DESIGN AND CONSTRUCTION OF A SOLAR THERMAL REFRIGERATION SYSTEM FOR PATNA, INDIA

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1. ABSTRACT

This paper describes the design and construction of a solar thermal adsorption refrigerator in Patna, Bihar, India. After a brief description of the local situation and planning prerequisites the reasons for choosing an ethanol based adsorption system are explained. The following sections are focused on the description of the design and the theory behind the system. Lastly, practical aspects that arose during the construction of the first prototype are mentioned.

2. INTRODUCTION

India is one of the most diverse countries in the world. Throughout the nation, people of different cultures, religions and ethnicities are speaking different languages and experience many different climates. Furthermore, the technological standard differs widely within the country. While the great power outage on the 30th and 31st of July 2012 as described in (Pidd 2012) might have shaken the nation, people in the state of Bihar, who experience a very unstable electricity supply day to day, were not too disrupted by these events. Here, the population is well-adjusted. While the upper class of this slowly developing state is usually running specifically dedicated generators to supply their houses during downtime, the lower class is, by necessity, still dependent on the supply from the grid. The status quo poses a big setback for energy intensive industries and institutions of public interest like schools and hospitals. The latter often run on a very small budget and often lack backup generators or cannot afford to run them. This makes a constant, reliable energy supply unobtainable as backup batteries on larger scales are too expensive. The power supply problem however is a premise, among others, for the advancement of effective storage systems for vaccines; most of which need constant storage temperatures between 35-46°F (2-8°C) according to (CDC 2012). If these conditions cannot be upheld, the vaccine has to be regarded as deteriorated and cannot be used. The problems with maintaining an intact cooling chain from distributor to end user seems to be severe yet pretty un-quantified. While (UNICEF innovation 2012) mentions “[M]illions of dollars’ worth of spoiled vaccines each year”, other sources, like (Palac et al. 2008) state that about 60% of all vaccines are spoiled during transport – though this number could not be verified.

The refrigerator described in this paper is intended to be used in local hospitals in the vicinity of Patna. It is designed as a grid-independent, reliable device suitable for the local conditions and climate. The cooling system was designed in Patna and built with materials locally available in order to build (up on) local expertise. Though the first prototype was costly, the project is aimed at providing cost-effective and affordable solutions through subsequent design and further prototyping. A potential further goal in the future might be the subsequent replacement of regular, mechanical air conditioners by solar powered air conditioners in order to reduce pollution and costs caused by the significant generator-dependent air conditioning in Patna.

3. DESIGN

When constructing projects for developing countries, considering the social or financial requirements is at least as important for the success of a project as the technical design itself. Based upon these criteria, a suitable system should be chosen on an individual basis. Planning and/or constructing the
refrigerator on site helps in ensuring the design is well-suited to
the needs and be easily reproducible on site.

3.1. PREVIOUS WORK/CHOICE OF DESIGN

This project is based upon previous research and prototyping in the field of solar refrigeration. Generally, research
is being done on three different principles to harvest solar
thermal energy for cooling purposes. These principles are
sketched in a second paper that summarizes the research being
done on the different refrigerator types so far. Beyond that, good
overviews of solar cooling technologies are given in (Hwang, et
al. 2008), (Pridasawas and Nemariam, Solar cooling 2003), and
(Best 2007).

In this concrete case several restrictions in the design choice
challenged the group, for example limited availability of
materials required many modifications to the design. The strong
interest in building a system with non-toxic ingredients as well
as the preference of cheap and easy to build materials pushed the
group towards standard single-glazed solar heat collectors which
operate on low temperature ranges. This makes an adsorption
system using ethanol (as found in alcoholic beverages) and
activated carbon the most viable option. These two ingredients
are comparably easy to obtain or even to produce in developing
countries. The use of more sophisticated vacuum tube collectors
or concentrating reflectors were considered in order to reach
higher temperatures, but were ultimately rejected: While the
former are costly and make construction dependent on external
sources, the latter only work with direct solar irradiation, which
is not always constantly available, especially during India’s
extensive rainy seasons.

3.1.1. DESIGN AND SIZING OF THE SYSTEM

The system’s basic design is mainly following the
construction experience from two earlier projects: A project
group from the University of Michigan published a most helpful
and detailed article about a similar ethanol-based refrigerator
design for developing countries (Somerton, et al. 2009)
(Wang und Oliveira 2005) is a good summary of
previous design work done on this refrigerator type.

General Function

The design phase in Patna mostly involved the sizing and
design of the individual components, the material selection, and
the experimentation with some peculiarities that were meant to
improve the function of the refrigerator.

The figure below gives a first impression of the refrigerator
design:

Figure 3-1. General refrigerator design.

The prototype build in Patna follows the general design of a
typical adsorption refrigerator sketched in Figure 3-1. Inside an
insulated, closed cool chamber (1), an evaporator (2) holds liquid
ethanol, which evaporates to cool the vaccines and is adsorbed
by activated coal (carbon) stored in pipes of a solar collector (3)
during the night. At this point, the system is at a vacuum
pressure, so this process happens at low temperatures. During the
day, the coal is heated up in the collector releasing ethanol vapor,
which causes the pressure in the system to rise. The ethanol is
led through a heat exchanger (4) into a storage
basin (5). The
basin was incorporated into the system to prevent hot ethanol
from streaming directly into the refrigerator. In the storage basin,
the ethanol will be trapped for the major part of the day cooling
down to ambient temperatures until it is released back into the
evaporator in the evening. The valves (6) are used to control the
flow of ethanol during the cycle. If both closed, they effectively
separate the system into two parts, whose pressure can be read
off two pressure gauges giving indication on the system’s stage (7).

**Cool chamber design**

![Cool chamber, front view with lid opened](image)

The cool chamber insulates the vaccines against ambient temperatures. Its innermost layer is a metal cube protecting the outer layers from moisture. The evaporator is placed on the bottom, lying flat, inside the cube. The space around the evaporator is filled up with distilled water. During operation, the water will be kept in the phase-change region (of its physical characteristics), that will in turn create an ice storage system at the bottom to stabilize temperature conditions. The free space above the water is reserved for the vaccines. The lid to the fridge is attached at the top of the cooling chamber. This attachment is of a thermodynamic advantage: With the cold source at the bottom, and the lid, being the point where heat is expected to leak in and thus the hottest point in the chamber, is at the top, heat transfer from the lid to the evaporator due to convection is minimized, as the air should remain stable, and not circulate. The space around the chamber is filled with insulation (showing black in Figure 3-2). This is because more insulation means less heat transfer and thus less heat load on the refrigerator, which is crucial to an efficient design. It is important to not penetrate the insulation at any point in order to avoid thermal bridges that can render the insulation ineffective. The only point at which the insulation has to be penetrated is the pipe leading the ethanol in and out of the cool chamber. This pipe should be made of plastic or any other material that is a poor heat conductor. The outer shell consists of metal, again for stability.

The design challenge here is the determination of the size of the inner chamber, insulation material and thickness, as well as the amount of water and ethanol used. This process turns out to be iterative: The amount of insulation determines the amount of heat that may enter inside the refrigerator. This determines the amount of ethanol which has to be maintained in the evaporator and the capacity of the ice storage system. Since these two are inside the inner chamber, this determines its volume needed, which determines the wall areas of the chambers and thus the amount of heat getting into the chamber… Thus, having an idea of which values to choose is important to double-check if everything is to fit in the end.

In order to obtain an overview over the local weather conditions, EPW-files for Patna which contain representative typical hourly weather data can be used. These files are available for many locations worldwide and can be obtained for free under (US department of energy 2011).

![Typical air temperature ranges in Patna, 24h max and min values](image)

According to these files, the highest temperatures the fridge typically encounters during the year are 43°C in May. Generally, for sizing the power of a device, extreme rather than typical conditions should be used, however, these were not obtainable from reliable sources in this case. Instead an additional safety margin was added on the calculations. Using the highest outside temperature and desired inside temperatures of 3°C, the load on the refrigerator can be determined using common conduction heat transfer equations:

\[
Q_{wall} = \frac{A_{wall}}{R_{insul}} \times (T_{amb} - T_{inside})
\]

The last missing variables in this equation are the wall area A and the thermal resistivity R of the wall which determines the amount of insulation that has to be used. The initial design choice of desired storage volume directly determines the wall area A. This value has to be checked later on to see if it meets the design conditions mentioned above. In this case, a fridge of a 50 L volume was desired. The inner chamber was designed as a cube in order to provide a minimum surface area and thus reduce the possibility for heat transportation. One wall is 0.136 m², resulting in a total area of 0.816 m². In order to make reasonable choices for the insulation, it is helpful to plot the heat loss Q through a cool chamber wall over the amount of insulation R used (Figure 3-4) with the help of Equation 3-1.
The graph shows that at some point adding insulation has little effect on minimizing heat gain to the point at which potential leakages in the prototype become the far more important sources of heat loss and overshadow any potential effect. A value of about R-7 was chosen to be the desired insulation. The thermal resistivity R follows the following equation:

\[ R = \frac{x}{k} \]  

(3-2)

With x being the thickness of insulation in meters and k being the thermal conductivity (a material specific property in W/m·°C). For this prototype, expanded polystyrene, also called thermocol (similar to Styrofoam), was used as insulation material (The Engineering Toolbox 2012). Using this property, the required insulation thickness for this insulation is:

\[ x = k \times R = 0.03 \frac{W}{m \cdot °C} \times \frac{7 m^2 \cdot °C}{W} \]

\[ = 0.21 m \approx 20 cm \]  

(3-3)

Using formula (3-1), the maximum conductive heat load on the six sides of this fridge that has to be removed by the ethanol evaporating can be calculated as:

\[ Q_{cond} = \frac{6 \times 0.136 m^2}{7 \frac{m^2 \cdot °C}{W}} \times \frac{(43°C - 3°C)}{W} \]

\[ = 4.66 W = 0.11 \frac{kWh}{day} \]  

(3-4)

Since ethanol has a specific heat of vaporization of 0.925 kJ/g = 0.2569 kWh/kg, about 0.43 kg or 0.541 kg were needed at minimum to meet the demands of just meeting the conduction heat loss. The sizing of the ice storage system is similar: The storage system was sized to provide for three days of autonomy without any sunlight. As the phase change from ice to water is of interest here, the specific heat of fusion for water which is 0.0334 kWh/kg = 0.0928 kWh/kg has to be used. As 3 days*(0.11 kWh/day)/(0.0928 kWh/kg)= 3.6 kg, 3.6 l of water are needed around the evaporator at minimum in order for the ice to cover the heat load for three days. However, as this is a prototype, with all uncertainties and air leakages involved, enough space to hold up to five liters of ethanol and 12 liters of water at maximum were planned in order to allow for further experimentation work and safety margins. So, 17 liters are needed for the cooling, making 2/3 of the space or 33 liters available for payload. This is enough for the purpose intended, verifying the initial space assumption. In placing the cool chamber, it is important to leave it out of direct sunlight. To achieve optimal results, the cool chamber is placed in a dark and cool room.

**Evaporator design**

The whole system has three dedicated heat exchangers: The evaporator, the collector, and the condenser which should all be designed with a primary focus on maximizing heat transfer. Formula (3-1) states that heat transfer can be increased by reducing the thermal resistivity R or by increasing the surface area A. Formula (3-2) shows that R can be minimized by decreasing the material thickness and choosing a material with high conductivity k.

**Material selection**

The material selection is crucial for the design of effective heat exchangers: Choosing a good heat conductor such as copper instead of an average heat conductor like stainless steel increases the conductivity and thus the heat transferred by a factor 25(!) However, choosing proper materials was challenging in Patna: while materials like steel (k=16 - 30) (The Engineering Toolbox 2012) and iron (k=60 – 80) are easy to process they are not the most effective heat conductors. Copper (k=400) and Aluminum (k=205) are much better but come with their own problems. Copper is very expensive on the market and can drive the system costs up quite substantially. Aluminum is available and much cheaper, but requires special welding experience and equipment. Both were not available in Patna. However as for the prototype, efficiency is of great interest and the evaporator is comparatively small holding only five liters, so copper was chosen as material. If the evaporator turns out to easily match the power required, other materials could be considered in further prototypes.

**Material thickness**

Two factors have to be considered here: The thinner the material, the better the heat transfer, but the more instable the construction. This is relevant as due to the characteristics of ethanol the system will have to be operated at quite low pressures.
The black line in this phase diagram shows the boiling point of ethanol over the system pressure. In order to operate the cool chamber, ethanol has to boil at temperatures just below 0°C in order to be able to form ice for the storage system (blue line). The graph in Figure 3-5 shows that the system has to be vacuumed to pressures of about $10^{-2}$ atm in order to start working during the evaporation phase. In the regeneration phase, the temperatures of ethanol should go up. While the temperature of the ethanol increases, the system pressure will also rise until the ethanol condenses. If for instance ethanol will be heated up to 78°C, the system will reach atmospheric pressure (green line). The material should be able to bear these pressure differences over long periods of time. Compared to other steam systems which work at several atm pressure, this is not severe; so in practice a thickness over 1-1.5 mm was acceptable. Oftentimes the availability of material on the market dictates what to choose. However, these pressures are demanding the system to be absolutely airtight which is problematic. Another factor that can greatly influence the stability of the evaporator is the shape.

Evaporator form

Far more stressful to the material than the pressure itself, are the pressure changes that the system undergoes during a cycle. At night, the system is at low pressure and this is when ethanol boils and is adsorbed. In the reverse phase, during the day, ethanol is forcibly released by the carbon being heated up. This causes the pressure and the boiling point to rise until the ethanol condenses. This will happen at about ambient pressure. The form of the evaporator will determine if it will be able to withstand these pressure differences. Big boxes or other objects with flat surfaces will bend inwards when the pressure falls to return when the pressure rises. Gradually, this might cause material fatigue on the welded joints of the evaporator. One of the best forms in terms of surface area and especially stability is pipes. A heat exchanger made from pipes usually has a significant surface area which helps it to absorb heat effectively. On the other hand, pipes hold relatively little liquid, and therefore one would need a lot of expensive material to construct them. They are also very hard to form and join using normally available methods. So in this case, a combined pipe-box-structure has been designed in order to reach a good compromise.

Collector design

The collector is the second heat exchanger in the system, designed to heat up quickly in sunlight and give off heat effectively during the night. The collector has to hold the coal in place while at the same time allowing the vaporous ethanol to access it freely. The collector design should be considered with great care, since the design determines the temperature.
differences that can be reached and thus the efficiency of the system since the temperature is the main driver of the cycle.

The first step in sizing the collector is the determination of the amount of coal needed to absorb all the ethanol used in the system at nighttime ambient temperatures. Unfortunately, this proved to be rather problematic. Firstly, reliable in-depth studies about adsorption characteristics of activated carbon which are publicly available seem to be rare. Secondly, the studies that are available indicate that coal of different constructions at the atomic level behave very differently (Takanohashi, Terao und Iino 1999). Furthermore, accurate models could not be used since the only sources of activated coal that could be obtained were from an aquarium shop and a water filter company. The coal was delivered as small, relatively uniform grains, but came in unmarked bags without further data in order to set up models with. Lastly, the project is set up with the long-term aim to self-produce activated carbon on site as described for instance in (Olomega und Orere 2012) in order to spare on costs. Because of the situation, experiments with the first prototypes might help more than modeling. For the first prototype the team started assuming average adsorption characteristics while designing enough capacity to stock up on coal later with a second back-up collector.

According to (El-Sharkawya, et al. 2008), high performance carbon can adsorb up to 1.2 kg or 1.52 liters of ethanol per kg. The design was performed with a more conservative ratio of 0.5 liters of ethanol per kg of carbon, to account for inaccuracies. Thus, 10 kg of activated carbon were used in the design to adsorb the ethanol. As the collector would be much larger than the evaporator, aluminum had to be used instead of copper for material costs. For the stability constraints previously, a pipe design was preferred. As previously said, it was not possible to weld aluminum in Patna, because of the difficult nature of the welding and tools required, so a collector had to be designed in which the pipes could be glued into.

Figure 3-7 shows the design of the collector, while Figure 3-8 shows an in-depth look at the design of the tubes (one inside another):

![Collector design](image)

![Pipe anatomy](image)

The carbon is filled into long, thick aluminum tubes, while another small and slightly longer aluminum tube rests in the center of the carbon (as shown in Figure 3-8). The inner tube is hollow and allows ethanol to reach the carbon uniformly through small slits punched in it (aluminum is very soft and thus easy to penetrate). This piping construction sits in a framework consisting of two steel headers and metal bars for stability (metal bars not depicted). The pipes are glued into stumps, which are welded to the headers, with silicon glue in order to provide an air tight seal. Inside the stumps, the pipes rest on a rubber ring, while inside the tube a metal wire mesh is wrapped around them to fix them in the middle of the outer tube. The whole construction sits on a corrugated iron sheet for stability and to allow for experimentation with water cooling. Both the corrugated sheet and the aluminum tubes are painted black (not depicted) for increased absorptivity, also known as blackbody radiation. The collector is encapsulated in a green house, whose glass can be closed during the day in order to trap the air for increased heating, and opened during the night to allow the air to escape for fast cooling (not depicted).

**Condenser and basin**

The valves and pipe design force the ethanol from the collector through the condenser into a basin. Both do not need to be especially sophisticated. The condenser is a large fin structure whose purpose is to draw as much heat as possible out of the ethanol. For that purpose, a small fan powered by a photovoltaic cell can optionally be placed under the condenser to increase convection.

The basin needs to be able to hold all of the ethanol used in the system at one time. The basin is a place for the ethanol to be
collected and to cool down to ambient temperatures before it flows back into the evaporator in liquid form so it does not heat up the cool chamber; heating up the refrigerator with hot ethanol would obviously very negatively impact the system. Because this happens over a long period of time, the heat exchanger properties of this basin are not of primary concern. Ideally, the ethanol should be stored in the basin just until after the evaporation process has started in the night. The fraction of now evaporated ethanol, trapped in the basin, should cool down the rest of the ethanol in the basin to even lower temperatures that are more suited for the cool chamber. Upon opening the valve, the ethanol flows in the evaporator. Overall, the basin is used to prevent huge temperature changes in the cool chamber.

4. CONSTRUCTION
Every little detail that has not been looked at during the design phase can be a huge obstacle in constructing the first prototype. This chapter contains practical experience of all issues that arose during manufacturing and ideas on how to tackle them.

4.1. COOL CHAMBER
The construction of the cool chamber was quite straightforward. However, with the methods available, a perfectly matching lid for the cool chamber could not be built. In order to minimize the leakage, the touching parts of the lid and the base have been applied a thick layer of silicon glue, see Figure 4-1. Once the glue was spread on, the lid was pressed on top of the fridge so that the glue would dry while being pushed down by weight sitting on top of it. The group used the weight on top of the lid in order to apply pressure to create a tight fit. A layer of plastic wrap in between prevented the two layers of glue from merging during the drying phase.

4.2. EVAPORATOR
The evaporator was the hardest part to weld. Each side needed 16 pipes joined to the outer box. It turned out that it was best to weld the pipes to the inner parts of the boxes before the boxes were welded shut. The pipes should be bent a little at the tip in order to stabilize the box; a sharp point would risk damaging the box and piercing through the copper. After that procedure, last leakages could be fixed by again applying a small ring of silicon glue at the joints from outside. In hindsight, nine pipes instead of 16 might have greatly reduced the complexity of this operation.

4.3. COLLECTOR
The use of metal spacers proved to be most helpful here. The first spacer is wrapped around the outer aluminum pipe and put in the stumps to ensure the outer pipe does not wiggle. This ensures that the pipes rest in the middle of the stumps and are therefore uniformly surrounded by glue. The other spacers used were small metal mesh rings with a hole in the middle. While filling the outer aluminum pipe with coal, the mesh spacers are added in equal distances from the header ensuring that the inner aluminum pipe is fixed in the center of the outer pipe the whole way up.
4.4. CONDENSER AND BASIN

For the condenser, a standard unit from an old fridge, ice cream truck, or car is more than sufficient. This saves time and costs as old standard units are easily available on local markets, also in scrap yards. In Figure 4-6, on the left, the condenser is lying down flat with the yellow fan below it, while the basin is the long silver cylindrical item towards the right.

4.5. PIPING SYSTEM AND VALVES

Thorroughness in assembly on the system is vital, as a system that is supposed to hold low pressures of about $10^{-2}$ atm over years has to be absolutely airtight. This turned out to be the biggest challenge in the construction and is not fully resolved in the prototype by today. The pipe connection is most prone for leakage. Using proper pipe fittings is essential and silicon glue proves to be a good help to fix the leakages occurring, providing you use the right amount. However, to date (August ’11), the leakage in this prototype is an issue still being worked on.

The valves can also be standard units from the market. Optionally, a check-valve could theoretically be used for the direct connection to further simplify the operation of the system. However, it is still to be tested if the occurring head loss by such a valve does indeed negatively impact the system.

4.6. ASSEMBLY

Before assembling the whole system, it is heavily recommended to test the individual parts for airtightness using a vacuum gauge. Occurring leakage is not always easy to locate. Two methods have proven to be very helpful in the construction of this prototype. The device-under-test can be set under high pressure and be submerged in a huge basin filled with water, if air bubbles appear, the leak is traceable. Larger parts can be tested by rubbing soap water on the outside, then after setting the unit under high pressure, the soap water will start to create bubbles at the point where air leaks out.

5. FUTURE PLANS

At present, before the first test runs can be conducted, the last leakages have to be located and fixed. This turned out to be quite time-consuming and might still take more time. After
starting the refrigeration system, first test data can be taken by monitoring all relevant temperatures in a seconds-scale over several months by a custom temperature logger. Among other things, this allows for an estimation of the system’s COP (coefficient of performance). After that, further tests and stages are planned. Firstly, the system’s ethanol and carbon usage can be optimized. Secondly, the effect of several design ideas, like a check-valve and an electrical fan at the condenser can be monitored. After that, using temperature sensors, the system’s function could be fully automated. Lastly, it is suspected that the system does not need a full day/night-cycle to evaporate/condense all the ethanol. If that turns out to be the case a multi-phase system could be created that allows the collector to cycle several times a day. At peak temperatures, the collector could be covered by a blanket, opened and the pipes be cooled with water. Then, the cycle could begin anew. This could effectively increase the capacity or reduce the amount of active materials needed.

6. CONCLUSION

At present, the system in Patna is a prototype under development. But since solid manufacturing expertise and huge interest in such a system accompanies the development, the team is confident to be able to create a refrigerator well-suited for the local environment in Patna. Cost-reduction will be the next challenge in order to allow for a large-scale distribution of such devices. According to the project team’s estimation, the potential fields of application for solar cooling are enormous in Patna. The field is also not limited to vaccine refrigeration. Common cheap freezers and refrigerators are desperately needed in areas that are not covered by stable electricity and where standard refrigerators are too expensive for the broad masses.

Air conditioning is a common luxury among those who can afford the high costs for material and electricity. For these proposes a desiccant system could also be considered and might be cheap and well-suited due to less complexity. A cheap system might open up a significant market of solar air conditioning for the masses as despite the many differences in this fascinating county, the interest in reliable, grid-independent, clean cooling applications are common to very large parts of the nation.

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