: Evaporator temperature during adsorption

Figure 27 shows the evaporator temperature during the first adsorption stage of adsorption-desorption, using activated carbon prepared by the double activation technique. During desorption, the maximum activated carbon temperature was 118°C. In the first cycle, adsorptive cooling has significantly improved; the lowest temperature of the evaporator was -7.8°C. However, no adsorptive cooling was obtained in the second or third cycle.
Figure 28: Evaporator temperature, saturation pressure of ethanol, and ethanol pressure on the evaporator side in the first adsorption-desorption process.

Figure 28 shows ethanol saturation pressure and pressure on the evaporator side during the adsorption-desorption process. The initial pressure on the evaporator side is equal to the ethanol saturation pressure at 21.3°C evaporation chamber temperature. The pressure on the evaporation side is almost equal to ethanol saturation pressure during and after the adsorption process. After desorption process, the pressure on the evaporator side did not return to its initial value, and when the system cooled, the pressure on the ethanol side was not equal to the ethanol saturation pressure.
Figure 29: Gauge pressure towards activated carbon side of the apparatus

Figure 29 shows gauge pressure on the activated carbon side during single adsorption-desorption. On the activated carbon side, the pressure rose significantly while the activated carbon was heated but returned to near the initial value after the activated carbon had cooled to room temperature.

This double activation process helped to get low temperatures during the first adsorption process. The adsorptive cooling during the first adsorption cycle showed the great possibility of getting a really low temperature with double activated carbon. However, adsorptive cooling on the multiple cycles adsorption-desorption was not achieved. The rise in pressure on ethanol side and no adsorptive cooling on multiple cycles suggest possible ethanol decomposition. This suggests that even after double activation, on toaster oven and heating under vacuum, contaminants were not removed completely from the activated carbon. Heating the activated carbon under inert conditions
at high temperature could help to remove contaminants and help in cyclic adsorption-desorption.

3.7 Preparation of Activated Carbon in High Temperature and Inert Condition

(Jasińska, Krzyżyńska, and Kozłowski 2008) and (Jasińska, Krzyżyńska, and Kozłowski 2011) studied the influence of activated carbon modifications on their catalytic activity in isopropanol, methanol, and ethanol conversion reactions. The researchers used a chemical activation process to influence activated carbon modifications for introducing new surface functional groups or change of the present active centers. They first removed active sites by heating the activated carbon to 800°C for 45 minutes with continuous the flow of inert (argon or helium) gas. To the product obtained after heating, different types of chemicals were used to modify the carbon functional groups or active centers. Thus, the obtained activated carbon was used to catalyze the decomposition of isopropanol, methanol, and ethanol.

In this thesis work, a similar experiment was performed to prepare activated carbon by heating it at high temperature under the inert conditions. Instead of chemical activation, the main aim of this experiment is to make activated carbon chemically neutral. The activated carbon was heated at 800°C for 45 minutes in the continuous flow of argon gas. The high-temperature heating and continuous flow of argon gas would help to remove contaminants from activated carbon, making it chemically neutral.

During the heating process, 18g of activated carbon was heated at 800°C for 45 minutes with a continuous flow of argon (an inert gas). The activated carbon obtained after heating was cooled to room temperature and transferred to the activated carbon container. 10 ml of 200 proof ethanol was used in the evaporation chamber. The carbon
container and evaporation chamber were connected to the system, and a vacuum was pulled. Then adsorption-desorption was performed.

Figure 30 shows evaporation chamber temperature, ethanol saturation pressure, and the pressure on the evaporator side. The ethanol saturation pressure and pressure on the evaporator side were nearly the same throughout adsorption-desorption process at respective evaporation chamber temperatures.

![Figure 30: Evaporator temperature, saturation pressure of ethanol, and ethanol pressure on the evaporator side in the first adsorption-desorption process.](image)

Figure 31 shows initial and final vacuum gauge pressure on the activated carbon side during the adsorption-desorption process. Initially, the gauge pressure on the activated carbon side was -28 inHg; the pressure remained constant during adsorption.
The gauge pressure increased to -23 inHg during desorption. After the system had cooled, the gauge pressure on the activated carbon side returned to the initial -28 inHg.

![Graph showing vacuum gauge pressure over time](image)

**Figure 31:** Initial and final vacuum gauge pressure on the activated carbon side during the adsorption-desorption process

The use of activated carbon prepared at higher temperature heating in a continuous flow of inert gas eliminated the pressure increase on the evaporator side of the refrigerator throughout the adsorption-desorption process, and the gauge pressure on the activated carbon side returned to its initial pressure when the system cooled down after adsorption-desorption. In contrast, the experiments described in sections 3.3 (normal activated carbon) and 3.5 (double activated carbon) showed higher pressure on evaporator side as compared to the ethanol saturation pressure. The same experiments (3.3 and 3.5) showed near initial pressure on activated carbon side. The use of activated carbon prepared at a high temperature in inert condition maintained initial pressure on
evaporator side and activated carbon side after the adsorption-desorption. The
decomposition of ethanol raises pressure on ethanol side after desorption. There was no
pressure rise on ethanol side after desorption. This balance of pressure is only possible if
there is no decomposition of ethanol during desorption.

The same pressure on ethanol side with ethanol saturation temperature and
returning of pressure on the activated carbon to initial pressure confirms that there is no
ethanol decomposition happening during desorption. This suggests multiple cycle
performance of adsorption-desorption could be obtained with activated carbon prepared
at a high temperature in inert condition.
CHAPTER 4
LIFE CYCLE ANALYSIS

4.1 Introduction to LCA

A Life Cycle Analysis (LCA) is a systematic approach to evaluate the cradle-to-grave environmental impact of a product. An LCA provides information to make a design decision that encompasses the life cycle of a product system from raw material extraction, manufacturing, transportation, use, and the end-of-life stages. Without performing LCA, environmental trade-offs are often buried and unclear; evaluating the individual components of a product poses the risk of removing one environmental problem only to replace it with another one.

Figure 32 shows the life cycle of a Photovoltaic system (PV). PV considered to be a green technology in terms of energy generation perspective, but if we expand the spectrum to the life cycle, it provides interesting insights, it uses large amount of energy and chemicals in the manufacturing stages. In addition, waters may be used to clean the solar panel and some energy can be used for certain PV tracking systems during the 25 years of use stages. Some PV systems equipped with tracking systems use electricity during the lifetime. Few PV manufacturers-initiated planning for the recycling of PV module however, proper end of life management is required as it use material and energy for recycling the solar panel.
LCA can be utilized in various levels from product design to policy decision making. One of the popular uses of LCA is to identify the environmental hotspots of the product systems. For example, as shown in Figure 33, civil aircraft has the largest environmental impact with regard to the percentile energy consumption in the use phase of the airplane because it needs fuels to fly. These jet fuels have their own life cycle environmental impact because it requires extraction of fuel from well, and deliver it to the refinery process, and then transport to the pumping station. Bicycle doesn’t use any external fuel to run in the use stage except human power. However, human power is not considered as an energy input in the life cycle analysis. Bicycle is the raw material intensive product system as mining activities for iron and aluminum bauxite are the one of the largest contributor of the bicycle’s life cycle environmental impact. Appliances
such as conventional refrigerators are use intensive product system as well as the amount of the electricity consumed throughout the life time of 10~15 years outweighs any other environmental loads in other life cycle stages. Other intended application of LCA is as follow:

1. Identify environmental “hot spots” in a product’s life cycle
2. Guide corporate product or process development (e.g., inform green design decisions)
3. Benchmark against similar products (iPhone vs android)
4. Compare different products or services (airplane, train, car)

Figure 33: Life cycle of civil aircraft, bicycle, and appliance
LCA is an internationally standardized methodology (ISO 14040 series) and there are 4 main LCA steps (figure 34). In a nutshell, goal and scope definition stages set the system boundary of a product (i.e., what extend of supply chain and life cycle to consider? Cradle-to-cradle? Only manufacturing and use?). The decision depends on the availability of time and resource for performing LCA. Considering geographical location is important. For example, power grid mix is quite different in different region. Functional unit is very important when we compare multiple product’s life cycle environmental impacts. For example, our study compared LCA of our STAR system along with conventional refrigeration system for refrigerating same amount of water for same amount of time duration. Second step is LCI, gather all the data associated with the material, energy input and different types of effluent to the environment. Carbon footprint is one of the analogous example of life cycle inventory data accounting. We account the amount of carbon generated in individual, household, industry, nation-wide, global levels. However, life cycle inventory analysis itself cannot provide real environmental impacts. For example, global warming potential (GWP) perspective, methane has 25 times more impact than CO₂, refrigerants such as HFC has 1,000 times higher impacts Therefore this type of weighting scheme has to be considered to address environmental impacts stages.

We tend to focus much on the GWP or carbon impacts as it is important constituent of the climate change. However, there are other important impact categories such as acidification, eutrophication, ozone depletion, carcinogen effects, smog, to name a few and the trade-off among these impacts should be carefully considered when we perform any LCA.
4.2 LCA of Refrigeration Systems

Life cycle assessment of several types of refrigeration systems are performed. (Shi et al. 2015) focused on only the refrigerator compressors often used in conventional fridges throughout each stage. The largest impact was during the use phase of the life cycle, as this is the stage where the most electricity is consumed. The results showed a close link between electricity consumption and environmental impact. In contrast, another study performed an LCA on a complete compressor refrigerator, as well as for a magnetic refrigerator (Monfared, Furberg, and Palm 2014).

The main environmental impact categories, including climate change, human toxicity, ozone depletion, and water depletion, were evaluated for both systems. The results demonstrated that the magnetic refrigerators had a greater environmental impact, primarily due to the use of rare earth metals, proving this system is not a suitable replacement in terms of benefitting the environment. (Finocchiaro et al. 2016) performed
an LCA study on their alternative heating and cooling system, “Freescoo,” which is composed of solar photovoltaics/thermal air collector, an integrated cooling tower, adsorption beds, and wet heat exchangers. The results showed that “Freescoo” had 96% lower energy and lower environmental impacts than the conventional system during the use phase, and in the categories global energy requirement, ionizing radiation, land use, and water resource depletion.

(Marco Beccali et. al 2012) compared the energy and environmental impacts of a conventional systems and a Solar Heating and Cooling (SHC) absorption in three locations: Palermo, Italy, Rio de Janerio, Brazil, and Zurich, Switzerland. The results showed that the conventional system with grid connected PV panels had the lowest energy and environmental impacts in Palermo, and Rio de Janerio while the SHC absorption system yielded the lower impacts in Zurich, Switzerland. (Gebreslassie et al. 2009) investigated an absorption cooling system with the ammonia-water pair. Using a multi-objective optimization approach, the results indicated that to reduce the environmental impact of the system, the economic performance also had to decrease. (Xiao, Zhang, and Yuan 2016) studied environmental impacts of recycling refrigerators in China by using a LCA software with CML 2001 methods. The results claimed that the environmental benefits brought by recycling mainly come from the resource and energy savings in the upstream production. However, recycling increases the ozone layer depletion potential because the crushing process releases the CFC-11. In addition, the environmental impacts of transportation may exceed the environmental benefit of recycling.
While there are some LCA studies on refrigeration alternatives, available literature on LCA for solar thermal adsorption refrigeration is rare, particularly for an activated carbon/ethanol working pair. Most of the research studies are not a full LCA, focused on GHG, and energy analysis.

4.3. Economic and Environmental Analysis of Adsorption Systems

A “cradle-to-gate” LCA on the process of activated carbon production from coconut shells in Indonesia was performed to determine the greatest contributor to environmental impact during the process (Arena, Lee, and Clift 2016). The results suggested that the sustainability of activated carbon production in Indonesia could be significantly improved through the use of biomass as fuel, which would reduce the process’ contribution to human toxicity by 60% and global warming by 80%. Additionally, the study showed the importance of using the off-gases of the process as fuel for the boiler in the process. Finally, the study highlighted the potential to decrease human toxicity potential by 90% and global warming by 60% by moving activated carbon processing to countries that use low-carbon sources to produce electricity.

A LCA focused on the environmental impacts associated with the production of activated carbon from olive-waste cakes was presented (Hjaila et al. 2013). Olive-waste cakes are a waste byproduct from industrial olive oil plants and do not have a definitive disposal or waste treatment solution. The LCA results indicated that producing activated carbon from olive-waste cakes emits more CO₂ equivalents than producing activated carbon from hard coal. The study showed that the impregnation had the greatest impact on the environment, followed by pyrolysis, and then by drying the washed activated carbon.
Some studies presented the energy demand and the greenhouse gas emissions generated from biochar production (Gabarrell et al. 2012), (Gaunt and Lehmann 2008), (Hammond et al. 2011), (Ibarrola, Shackley, and Hammond 2012), (Alhashimi and Aktas 2017). Results showed that the economic performance of biochar could not be generalized, however, with the available data, the study showed that for adsorption of contaminants such as chromium, zinc, lead, and copper, the economic performance of biochar was comparable to that of activated carbon. The environmental impact of biochar was found to be significantly less in the categories of energy demand and GWP, even when accounting for potential long-distance transportation. Despite these results, biochar still may not yet be a viable replacement for activated carbon due to its variation in material property based on differences of raw materials.

In addition to using LCA to select the working adsorption pair materials, the materials used to build the system must also be evaluated. For example, (L. Simões, Costa Pinto, and Bernardo 2013) examined the life cycle impact, environmental and social costs of using virgin high density polyethylene (HDPE) compared to recycled HDPE for the piping purpose. The result indicated that the recycled HDPE had a higher contribution to the respiratory inorganics because of the high gaseous emissions produced from the electrical energy needed to recycle the material, while the virgin HDPE had the highest impact in the fossil fuels category.

A study presented the total equivalent warming impact (TEWI) of an adsorption cooling system using a LiBr-water working pair (Florides et al. 2002). Overall heat transfer coefficients were theoretically and experimentally determined for the generator, condenser, evaporator, and adsorber in the system. An investigation of adsorptive cooling
using a silica gel/water pair compared to conventional cooling was performed by (Cellura et al. 2010). The results demonstrated that while adsorption refrigeration consistently has less impact on the environment, the location of the system is implemented in has a large role in how well the system performs. A study compared an economic and environmental aspects of different solar cooling methodology (Otanicar, Taylor, and Phelan 2012). The adsorption system was estimated to release ~12 g CO2/kWh of thermal energy over the system’s lifetime. The lower COP values of current adsorption systems limits both the economic viability of the system and increases the environmental impact. These results indicate adsorption technology has potential to become a viable replacement for the conventional refrigeration systems; however, there is still much improvement to be made as far as the COP of the technology is concerned.

4.4 Comparative Environmental Life Cycle Analysis

A comparative environmental life cycle analysis of the conventional refrigerators and STAR system was performed. Table 4 lists four-different life cycle scenarios considered. First and second scenarios estimate the life cycle environmental impact of the conventional refrigeration system which use different refrigerants with different energy efficiency. All the system Bill of Material (BOM) has been found form literatures and numbers are inputted to SimaPro LCA software. Third and fourth scenarios are the LCA of two progressive versions of the bench-scale STAR systems. Both bench scale prototypes use ethanol-activated carbon adsorption pair as mentioned earlier in this thesis. Version two has improved the cooling capacity by improving diverse aspect of the design of the system.
Table 4: LCA scenarios for conventional refrigerators (S1 and S2) and STAR refrigerators (S3 and S4)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy consumption</td>
<td>1095 kWh-yr</td>
<td>365 kWh – yr</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Life cycle material and energy consumption</td>
<td>System BOM from literature (Japanese)</td>
<td>System BOM from literature (Chinese)</td>
<td>measured system BOM of STAR-V1</td>
<td>measured system BOM of STAR-V2</td>
</tr>
<tr>
<td>Refrigerant or Adsorption Pair</td>
<td>CFC/HCFC (R22)</td>
<td>HFC (R134a)</td>
<td>Ethanol – Activated Carbon</td>
<td>Ethanol – Activated Carbon</td>
</tr>
</tbody>
</table>

Figure 35 shows the example of the life cycle inventory (LCI) flow of the product manufacturing (assembly) stage of conventional refrigeration system.

**Figure 35**: Example of LCI: Production of conventional fridge
Based on the LCI data given from literature (Horie 2004) Life Cycle Impact Analysis (LCIA) of conventional refrigerator is performed. The total life cycle environmental impact of the four-different scenario was analyzed. Among many impact assessment measures, the LCA study adopted “Tool for the Reduction and Assessment of Chemical and other Environmental Impact” (TRACI)(Bare 2011). TRACI 2.0 is a life cycle impact assessment tool developed by the US Environmental Protection Agency (EPA)’s National Risk Management Research Laboratory. It allows for quantification of the potential environmental effects such as global warming, ozone depletion, acidification, smog formation, human health criteria-related effects, eco-toxicity, and fossil fuel depletion effects. TRACI 2.0 is the best applicable environmental impact assessment tool to the North America case studies such as our STAR design.

In terms of the GWP, conventional household appliances including refrigerators consume significant amount of electricity during “use stage” of life cycle. In most homes the refrigerator is the second largest electricity consuming appliances (13.7%), right after the air conditioner (14.1%)(2015 RECS: Overview 2018). An old 1990-era 18 cf. fridge uses on average 1095 kWh a year, while a modern energy-efficient model uses only 365 kWh a year. However, STAR design doesn’t require any electricity during the use stage of the life cycle. Although both STAR prototypes are focused on small scale rural area application, we can readily estimate the life cycle use stage’s energy saving benefits of STAR compared to conventional household refrigerators.

Table 5 lists the life cycle environmental impact caused by annual electricity consumption of an old 1990-era (S1) and a modern energy-efficient models (S2) with an assumption of average low voltage U.S. grid-mix infrastructure. Since STAR will acquire
input energy from a solar thermal system and doesn’t require electricity during the use stages, all the environmental impacts shown in Table 5 can be avoided annually.

Table 5: Environmental impact of conventional refrigerator S1 and S2

<table>
<thead>
<tr>
<th>Impact category</th>
<th>Unit</th>
<th>1990 era -Old Fridge (1400 kWh/yr)</th>
<th>Energy Efficient Fridge (350 kWh/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global warming</td>
<td>kg CO2 eq</td>
<td>1.17E+03</td>
<td>2.92E+02</td>
</tr>
<tr>
<td>Acidification</td>
<td>H+ moles eq</td>
<td>4.18E+02</td>
<td>1.04E+02</td>
</tr>
<tr>
<td>Carcinogenics</td>
<td>kg benzen eq</td>
<td>4.61E+00</td>
<td>1.15E+00</td>
</tr>
<tr>
<td>Non carcinogenics</td>
<td>kg toluen eq</td>
<td>2.74E+04</td>
<td>6.85E+03</td>
</tr>
<tr>
<td>Respiratory effects</td>
<td>kg PM2.5 eq</td>
<td>2.22E+00</td>
<td>5.56E-01</td>
</tr>
<tr>
<td>Eutrophication</td>
<td>kg N eq</td>
<td>4.78E+00</td>
<td>1.20E+00</td>
</tr>
<tr>
<td>Ozone depletion</td>
<td>kg CFC-11 eq</td>
<td>3.10E-05</td>
<td>7.75E-06</td>
</tr>
<tr>
<td>Ecotoxicity</td>
<td>kg 2,4-D eq</td>
<td>3.73E+03</td>
<td>9.33E+02</td>
</tr>
<tr>
<td>Smog</td>
<td>g NOx eq</td>
<td>2.26E+00</td>
<td>5.64E-01</td>
</tr>
</tbody>
</table>

Figure 36: shows the simplified process trees of the scenario 1 (S1). It shows only 13 nodes (i.e. supply chain) out of total 2008 nodes associated with the construction of the old model of the conventional refrigerator. It shows the relative importance of supply chain regarding to the global warming potential (GWP); 33 percent and 46 percent of total GWP is contributed by the yearly use of the electricity and the use of HCFC (R22).
Figure 36: Relative importance the process chain of the conventional refrigerator (S1) in terms of GWP

Figure 37 shows the percentile contribution of each component (material, refrigerant, annual electricity consumption) of the conventional refrigerator (scenario 1) for various environmental impact categories. Yellow bar and red bar indicate the percentile contribution of the annual electricity consumption and the use of HCFC (R22) throughout the lifetime of the conventional refrigerator respectively. In terms of life cycle impacts, 1095 kWh of annual electricity consumption contributes about 33% of global warming potential (GWP) as shown in the Figure 36, about 70% of acidification (AC),
about 60% of the respiratory effect, about 60% of the smog, more than 50% of the eutrophication and ecotoxicity impacts of a conventional refrigerator (SC1). If the analysis extrapolates to 10~15 years of use of the refrigerator, the impacts by the electricity consumption will increase 10~15 times higher. Refrigerant HCFC contributes about 42% of GWP and 100% of the Ozone Depletion impact.

Figure 37: LCA results of conventional refrigerator

As shown in Figure 37, In terms of the material used for the component of the conventional refrigerator, steel and copper have relatively larger impact than other materials and chemicals utilized for the production of an old conventional refrigerator mainly because a relatively large amount of the copper and steel are used. Figure 38 shows the relative contribution for the eutrophication impact category. About 41 percent and 38 percent of the eutrophication impacts are attributed by the copper mining activities and electricity production respectively. Only 21 nodes are shown out of 2008 nodes of processes involved in the supply chain of an old conventional refrigerator.
Table 6 and Table 7 lists the BOM for two version of the STAR system. STAR version 1 is the horizontal system developed in 2016 whereas the STAR version 2 is the vertical system developed in 2017.
Table 6: Bill of material for horizontal STAR-V1 (2016) model (S3)

<table>
<thead>
<tr>
<th>Sub-assembly</th>
<th>Quantity</th>
<th>Unit</th>
<th>Material/Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adsorbet Bed</td>
<td>62 grams</td>
<td>8 oz. mason jar</td>
<td>granular activated charcoal</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>rubber gasket</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>copper plate, 3” diameter</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>threaded brass fitting, 0.25”</td>
<td></td>
</tr>
<tr>
<td>process</td>
<td></td>
<td>glue rubber gasket to copper plate</td>
<td></td>
</tr>
<tr>
<td>process</td>
<td></td>
<td>solder threaded brass fitting to copper plate</td>
<td></td>
</tr>
<tr>
<td>Evaporator</td>
<td>1</td>
<td>vacuum trap glass</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>8 oz. styrofoam cup w/ lid</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>hose and tube clamp, galvanized steel</td>
<td></td>
</tr>
<tr>
<td>Heat Exchanger</td>
<td>2</td>
<td>threaded brass fitting, 0.25”</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6 inch</td>
<td>0.25” diameter copper tube</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.25” compression fitting</td>
<td></td>
</tr>
<tr>
<td>General</td>
<td>1 fluid oz.</td>
<td>high vacuum grease</td>
<td></td>
</tr>
<tr>
<td></td>
<td>38.5 grams</td>
<td>anhydrous ethanol</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3 feet</td>
<td>Nylon tubing, 10 mm OD</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3 feet</td>
<td>Nylon tubing, 12 mm OD</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>Absolute pressure guage</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1 quart</td>
<td>distilled water for washing</td>
<td></td>
</tr>
<tr>
<td>process</td>
<td></td>
<td>evacuate system with vacuum pump</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>push-to-connect tube fittings</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>nylon ball valve with push to connect fittings</td>
<td></td>
</tr>
</tbody>
</table>

Table 7: Bill of material of vertical STAR-V2 (2017) model (S4)

<table>
<thead>
<tr>
<th>Equipment Used</th>
<th>Mass (kg)</th>
<th>Quantity</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Activated Carbon Chamber</td>
<td>0.244</td>
<td>1</td>
<td>Copper</td>
</tr>
<tr>
<td>Pressure gauge Connector</td>
<td>0.08</td>
<td>2</td>
<td>Stainless Steel</td>
</tr>
<tr>
<td>Gauge Connector to pipe</td>
<td>0.018</td>
<td>3</td>
<td>Stainless Steel</td>
</tr>
<tr>
<td>Pipe Clamps</td>
<td>0.006</td>
<td>4</td>
<td>Aluminum</td>
</tr>
<tr>
<td>Regulator Valve</td>
<td>0.059</td>
<td>4</td>
<td>Nylon</td>
</tr>
<tr>
<td>Elbow</td>
<td>0.006</td>
<td>1</td>
<td>Nylon</td>
</tr>
<tr>
<td>Tee</td>
<td>0.009</td>
<td>3</td>
<td>Nylon</td>
</tr>
<tr>
<td>Reducer</td>
<td>0.018</td>
<td>2</td>
<td>Nylon</td>
</tr>
<tr>
<td>Pipe</td>
<td>0.03</td>
<td>N/A</td>
<td>Nylon</td>
</tr>
<tr>
<td>Cable Tie</td>
<td>0.0012</td>
<td>7</td>
<td>Nylon</td>
</tr>
<tr>
<td>Glass Tube</td>
<td>0.152</td>
<td>2</td>
<td>Silica Glass</td>
</tr>
<tr>
<td>Toaster Oven Tray</td>
<td>0.528</td>
<td>1</td>
<td>Silica Glass</td>
</tr>
<tr>
<td>Measuring Cylinder</td>
<td>0.02</td>
<td>1</td>
<td>Silica Glass</td>
</tr>
<tr>
<td>Plywood</td>
<td></td>
<td>1</td>
<td>Chestnut Tree</td>
</tr>
<tr>
<td>Activated Carbon</td>
<td>0.02</td>
<td>N/A</td>
<td>Carbon</td>
</tr>
<tr>
<td>Liquid Ethanol</td>
<td>0.008</td>
<td>N/A</td>
<td>Ethanol</td>
</tr>
<tr>
<td>Fabric</td>
<td>N/A</td>
<td>N/A</td>
<td>Cotton</td>
</tr>
</tbody>
</table>

Figure 39 shows the percentile breakdown of various lifecycle environmental impacts generated from the components of the horizontal prototype (S3). It provides
important insights about the relative level of contribution of components and trade-off decision among different environmental impacts. For example, about 38%, 35%, 14%, 6%, and 4% of the life cycle global warming potential (GWP) impacts are accrued from the production stages of nylon, brass, copper, glass, and aluminum, respectively. This information can be used to enhance the specific life cycle environmental impact by applying various design for environment (DfE) strategies such as using renewable materials or alternative materials for the environmental hotspots.

**Figure 39:** Life cycle environmental impacts of the horizontal STAR design by utilizing U.S. EPA’s TRACI Method
Figure 40 shows the environmental impact of the vertical STAR system (V4). Our current vertical system utilizes very thick plywood and it outweighs other component’s environmental impacts. This initial life cycle assessment suggests it is one of the hot environmental spots to improve for further design. We are pretty sure that the volume of the current plywood can be reduced by 10 times and it is suffice enough to hold other apparatus in the vertical system. All the nylon parts used for regulator valve, elbow, tee, reducer, pipe tubing, and cable tie have relatively high contribution to almost all the environmental impact categories considered for the analysis. Chromium used for the pressure gauge connector and other connectors to the piping system also contributes about 10 percent of environmental categories. Amount of the activated carbon and ethanol utilized for the vertical STAR system has very low impact to the current vertical STAR system as the amount used for the bench scale is very small; 23 grams of activated carbon and 10 grams of anhydrous ethanol are used.

However, the amount of the activated carbon and ethanol will be increased significantly for scale-up design and this issue should be considered as one of the design trade-off criteria for the future scaled up STAR system.
**Figure 40:** Life cycle environmental impacts of the vertical STAR design by utilizing U.S. EPA’s TRACI Method

Figure 41 shows the comparison of life cycle environmental impacts of four different scenarios considered in this study. It compares annual use of each refrigerator for refrigerating 20 ml of water for 24 hours. STAR system has much less environmental burden in all categories mainly because it doesn’t use electricity and use much less energy intensive materials. Second version of star system improved environmental performances because the cooling capacity has increased. R134a (refrigerant for S2) has greater impact than R22 (CFC) in terms of GWP but still the GWP of S1 is larger since the old conventional refrigerator consumes three times more electricity because of the efficiency. HFC (R134a) eliminated the ozone depletion impact.
4.5 Economic, Environmental and Social Impact of STAR System

This research has the potential to make a significant economic, environmental and social impact. The worldwide market for refrigeration equipment is approximately 100 billion dollars; over 80 million domestic refrigerators alone are produced each year. This market is dominated by the conventional vapor compression cycles that use ammonia and hydrofluorocarbons as refrigerants and rely upon electricity for operation.

However, despite its broad success, conventional refrigeration technology has overshot markets like the Bihar state in India-regions without a reliable electric grid where the residents cannot afford solar powered electrical appliances. While demand for refrigeration in these regions is far lower than in industrialized countries, there are a few critical applications, such as refrigerating vaccines, where the need for refrigeration is urgent and immediate. Lack of refrigeration and safe storage of vaccine is key issues in such areas.
This technology may also have a significant environmental impact. Refrigeration uses approximately 9% of the world’s electricity production, and in the United States alone, air conditioning and refrigeration consume 20% of residential electricity demand. The electricity consumption accounts for nearly 1 billion tons of CO₂-equivalent greenhouse gas emissions. Moreover, leaks from conventional refrigeration systems continue to pose a serious environmental challenge. The chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) once commonly used in conventional refrigeration damage the ozone layer; and their replacements, and hydrofluorocarbons (HFCs) do not damage the ozone layer, they have a global warming potential that is thousands of times greater than carbon dioxide.
CHAPTER 5
CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

A vertically oriented bench scale system was built to address the limitation of the horizontal prototype. The experimental analysis was performed on bench scale system setup and vertical system setup.

The experiments performed for selecting an activated carbon container identified a copper tube as an appropriate material. Using a copper tube as the activated carbon container gives higher rates of heat transfer, better thermal stability, ease of fabrication, and safe operation at high temperature. Bench-scale desorption studies showed that better desorption happens at elevated desorption temperature and during the short time durations. However, there is a gradual loss in the system vacuum at higher temperature heating (above 120°C). The best temperature heating for proper desorption of ethanol without losing the system vacuum is around 110°C.

Initial experiments by a normal process (using same initially charged ethanol and activated carbon) on vertical system showed a decrease in adsorptive cooling on multiple cycles of adsorption-desorption. The same experiments showed an increase in pressure on the evaporator side, and that pressure on the activated carbon side returned to near initial pressure after each desorption process. The pressure increase on the evaporator side suggests a loss in the vacuum of the system, less desorption of ethanol, or the formation
of a third species during desorption which is not condensing and increasing system pressure.

Experiments using the same activated carbon but replacing the ethanol after every adsorption-desorption and pulling a vacuum on both sides showed decreased in adsorptive cooling on multiple cycle operation. The use of the same activated carbon and returning of pressure on the activated carbon side confirmed re-adsorption of third species on activated carbon formed during desorption on the activated carbon side.

Experiments using the same ethanol but replacing the activated carbon after every adsorption-desorption and pulling a vacuum on both sides showed similar adsorptive cooling during the first and second adsorption cycles. The use of fresh activated carbon, and pulling a vacuum helped in the removal of non-condensing species after desorption which enabled to repetitive adsorptive cooling. This confirmed the formation of third species during desorption which was increasing the pressure on the ethanol side, which may prevent, multiple cycles of adsorptive cooling with the same charge of ethanol and activated carbon.

Desorbed ethanol samples were collected at various desorption temperatures and sent for GC/MS chemical analysis. The GC/MS analysis of ethanol sample collected at desorption temperature of 150°C showed ethanol and along with other species like carbon dioxide, lots of water, acetaldehyde, formic acid ethyl ester, and methyl isobutane ketone (MIBK). The GC/MS analysis desorbed ethanol sample at desorption temperature around 120°C showed ethanol and along with other species like carbon dioxide, lots of water, formic acid ethyl ester, caprolactam, and butyl benzene sulfonamide. The chemical analysis of the ethanol samples confirmed ethanol decomposition at a higher desorption
temperature (above 120°C). Thus, to limit and to control desorption heating, Arduino Uno based temperature control system was integrated into the system.

The activated carbon was double activated by heating on a toaster oven and under a vacuum. During the double activation process, activated carbon was heated at 150°C for 30 minutes on toaster oven, and then the activated carbon was heated at 300°C for 30 minutes under a vacuum. The use of activated carbon prepared by this double activation process showed significant improvement in adsorptive cooling on the first adsorption. However, adsorptive cooling on multiple cycles was not achieved. Similar increase in pressure like normal process on the evaporator side was noticed. This result suggested that the double activation process of heating activated carbon in a toaster oven and under a vacuum was not fully able to remove contaminants like air and moisture.

A sample of activated carbon was prepared at a temperature heating of 800°C in a continuous flow of argon gas. This sample was used to run a single adsorption-desorption cycle. This experiment showed that the pressure on the evaporator side was equal to ethanol saturation pressure and pressure on the activated carbon side returned to the initial pressure. This confirms that there is no ethanol decomposition happening during desorption, and suggests multiple cycles of adsorption-desorption could be obtained with activated carbon prepared at a high temperature in an inert condition.

5.2 Recommendations

Preheating process of the activated carbon is essential to remove contaminants like air and moisture. The study should focus on preheating of activated carbon exposed to normal room conditions and understanding effects of such preheated activated carbon on the adsorption-desorption process for real application of STAR technology. It is also
crucial to design an experimental setup to preheat activated carbon at a higher temperature in a continuous flow of inert gas. The study of multiple cycle adsorptions-desorption by such preheated carbon is an urgent need. A detailed analysis of desorbed gas and liquid sample by Gas chromatography (GC)/Mass Spectroscopy (MS) test can help to narrow down the exact heating temperature for ethanol decomposition and species formed during such decomposition.

The currently used activated carbon GAC-816C (8*16 Mesh) activated carbon is generally used for air or water purification process. The process of activation and adsorption-desorption capacity of GAC-816C are unknown. The switching of activated carbon to higher adsorption/desorption capacity could yield a better result. The possible switch could be to Maxsorb III or Activated Carbon Fiber (ACF).

The absence of a condenser on STAR vertical system made it difficult to cool desorbed ethanol during desorption. A condenser should be added to the vertical STAR system and into the next prototype. The analysis of a scaled-up system with larger evaporator and carbon container could yield a more significant result in real life applications.
REFERENCES


Bare, Jane. 2011. “TRACI 2.0: The Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts 2.0.” *Clean Technologies and Environmental Engineering*


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APPENDIX A

Soldering of Copper Tube

1. The soldering tools such as propane soldering torch, solder, flux, copper pipe, copper cap and threaded female brass connector were collected for assembly.

2. The tube cutter was used to cut copper tube; tube cutter was used for a clean cut. The pipe was clamped between the cutter wheel and guide wheel. Then the cutter was rotated scoring the pipe deeper until the pipe snapped off.

3. The wire brush was used to remove inside and outside burr. The mating areas of tubing and fittings were cleaned to ensure a solid and leak-proof joint. The emery cloth and wire brush were used for cleaning.

5. With the help of painting brush a layer of flux was applied to the surfaces to be joined and insides of the fittings. The flux cleans the copper surface and enables to flow evenly.

6. Propane soldering torch was used to heat the joint and solder was applied against the joint on opposite side of the flame. The solder was applied until it melted and flowed into the joint.

7. Enough time was allowed to cool and harden the joints before moving the assembled joints.
APPENDIX B

Arduino Connection

1. Arduino Uno board and A.C Light Dimmer Controller board were fixed on plastic board with the help of M3 nuts and bolts. Double-sided tape was used for fixing the breadboard on plastic board.

2. Two pin terminal block and pin header were soldered to the amplifier board. A K-type thermocouple was connected to the 2-pin terminal block. With the help of color coding, red wire of the thermocouple was connected to red end and yellow wire to the yellow end. The same process was repeated for the next amplifier and thermocouple.

3. The pin header of the thermocouple was connected to an amplifier and then assembled to the breadboard.

4. The open source Arduino Software was downloaded and installed on the computer from https://www.arduino.cc/en/Main/Software. The library file Adafruit – MAX31855-library-master was downloaded from adafruit on the library of installed Arduino Software.

5. The following procedure was followed to set up the software - Tools > Board > Select Arduino/Genuino Uno.
6. Codes were typed on the Arduino screen. The jumper wire that comes with Arduino was used for the connection. The channels ch1 and ch2 of the relay were defined, which were connected to the digital side of Arduino 9 and 10.

**Description of Points**

<table>
<thead>
<tr>
<th>A.C Control Module</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>GND</td>
<td>Ground of low voltage Side</td>
</tr>
<tr>
<td>VCC</td>
<td>Device power, D.C 5 Volts</td>
</tr>
<tr>
<td>SYNC</td>
<td>Zero-cross detector output positive impulse</td>
</tr>
<tr>
<td>CH1</td>
<td>Triac gate input pin for 1 channel</td>
</tr>
<tr>
<td>CH2</td>
<td>Triac gate input pin for 2 channels</td>
</tr>
<tr>
<td>AC – Input</td>
<td>A.C voltage (110-220 V)</td>
</tr>
<tr>
<td>CHANNEL 1</td>
<td>Connect load on 1 channel</td>
</tr>
<tr>
<td>CHANNEL 2</td>
<td>Connect load on 2 channels</td>
</tr>
</tbody>
</table>

**Description of Amplifiers**

<table>
<thead>
<tr>
<th>Amplifier</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vin</td>
<td>Power pin (3-5 V)</td>
</tr>
<tr>
<td>GND</td>
<td>Common Ground for power and logic</td>
</tr>
<tr>
<td>DO</td>
<td>Serial Data Out / Master In Slave Out pin, for data sent from the MAX31856 to your processor</td>
</tr>
<tr>
<td>CS</td>
<td>Chip Select pin, It’s an input to the chip</td>
</tr>
<tr>
<td>CLK</td>
<td>Clock pin, it’s an input to the chip</td>
</tr>
</tbody>
</table>

7. The GND and VCC from relay board were connected to the bus terminal of the breadboard. GND and VCC from both amplifiers were connected to breadboard and then to the Arduino board.

8. The MAXDO, MAXCS, MAXCLK, MAXCS2 were defined in the code with digital Input-Output (IO) points of Arduino as point 3,4,5,6. Connect DO, MS, CLK from both amplifier to the Arduino board.
9. The A.C supply wire was connected to the A.C channel of A.C Light Dimmer controller board and two wires from the same board were connected to the heat lamps. The A.C power was plugged in. The Arduino code was launched. The real-time temperature of heat lamp can be viewed from Tools> Serial Monitor. The state (on/off) of Heat lamp 1 and Heat lamp 2 also can be checked from the same window.

10. For the desired temperature, the value of reference temperature can be changed. The temperature control is based on the on/off of the system, so it is not 100% accurate on providing exact and constant temperature.
APPENDIX C

Arduino Code

/*****************************/

This is an example for the Adafruit Thermocouple Sensor w/MAX31855K

Designed specifically to work with the Adafruit Thermocouple Sensor

----> https://www.adafruit.com/products/269

These displays use SPI to communicate, 3 pins are required to interface Adafruit invests
time and resources providing this open source code, please support Adafruit and open-source hardware by purchasing products from Adafruit!

Written by Limor Fried/Ladyada for Adafruit Industries.BSD license, all text above must be included in any redistribution

/*****************************/

#include <SPI.h>

#include "Adafruit_MAX31855.h"

const int ch1 = 9;

const int ch2 = 10;

float ref1=0; // in degree C

double c = 0
double c2 = 0;

// Default connection is using software SPI, but comment and uncomment one of
// the two examples below to switch between software SPI and hardware SPI:

// Example creating a thermocouple instance with software SPI on any three
// digital IO pins.
#define MAXDO   3
#define MAXCS  4
#define MAXCLK  5
#define MAXCS2 6

// initialize the Thermocouple
Adafruit_MAX31855 thermocouple (MAXCLK, MAXCS, MAXDO);
Adafruit_MAX31855 thermocouple2(MAXCLK, MAXCS2, MAXDO);

// Example creating a thermocouple instance with hardware SPI
// on a given CS pin.

#define MAXCS 10

//Adafruit_MAX31855 thermocouple(MAXCS);

void setup () {
    Serial.begin(9600);
    pinMode(ch2, OUTPUT);
    pinMode(ch1, OUTPUT);
    digitalWrite(ch1,0);
    digitalWrite(ch2,0);
    while (! Serial) delay (1); // wait for Serial on Leonardo/Zero, etc
Serial.println("MAX31855 test");

// wait for MAX chip to stabilize
delay (500);

}  
void lamp1(int state = 0)  
{  
digitalWrite(ch2, state);  
}

void lamp2(int state = 0)  
{  
digitalWrite(ch1, state);  
}

void loop ()  
{  
  // basic readout test, just print the current temp  
c = thermocouple.readCelsius();  
c2 = thermocouple2.readCelsius();  
  if (isnan(c)) {  
    Serial.println("Something wrong with thermocouple!");  
  }  
  //--------------- Lamp 1 --------------------------  
  if (c < ref1)  
  {  
    
}
lamp1(1);
Serial.print("Lamp 1 ON \t");
}
else if (c > ref1)
{
lamp1(0);
Serial.print("Lamp 1 OFF \t");
}
Serial.print("T1 = "); Serial.print(c);Serial.print("\t");
delay (200);

/////////////////////////////////////////////////////////////////////
///////////////////////// Lamp 2 /////////////////////////////////////
if(c2<ref1)
{
lamp2(1);
Serial.print("\t Lamp 2 ON \t");
}
else if(c2>ref1)
{
lamp2(0);
Serial.print("Lamp 2 OFF \t");
}
Serial.print(" \t T2 = "); Serial.println(c2);
delay (200);

////////////////////////////////////////////////////////////////////

}
APPENDIX D

Experimental Procedure for Vertical System

Part a (Adsorption Process)

1. The ethanol chamber, adsorbent bed, and all connecting parts were rinsed with water and dried. (Usually done as the final step of the previous experiment)

2. All the parts were assembled together.

3. The vacuum pump was connected to vacuum trap. With the help of vacuum trap, the vacuum was pulled out of the system. The vacuum was pulled till the vacuum pressure reading on both pressure gauge was -28 inHg. Vacuum leakage was checked and fixed. Then vacuum was released to the atmospheric pressure by opening all the valves.

4. The activated carbon was baked in Pyrex storage pan at 150°C for 20 minutes on Black + Decker Toaster Oven.

5. After baking the activated carbon, the required amount of activated carbon was weighed on AND GF 300 weighing scale. The weighed activated carbon was placed into the adsorbent bed with the help of funnel and connected to the system. The valve toward adsorbent bed was closed after connecting bed to the system.

6. The required amount of ethanol was measured by measuring cylinder and poured into Chem glass and vacuum greased on with the top connector, and the unused end of the
The valve toward ethanol chamber was closed after connecting chamber to the system.

7. The vacuum trap and vacuum pump were connected to pull a vacuum. The vacuum pump was turned on and valve towards activated carbon chamber was opened. The vacuum was pulled till pressure reading on the pressure gauge toward adsorbent bed showed -28 inHg pressure reading and valve toward adsorbent bed were closed.

8. Similarly, the vacuum was pulled toward the ethanol side till pressure dropped to -28 inHg and the valve towards the vacuum trap was closed. The pressure will drop to ~27 inHg due to ethanol vapor pressure.

9. The temperature probes from the Omega HH 147U data logger thermometer were connected at the outer section of the adsorbent bed, the inner section of the adsorbent bed, end of ethanol chamber and ambient room temperature. The temperature reading from the thermocouple was directly recorded into the computer with help of Omega Temp Monitor_S2 software.

10. The lower section of the evaporator was insulated with the help of felt batting.

11. The pressure was recorded at the beginning, middle and end of each experiment cycle.

12. The atmospheric pressure for Dayton, OH was recorded from online weather portal at: http://w1.weather.gov/data/obhistory/KDAY.html

**Part b (Desorption Process)**

1. The valve toward ethanol side was closed.

2. A heat lamp was turned on; the temperature of heat lamp was set up according to desired heating temperature. The desired heating temperature was controlled by using
Arduino system which could be changed as per required. The Arduino system-controlled temperature of heat lamp which further controlled the temperature of the adsorbent bed.

3. The desorbed ethanol was collected in the closed tubing between valve toward adsorbent bed and valve toward ethanol side.

4. The pressure was recorded at the beginning, middle and end of the experiment.

5. The temperature probes from the Omega HH 147U data logger thermometer were connected at the outer section of the adsorbent bed, the inner section of the adsorbent bed, end of ethanol chamber and ambient room temperature. The temperature reading from the thermocouple was directly recorded into the computer with help of Omega Temp Monitor_S2 software.

6. At the end of desorption process, valve toward adsorbent bed was closed and ethanol vapor and condensed ethanol liquid in-between the tubing was allowed to come back to the evaporator.

7. After the final process the volume of ethanol left on the ethanol chamber was measured using measuring cylinder and mass of activated carbon present on the adsorbent bed was weighed.
Sample test result for refrig 1. showed ethanol with some water
Sample test result for refrig 3. showed ethanol with other impurities.

Sample test result for refrig 5b. showed ethanol with other impurities.
APPENDIX E

Experimental Procedure for Current Process

1. Place certain amount of activated carbon on the Pyrex glass and bake at 150°C for 30 minutes on Black + Decker toaster oven.

2. Weigh 20g of baked activated carbon and transfer it into the adsorbent bed (copper tube). Connect the copper tube to the vertical system. Close the valve towards ethanol side. Pull the vacuum towards the activated carbon side till vacuum gauge pressure is -28 inHg. After pulling close the valve towards vacuum trap. Record vacuum gauge pressure, and the temperature.

3. Turn on the heat lamps for 30 minutes at heat lamp temperature of 300°C. At the end of heating process, pull the vacuum and turn off the heat lamp. Close the valve towards the activated carbon side, open valve toward ethanol side and towards vacuum trap. Let the adsorbent bed cool till its temperature drops to room temperature.

4. Measure 10 ml of 200 proof anhydrous ethanol and pour it into ethanol chamber. Connect ethanol chamber to the vertical setup. Pull the vacuum towards the ethanol side till the vacuum gauge pressure is -28inHg and close the valve towards vacuum trap.

5. Record vacuum gauge pressure for all the process. The pressure will rise towards ethanol side depending upon the ethanol temperature and atmospheric pressure at that time (Usually -26 inHg to -27 inHg).
6. Run the adsorption process opening valve towards the activated carbon. Record temperature, vacuum gauge pressure and atmospheric pressure. The atmospheric pressure for Dayton, OH was recorded from online weather portal at:

http://w1.weather.gov/data/obhistory/KDAY.html

7. Record temperature of the: outer layer of copper tube, activated carbon inside the copper tube, room, and evaporator by using Omega Temp Monitor_S2 software for 2 hours of adsorption.

8. Run adsorption process over a night so that all the ethanol is adsorbed into activated carbon.

9. After an overnight adsorption, place some ice on the yeti cup (now evaporator acts as condenser).

10. Run desorption for 1.5 hours at controlled desorption heating temperature. Use Arduino Uno temperature controller to control the heating temperature. Set heat lamp temperature around 200°C and limit activated carbon temperature to 110°C – 115°C during the desorption.

11. Follow step 7. The liquid ethanol is condensed on the ethanol chamber. At the end of desorption process close valve towards activated carbon side. Let the copper tube cool to room temperature.

12. For multiple cycle operation repeat process from step 8 to 11.