Stored Energy Solar Cookstove for Rajasthan, India

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1. Background and Context

1.1 Introduction

The lush forests in India comprise 8% of the world's total biodiversity[1] and contribute roughly 235.78 billion rupees to the national GDP[2]. However pressure from increasing populations – both human and livestock – are destroying this incredible resource. In India, an estimated 800 million people use biomass for cooking[3] and 55% of the forest's national GDP contribution is in the form of firewood[2]. The burning of wood as fuel leads to massive increases in deforestation and greenhouse gas emissions. Conservation efforts to protect the forests began in the early 1900s[4], but conservation-based restrictions and banning of wood collection in protected areas has led to illicit activity instead of a decrease in forest usage. This has been well documented for the Kumbalgarh Wildlife Sanctuary (KWS) in Rajasthan, India which is the home of threatened wildlife including the Sloth Bear, Starred Tortoise, and Sterculia Urens. The KWS also forms an important ecological barrier preventing the extension of the Thar Desert into the Aravalli hill ranges.[1,5,6] There are 22 villages located inside the KWS and 138 in close proximity requiring increasing amounts of wood for fuel and cleared land for farming and livestock. A typical household in the area consumes 6-8 kg firewood per day and ~30% of households sell ~10kg wood per day.[1] The inhabitants of these villages are well aware of the effects of deforestation evident in the scarcity of wood resources, crop raiding by animals in the KWS that are losing their natural habitat, and recent climate changes including a decrease in rainfall and an increase in the frequency of drought.[1] Women now spend up to 7 hours per day collecting firewood due to scarce wood resources[7] and even risk rape and extortion by venturing into protected lands when wood is not available elsewhere.[8]

1.2 Climate Healers and the Solar Cookstove Solution

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[1] Personal Communication with the Foundation for Ecological Security (FES).
[2] Personally communicated by FES representative from a report from the Insitute of Economic Growth (IEG), New Delhi, India, 2002.
[3]https://www.engineeringforchange.org/workspace/view/22/1#tabs=/workspace/files/22/1
[4] http://rajforest.nic.in/general_intro.htm
[5] P Robbins, K McSweney, A Chhangani, JL Rice. Conservation as it is: Illicit resource use in a wildlife reserve in India. *Human Ecology* 37 (5) 2009.
[6] PF Robbins, AK Chhangani J Rice, E Trigosa, SM Mohnot. Enforcement authority and vegetation change at Kumbhalgarh Wildlife Sanctuary, Rajasthan, India. *Environmental Management* 40 2007.
[7] Poster presented by students of the University of Iowa titled "Rural India Solar Cooker Implementation" by B Behrendt, W Davies, E Guio, J Mahlik, A Moffitt, B O'Loughlin, E Osgood, J Richards, & M Toth.
[8] Personal communication with Sailesh Rao of Climate Healers.

An alternative to cooking with firewood would greatly decrease the pressures on the KWS and the greater forests of India while simultaneously decreasing greenhouse gas emissions and saving time for the women who currently spend hours collecting wood. Furthermore an alternative to burning biomass indoors would decrease harmful smoke inhalation and resulting respiratory diseases. NGO (Non-Government Organization) Climate Healers began partnering with local environmental NGO FES (Foundation for Ecological Security) in 2008 to develop such an alternative. FES has worked in the region since 2002, gaining a deep knowledge of the complex issues surrounding deforestation of the KWS. FES also partners with the Indian Rural Employment Board to fulfill the Indian government's National Rural Employment Guarantee of 100 days of employment at 100 rupees per day for one member of each household. FES proposes and oversees projects for the Indian government, but is running out of work to be done.[9]

To eliminate the use of firewood for cooking, Climate Healers proposed a solar cookstove to replace the 3-stone fire currently used to burn biomass for cooking. The solar cookstove would take advantage of the impressive solar irradiation of the region and would ideally be manufactured in the villages to provide employment projects through FES and the Indian government. Climate Healers chose to focus first on the village of Karech as a representative of the dry Rajasthan region and Hadagori as a representative of the Orissa region known for monsoons. The work described in this report focuses specifically on Karech with the hope of expanding to all forest-proximal regions of India once the concept has been proven.

Karech is a village of 240 households where nearly every household must take advantage of the government's National Rural Employment Guarantee. Initial contact and communication with the village of Karech involved the distribution of 2 solar lights per household, which led to impressive popularity and respect for Climate Healers as the solar lights allowed the villagers to work and study at night, avoid snakes when venturing into the forest in the early morning, and create a festive environment for weddings and festivals.[10]

Six prototypes of the first Namaste solar cookstove developed by Climate Healers were introduced in the villages of Karech and Hadagori in January 2010. The response was overwhelmingly negative due mostly to the fact that the Namaste stove requires use during the day when the inhabitants of the village are busy with work and other chores. This was noted to be in stark opposition to the solar lights, which could charge unattended all day and be used at night. Other feedback from members of the villages who tested the stove included:

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[9] Personal communication with Sailesh Rao of Climate Healers.

[10] Climate Healers Project Report from August 2010 available on the Engineering for Change website:
https://www.engineeringforchange.org/workspace/view/22/1#tabs=/workspace/files/22/1

- The Namaste stove can only be used outdoors and during the day; whereas traditional cooking is done indoors before sunrise and after sunset.
- The Namaste stove is unstable given the hilly terrain and windy conditions of Karech.
- The Namaste stove is too tall for the traditional approach of cooking while seated.
- The Namaste stove is inconvenient because it requires constant adjusting and attendance.
- The height and attention required make it difficult to hold a child while using the Namaste stove.

Climate Healers therefore resolved to design a stored energy solar cookstove to enable cooking at typical mealtimes in Karech: after sunset and before sunrise.[11]

1.3 The challenge of the stored energy solar cookstove

The ideal stored energy solar cookstove must meet the following design constraints:

- Solar energy storage: Numerous solar cookstoves and solar ovens without storage exist as models for solar collection and are discussed in section 2. Solar storage options include storage in the form of electricity, sensible storage materials (sand, vegetable oil, engine oil), latent heat storage materials (acetamide, stearic acid, acetanilide, erythritol …), or chemical storage. Each of these options is explored in detail in section 2, but many are still in development for small-scale applications.[12] This addresses the needs of the primary stakeholders – the women of Karech.
- Use of local materials: Local materials in the village of Karech include sand, bamboo, brick, and of course the wood that we aim to protect. Outside resources must be brought in on rough and curvy roads. There is one general store in the village of Karech supplied via these roads.[13] This addresses the need of stakeholder Climate Healers to keep costs low and decrease impact on the environment.
- Manufacturing in the village: Manufacturing in the village would provide projects for the National Rural Employment Guarantee and therefore funding through the Indian government. In addition, users of the stove

[11] Climate Healers Project Report from August 2010 available on the Engineering for Change website:
https://www.engineeringforchange.org/workspace/view/22/1#tabs=/workspace/files/22/1

[12] RM Muthusivagami, R Velragj, R Sethumadhavan. Solar cookers with and without thermal storage – A review. *Renewable and Sustainable Energy Reviews* (14) 2010.

[13] Personal communication with Sailesh Rao of Climate Healers.

would have an invested interest having constructed the stove themselves and be more likely to be able to fix a broken stove. This addresses the need of stakeholders FES and the Indian government such that they could use cookstove manufacturing as a project for the National Rural Employment Guarantee. This would also aid the inhabitants of Karech as they would be more familiar with the cookstoves increasing their ability to fix any problems that arise.

- Cooking of traditional meals: Meals in Karech are prepared by the women and involve roti – a dry dough of flour and water that puffs upon frying at high heat for several minutes, dahl – lentils that are added to boiling water and then simmered for roughly 20 minutes, and tea – which also requires boiling water. A meal consists of roughly 2 roti for each member a family of 5-6 plus dahl and tea. When asked if they would use a solar stove, inhabitants of Karech claimed that if Climate Healers could show the how to cook roti, they would use the solar cookstove. We therefore based our design constraints on cooking roti as described in section 4. This again addresses the need of the primary stakeholders: the people of Karech.

Small-scale energy storage for thermal applications such as cooking is a difficult and unsolved problem. The addition of local manufacturing and resources adds an extra layer of complexity.

2. Preliminary Design: Brainstorming and Research

We purposefully included all brainstorming ideas in this report – even the wild and crazy ideas – as these may prove inspirational in the future. In the spirit of brainstorming, we did not want to narrow, discourage, or judge; however in this section we do offer the pros and cons of each potential solution.

2.1 Thermal energy based ideas

2.1.1 Collection

In this section approaches to collect the radiated sunlight and transport it to the storage unit will be discussed. All approaches include a cylindrical parabolic mirror as first reflector, as shown in Figure 2.1. This collection design was used for brainstorming as it is the current collection design proposed by Climate Healers.

Direct collection: This is the simplest option. Reflected light is directly stored in a suitable storage medium inside an evacuated glass tube placed in the focus point of the parabolic mirror. (Setup similar to Fig. 2.1, but the evacuated tube would contain the storage medium without an external storage system.)

Optical collection: Optical collection requires at least one additional mirror to transport the reflected light to the storage unit.

Heat pipe: The reflected light will be concentrated on an evacuated glass tube containing a heat pipe, which transports the energy to a storage unit (fig. 2.1).

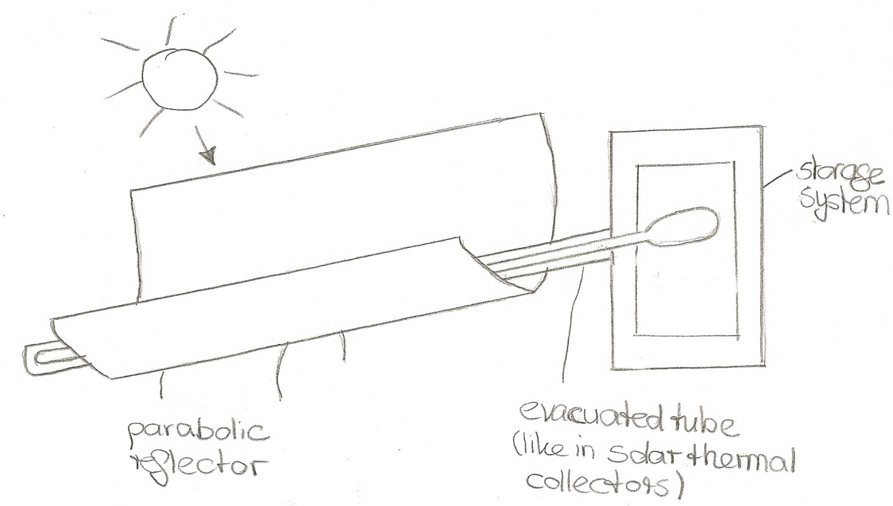


Fig. 2.1: Heat pipe collection system.

The heat pipe system has the following advantages:

- It is well known for roof top solar thermal water heating systems,
- the evacuated heat pipes are available in China,
- the separation of collection and storage, and

- a bigger storage volume is possible.

And disadvantages:

- the separation of collection and storage makes the system bigger.

2.1.2 Storage

Storage of thermal energy includes two options: sensible heat storage and latent heat storage. These options are described in further detail in section 4.1. Desired characteristics of the storage material are:

- High specific heat capacity,
- long term stability under thermal cycling,
- compatibility with its containment, and
- low cost.

Sensible heat storage: Sensible heat storage (SHS) occurs by adding energy in form of heat to a storage medium and increasing its temperature without changing its phase (fig. 2.2).

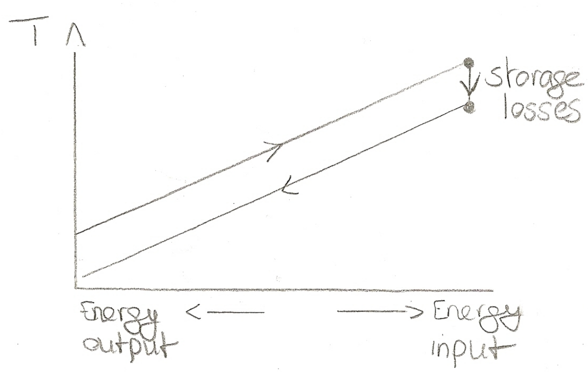


Fig. 2.2: Sensible heat storage.

Possible storage media are liquids like water, salty water, molten salts, and oils and solids like rocks, sand, building fabric, and metals.

Water would be most desired, since it has the highest heat capacity of all storage media, but it has a low temperature of evaporation so that SHS above a temperature of 100 degree Celsius would require putting the system under pressure to prevent vaporization.

Oils and molten salts have about 25-40% of the heat capacity of water but have a lower vapor pressure, so that they can operate at higher temperatures of 300 degree Celsius and above.

Solid storage media can be used for low to high temperature storage. The specific heat capacity of stones and sand is ~0.25 and 0.5 of the specific heat capacity of water so that the mass necessary to store the same amount of energy is ~4 and 2 times higher respectively.

Advantages of sensible heat storage systems include, that

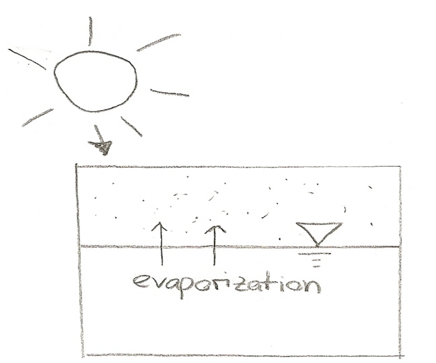
- the material is cheap and highly available,
- the material is non-toxic and safe,
- the system is simple in design, and
- the system is robust, (stable and does not degrade over time).

Disadvantages of sensible heat storage systems are that

- it cannot store and deliver the energy at a constant temperature,
- the conductivity is low,
- the storage unit has a big volume and mass, and
- higher temperatures require more insulation is necessary to prevent losses.

Latent heat storage:

Latent heat storage (LHS) systems make use of the energy stored when a material changes from one phase to another (fig. 2.3). Phase change can occur from solid to solid, solid to liquid, and liquid to gas. Only few solid-solid phase change materials (PCM) have the right heats of fusion and transition temperatures for thermal storage applications. Liquid-gas PCMs usually have high heats of transformations, however, due to the large volume change during transformation, they are not usually considered for practical applications. Solid-liquid PCMs are useful because they store a relatively large quantity of heat over a narrow temperature range, without a corresponding large volume change (Hasnain[14]).



[14]Hasnain, S. M.: *Review on sustainable thermal energy storage technologies, part 1: heat storage materials and techniques.* Energy Conversion and Management, 39:1127-1138, 1998.

Fig. 2.3: Latent heat storage.

Advantages of latent heat storage include

- low weight and volume of the storage unit,
- energy storage and delivery at constant temperature, and
- that the whole storage volume can be reached easily due to a high thermal conductivity.

Disadvantages of LHSs are:

- Degradation of the PCM over time,
- safety issues due to PCM and potentially higher pressure
- complex design, and
- high cost.

Ataer[15] and Hasnain[14] provide more information about sensible and latent heat storage systems.

2.1.3 Delivery

Heat delivery systems have the function of transporting the heat from the storage unit to the burner at a certain temperature and power. In order to vary temperature and power a device to control those should be included.

<u>Heat pipe/thermosyphon:</u>

Heat pipes and thermosyphons use liquid to gas PCMs as heat transfer medium. Two different possible systems are pictured in figure 2.4.

The bottom part of the heat pipe is inside the hot storage unit so that the liquid will evaporate, flow up to the heat sink, condense, and flow down again. The difference between a heat pipe and a thermosyphon is that heat pipes contain a wick fixed to the inside surface so that in addition to gravity, capillary forces return the condensate to the evaporator.

[15]Ataer, O. E.: *Storage of thermal energy.* in Energy Storage Systems, Edited by Y. A. Gogus, in Encyclopedia of Life Support Systems (EOLSS), Eolss Publishers, Oxford, UK, 2006.

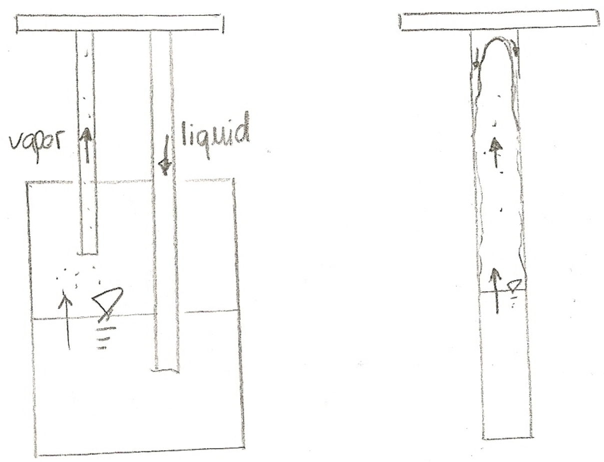


Fig. 2.4. Heat pipes/thermosyphons.

Heat pipes/thermosyphons have the advantages of

- a high thermal conductivity,
- heat transfer between places of different temperature is possible,
- the heat flux is easily tunable with a valve, and
- it is possible to transport the energy from outdoors (collection) to indoors (traditional cooking location) with a tube through the wall.

And disadvantages of;

- you have to find a suitable PCM for the temperature range,
- there are safety issues when the system is under pressure,
- the PCM is degrading over time,
- the cost is high,
- the design very complex,
- the system not very robust so that long time testing is necessary, and
- maintenance might be difficult because of the complexity of the system so that it might be hard to find the reason of failure.

More information about heat pipes and thermosyphons in Heat Pipes by Reay and Kew[16].

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[16]Reay, D.A. and P.A. Kew: *Heat Pipes - Theory, Design and Applications.* Butterworth-Heinemann, Oxford, 5th edition, 2006.

Conductive heat transport:

Heat can also be transported by conduction through metal only. One or more metal rods connect the storage unit with the hot plate.

Advantages of this design are:

- the simplicity in design,
- the low cost,
- the long lifetime, and
- the reason of failure is obvious so that maintenance is easy.

Issues with a conductive heat transport system might be:

- finding a way to control temperature and power,
- the compatibility with other materials (rust might be an issue), and
- the lower conductance of metal compared with a heat pipe system.

Advanced heat exchanger:

In an advanced heat pipe system a two fluid heat exchanger is improved with small heat pipes connecting the two channels (fig. 2.5).

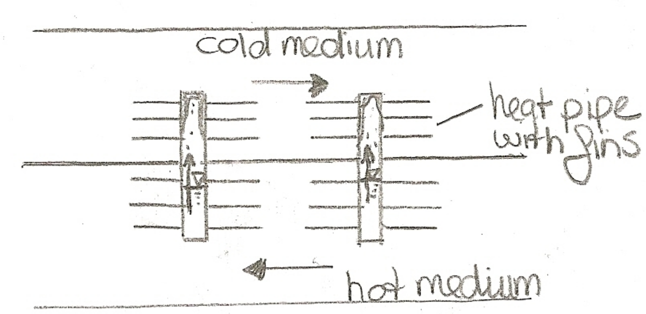

Fig. 2.5: Advanced heat exchanger.

Advantages are:

- Good heat transfer,
- separation of storage unit and burner, and
- transport of energy into the house is possible.

Disadvantages include:

- The integration of a two fluid heat exchanger into the storage unit,
- it might occupy a bigger space,
- and the higher costs.

Modular cooking:

The idea is to store energy in small separate modules during the day and bring them into the house to cook on them during the night.

Advantages:

- an easy concept, and
- you cook inside the house without putting a hole in the wall,

Disadvantages:

- the achievable power might not be high enough,
- losses to the environment might be higher, and
- people have to be around to exchange the modules while charging.

2.1.4 Complete solutions

Heat pump system:

A heat pump is a system where a fluid is heated at the heat source (solar collection), is pumped to the heat sink (burner) where it releases its heat and then gets transported back to the source (fig. 2.6). The tubing outside the house is laid into the surface of the ground.

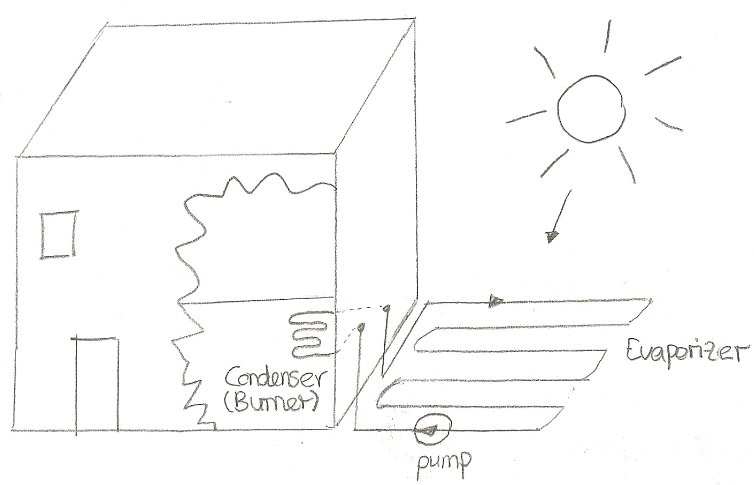

Fig. 2.6: Heat pump system.

Advantages of this technology are:

- It's proven for heating and cooling,
- cooking inside the house is possible, and

- it's simple since it only uses pipes and a pump.

On the other hand possible issues might be

- that it has not been used for cooking yet,
- that the pump and the tubing is expensive,
- that the energy stored in the pipes is not enough, and
- the losses might be too high.

Pizza oven:

The pizza oven idea is to use This could be accomplished by This could be integrated with the modular cooking idea described earlier or used to cook roti throughout the day.

Advantages:

- This technology has been used extensively
- And does not require attendance during the day.

Disadvantages:

- Solar ovens are not compatible with

Cooking slowly over the day:

There are already a lot of ideas for cooking slowly over the day out there. For example the HotPot[17], a special panel cooker, which has a dark pot suspended inside a clear pot or box cookers. Alternatively, a pizza oven design would require an insulated cube of sand with a slit inside to bake the roti. Another option includes an insulated bulk of sand in the ground with a window on top where the solar radiation comes inside and heats the sand.

Advantages of slowly cooking over the day includes:

- It is cheap,
- simple, and
- already proven

Disadvantages are:

- Somebody has to observe the food to avoid burning
- traditional cooking of roti, which requires high heat for several minutes only.
- Either way, slow cooking requires a change in traditional habits.

[17]http://www.she-inc.org/cooking.php

Hybrid storage system:

In a hybrid system two or more solar cooking systems are combined. In this case we imagine a water storage tank combined with insulated cavity and a HotPot. The HotPot will cook Dahl slowly over the day, the insulated cavity will bake the Roti and the water tank preheats water for cooking tea and Dahl and can also be used for other purposes such as bathing.

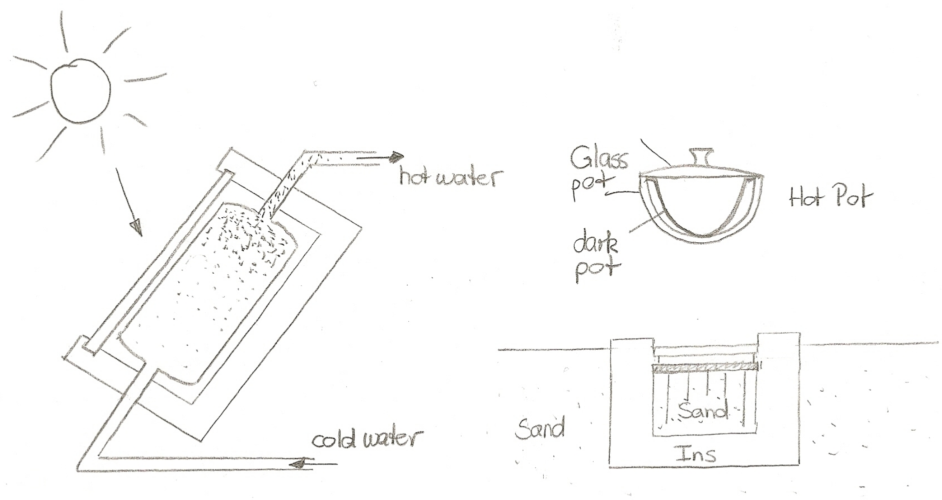

Fig. 2.7: Hybrid system.

Advantages of a hybrid system are:

- Hot water as extra service (luxury item) and preheating for cooking,
- water storage system easy and well known,
- HotPot commercially available or easy and cheap to build,
- sand storage easy (hole in ground, insulator, absorber and glass plate),
- less storage for each system, and
- high reliability.

Disadvantages might be

- that it is more complicated to use three different systems, and
- that a change in habits is necessary to cook Roti in the insulated cavity

2.2 Electrical energy based ideas

An alternative to thermal solar energy storage, transport, and cooking is to generate electricity, store the electricity in batteries and use an electrical stove for cooking.

2.2.1 Generation

Solar photovoltaics (PV):

Using solar PV panels would be a direct method to generate electricity from solar radiation.

The advantages of this generation method are

- that the losses are small through direct generation of solar to electrical energy
- the energy can be directly stored into a chemical storage unit,
- it is a proven technology, and
- it is quiet.

Disadvantages are:

- PV modules are quite expensive
- losses upon conversion back to thermal for delivery are potentially high, and
- an engine has to connect the PV modules with the mechanical or gravitational storage mechanism.

Thermoelectric device:

A thermoelectric device uses the temperature difference between concentrated solar radiation and the environment to generate electricity by a phenomenon called the Seebeck effect.

Advantages are

- the direct transformation to electrical energy without thermal energy,
- the direct connection to a chemical storage unit, and
- that it is quiet.

Disadvantages include

- high cost,
- the low voltage, and
- that it cannot be directly connected to a mechanical or gravitational storage mechanism.

2.2.2 Storage

Storage in batteries:

Advantages of the battery storage are:

- that it is soundless
- easy,
- small, and
- that the losses are very small.

Issues with the battery storage are

- the high weight,
- the high prize, and
- the short lifetime.

Storage by hydrogen storage:

A hydrogen storage has the advantages that

- it is soundless,
- that the hydrogen can be burned to cook or transformed to electricity with a fuel cell, and
- it does not degrade over time.

On the other hand there are

- safety issues in storage and handling of hydrogen and
- the storage cylinders are expensive.

2.2.3 Complete systems

PV + hydrogen storage:

An example of a complete system for electrical energy based systems is a combination of PV generation and hydrogen storage (fig. 2.9). The conversion of electricity to hydrogen will be done by electrolysis. The stored hydrogen can either be burned or transformed to electricity by a fuel cell.

An advantages of this system is

- that it is quiet.

Disadvantages are:

- The complexity of the system,
- the costs, and
- that it involves many conversion steps that create losses.

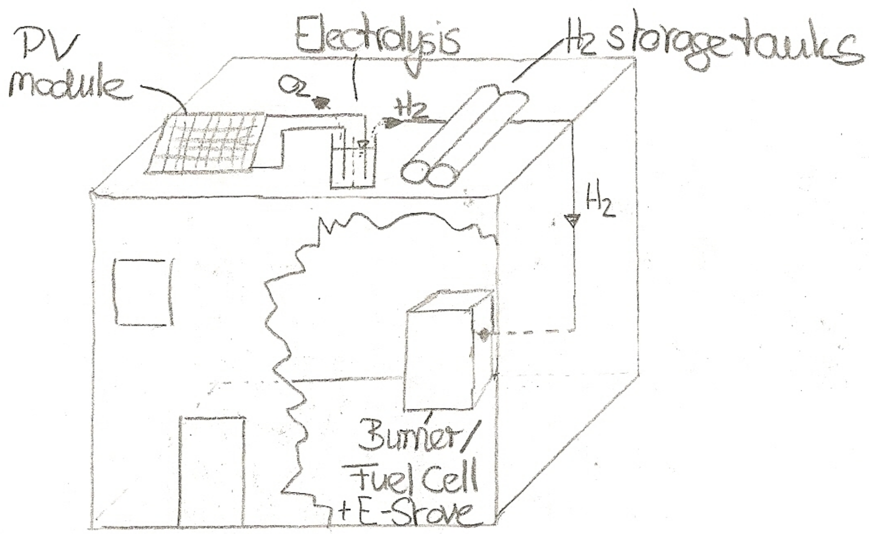

Fig. 2.9: PV and hydrogen combined system.

2.3 Mechanical energy based ideas

2.3.1 Generation

<u>Stirling engine:</u>

A Stirling engine uses air or other gas as working fluid, which undergoes cyclic compression and expansion by pushing the gas alternating from the heat source to the heat sink. The translatory movement of the piston gets transformed into a rotating movement of the crank shaft which can be connected to the shaft of a generator or directly to a pump, fly wheel, etc., which will store the energy.

Advantages of the Stirling engine are

- that it can be directly connected to the mechanical or gravitational storage mechanism,
- it is a proven technology, and
- it is commercial available.

Issues with a Stirling engine might be

- that it is expensive,
- noisy, and
- it contains moving parts so that maintenance is more frequently necessary

Steam turbine:

In this case the concentrated solar radiation heats, evaporates, and superheats water and pumps it into a turbine where the superheated gas expands. In a following condenser the gas is liquified and starts the cycle again. The turbine is either connected to a generator or directly connected to the storage mechanism.

Advantages are

- that the turbine can be directly connected to a mechanical or gravitational storage mechanism and
- that the technology is proven.

Disadvantages are

- safety issues with high pressurized superheated gas,
- the complexity of the system,
- the size of the system,
- that it is noisy, and
- requires frequent maintenance procedures.

2.3.2 Storage

Storage in gravitational energy:

Storage in gravitational energy can be done by either by a water pump storage system or a weight lifting system (fig. 2.8).

Advantages are

- that there are (almost) no losses during storage and
- that the system is well-known for large scale electricity buffering.

Disadvantages include

- the size of the system,
- the complexity of the system,
- that it is noisy, and
- that it is expensive.

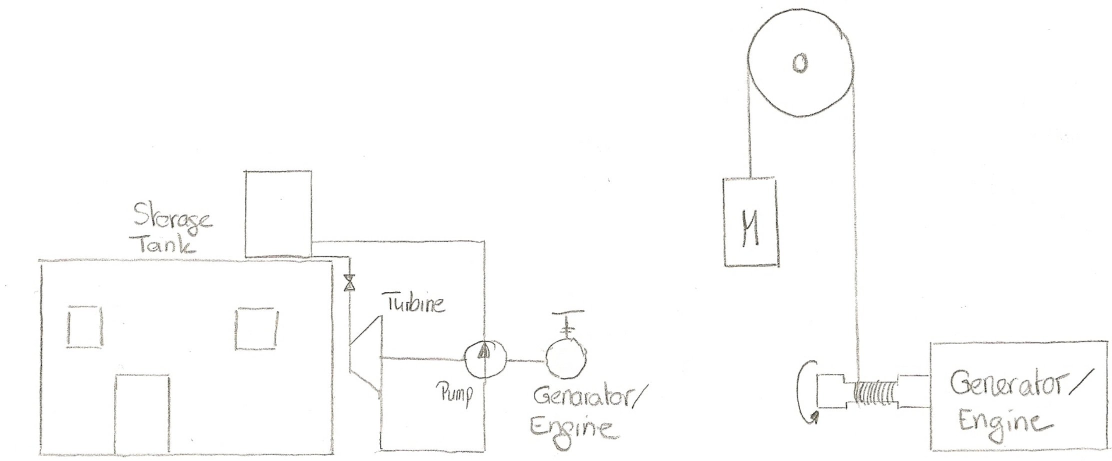

Fig. 2.8: Storage in gravitational energy: pump water system (left) and weight lifting system (right).

<u>Storage in mechanical energy:</u>

Storage in mechanical energy can be done by a flywheel. The flywheel gets accelerated to store the energy and releases the energy by braking.

Advantages are

- the size of the flywheel is small and
- it is quiet.

Issues might be

- that not enough energy can be stored in a flywheel and
- that it is expensive.

2.4 Alternative Fuels

In this section some alternative fuels to direct solar radiation will be discussed.

<u>Animal dung and/or waste:</u>

To handle and burn animal dung or waste has the following advantages:

- it is available,
- it is free,
- it is already dried though the sun,
- it disposes waste and dung, and
- it does not change cooking habits.

Disadvantages might be

- health hazards of handling waste,
- hazardous gases (or at least an unpleasant odor) when burning

Sustainably grown plants:

Here the sun is used indirectly to grow plants for burning as it is shown on the schematic on figure 2.10.

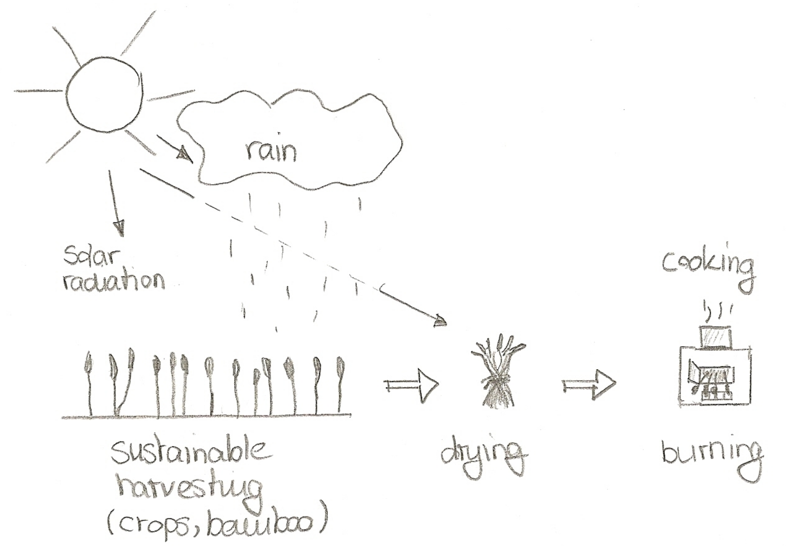

Figure 2.10.

Advantages of this approach are

- that there is no change in cooking habits,
- it is very simple, and
- it does not involve high technology.

Disadvantages:

- the plants have to be grown and harvested which takes extra time,
- it is not known which plants can be grown in the Rajasthan environment, and
- Smoke inhalation remains a problem.

3. Collaboration: Introduction to the Hawkeye Cooker and design trade-offs

3.1 Hawkeye Cooker: description and design trade-offs

Climate Healers founder Sailesh Rao told us in our first meeting that a class of about 30 undergraduate students at the University of Iowa[18] is working on designing the stored solar cook stove as well and that they are concentrating on collection and storage. Until our first Skype meeting with Iowa, which took place in the beginning of March, we had not planned to collaborate on a prototype. Iowa presented us their approach, shown in Figure 3.1 A cylindrical parabolic mirror concentrates the solar radiation on a second V-shaped mirror in the focal point which reflects the light down through insulated glass to an absorber plate in the storage unit. The storage unit consists of sand and aluminum cans arranged in an array to maximize conduction throughout the unit. The sand unit is kept together by cement boards, which are surrounded by rice husks that insulate the storage unit from the environment. The cooking surface is thermally connected with the storage unit by a heat delivery system. The Hawkeye solar cooker includes two separate storage units for evening and morning cooking. Each unit is mounted on casters and rails so that it can be rolled into the house for cooking[19].

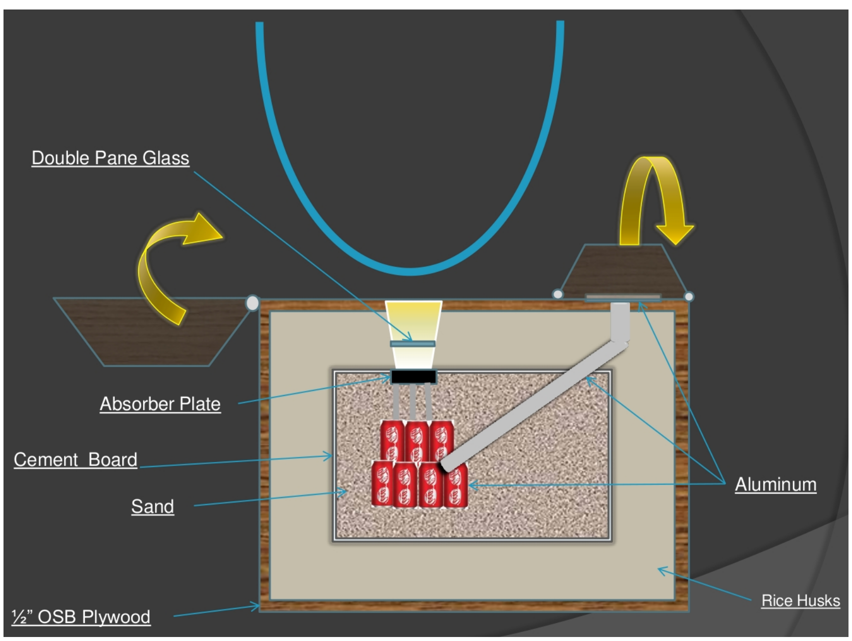

Fig. 3.1: Hawkeye Cooker[20].

[18]http://www.uiowa.edu/
[19]Iowa class presentation slides and personal communication
[20]Iowa class presentation slides

The Iowa team aimed to use local materials resulting in a design using sand and aluminium cans for energy storage. This is a sensible heat storage system, which is big in size (storage size alone: 6 feet x 3 feet and ~500 lbs) and cannot store and deliver heat at a constant temperature. The circumstance makes the design of a heat delivery system more complex and the losses higher. [19]

Our first meeting with Iowa occurred after already brainstorming design ideas and researching storage options and material options. Several of our ideas overlapped with theirs such as the use of local materials, sand, and aluminum as heat storage and the need to break down the design into solar collection, heat storage, and heat delivery. The Iowa team had plans and designs in progress for all elements of the stored energy solar cookstove except the heat delivery. We therefore took on the task of designing a heat delivery system that could integrate with the Iowa team's developing storage design for successful cooking of roti.

3.2 Design constraints for heat delivery

Iowa's design approach and first simulation set some design constraints for us. The fact that they use a sensible heat storage system with variable storage temperature requires a temperature control unit in our heat delivery system. Another constraint is the temperature available in the storage tank during cooking. Iowa's temperature simulation predicts storage temperatures of 90 to 200 degrees Celsius for the morning cooking and 250 to 400 degree Celsius temperature ranges for evening cooking times. [19]

3.3 Redefinition of Berkeley team goals

Our overall team goals remain as originally defined: to preserve the forests of Rajasthan and improve the standard of living and quality of life in Karech. To accomplish this we originally defined both optimal and minimal goals as follows:

- Optimal: Design a stored energy solar cookstove that can successfully cook roti in the evening and the next morning.
    - Minimal: Design a stored energy solar cookstove that can successfully cook roti in the evening.
- Optimal: Use all local materials.
    - Minimal: Use local materials as much as possible.
- Optimal: Design such that material costs are less than $50.
    - Minimal: Design such that material costs are less than $100. (Both recommendations from Climate Healers.)

Once we decided to collaborate with Iowa, our goals changed to reflect this new focus:

- Optimal: Design a heat delivery system that can successfully harness the heat stored in the sand/aluminum storage system designed by the Iowa team and deliver heat to a cooking surface to cook roti to the standards of the Karech village.
    - Minimal: Harness the heat provided by the Iowa team evening cooking prototype too cook roti to the standards of the Karech village.
- Optimal: Develop alternative approaches to the Hawkeye Cooker design.
    - Minimal: Develop options for improving both the heat delivery system and stored energy solar cookstove design as a whole for implementation in the future.

While local materials and low cost are still optimal goals, they are secondary at this point to a working heat delivery prototype for integration into a complete stored energy solar cookstove prototype. This prototype will likely be the first of many iterations.

4. Calculations and Experiments Leading to Design Constraints

In the first half of the semester, our group worked to build partnerships, evaluate potential designs, and conduct experiments aimed at developing design constraints. We have met several times with Sailesh Rao of the Climate Healers parent project, maintaining contact through email and meetings in person. We have met weeky with the Iowa undergraduate class working on this project in parallel. We have attended their design presentations via Skype, offering feedback, learning about their aspects of the project, and working toward eventual integration. In addition, we have met with local contacts to successfully secure fabrication facilities, and we have initiated contact with heat transfer experts to help address technical questions.

4.1 Storage Media Considerations

Prior to meeting with Iowa and learning about their design, we evaluated several potential options for solar collection and thermal storage, as well as heat delivery. A principle consideration for thermal storage was whether energy would be stored in heat capacity (temperature change) or latent heat (phase change). Storing energy in a phase change offers the advantage that the temperature remains constant; all energy is therefore equally capable of doing work. In contrast, storing energy in temperature change requires a high initial temperature. As stored energy is used or lost, the temperature of the storage media falls. Since the power available is dependent on the temperature *difference*, decreasing temperatures mean a decreasing maximum available power. While the phase change system offers advantages, it requires a material with a phase transition within a specific temperature range, in addition to requirements based on energy capacity, safety, affordability, and preference for local materials.

For the thermal storage material search, we considered metals, waxes, molten salts, glasses, and sand (see Appendix A). Of elemental metals, only Bi, Cd, In, Li, Pb, Po, Sn, and Th had melting points in a feasible range (150 400 °C). Unfortunately, Cd, Pb, and Th have toxicity concerns; Po is radioactive; In is prohibitively expensive; and Li burns in contact with water. Bi and Sn are substantially cheaper, but not sufficiently so given the required quantities. Though low melting temperature alloys are also available, most rely on the same metals and suffer from related problems.

For typical waxes, the melting points are too low, though high heat capacity suggests they might be usable in temperature change configurations. Unfortunately, the liquid waxes will flash at temperatures above 200-250 °C. Specialty waxes can reach higher temperatures, but are substantially more expensive. Salts generally melt much higher than our desired temperatures, and slurries will lose their water above 100 °C. Finally, glasses transition at a range of temperatures but due to their unique phase change, lack latent heat of fusion. Other materials that were suggested but not explored include nitrates, hydroxides, and rubber.

Without a good phase change material, few *feasible* materials outperform sand for storing energy in temperature change. Given the advantages in cost and local availability, this looked the most promising. For a given energy storage requirement, the volume of sand can be found:

$$V_{sand} = \frac{E_{required}}{\rho_{sand} c_p \Delta T}$$

In our case ($E_{required}$ = 4kW hrs, ΔT=150K, targets provided by Climate Healers), this gave $V_{sand} \approx 0.06\ m^3$, far more than could fit at the focus of the parabolic mirror as initially envisioned by Climate Healers.

When we met with the Iowa team, we discovered that they had come to the same conclusions, with regard to both using sand and separating the storage from the collector. With initial information on their design and a greater understanding of our expected role, we began experiments aimed at developing design specifications for the heat transfer mechanism.

4.2 Experiment 1: Can hot sand alone cook roti?

Preparing roti had proved the most demanding of the Karech cook tasks, requiring the highest temperatures and the most power. Our first experiment involved determining if the thermal conductivity through a block of sand could provide enough power to cook a roti placed on the top. For this, we calculated the amount of sand required based on initial estimates for energy and temperature, heated the sand in a kitchen oven, and monitored the rise with thermometry. At temperature, the sand was removed and poured into a shallow glass tray. Aluminum foil was placed on top, followed by roti dough. The result was virtually no change in the dough – simple conduction was insufficient.

In addition to the limited conductivity of dry sand, several other factors may have contributed to the failure. First, one thermometer maxed out before reaching our target temperature, we cannot be sure the interior sand reached full temperature. Second, heat may have been lost when the sand was transferred from the pot to the tray. Finally, the shallow tray may have created a “worst-case scenario” with regard to thermal conduction. While these effects may have impacted performance, it seems unlikely they could account for the full failure. That is, even if these factors were mitigated, we expect the power delivered would still prove insufficient.

4.3 Experiment 2: Power and temperature required for roti

The second experiment aimed to quantify the temperature and power requirements for making a roti. For this test, we cooked thirteen rotis under different conditions on a gas stove, varying input power and initial pan temperature. Pan temperature was measured via a thermocouple clipped to the pan. Input power was measured through temperature rise in a known volume of water within a covered pot placed on the burner. Power losses to ambient were measured (as a function of temperature) by monitoring temperature fall in each vessel when removed from the gas. We recorded cooking times for each trial. Dr. Rao, a skilled native cook, was on hand to evaluate "doneness" and roti quality. The results are summarized in figure 4.1.

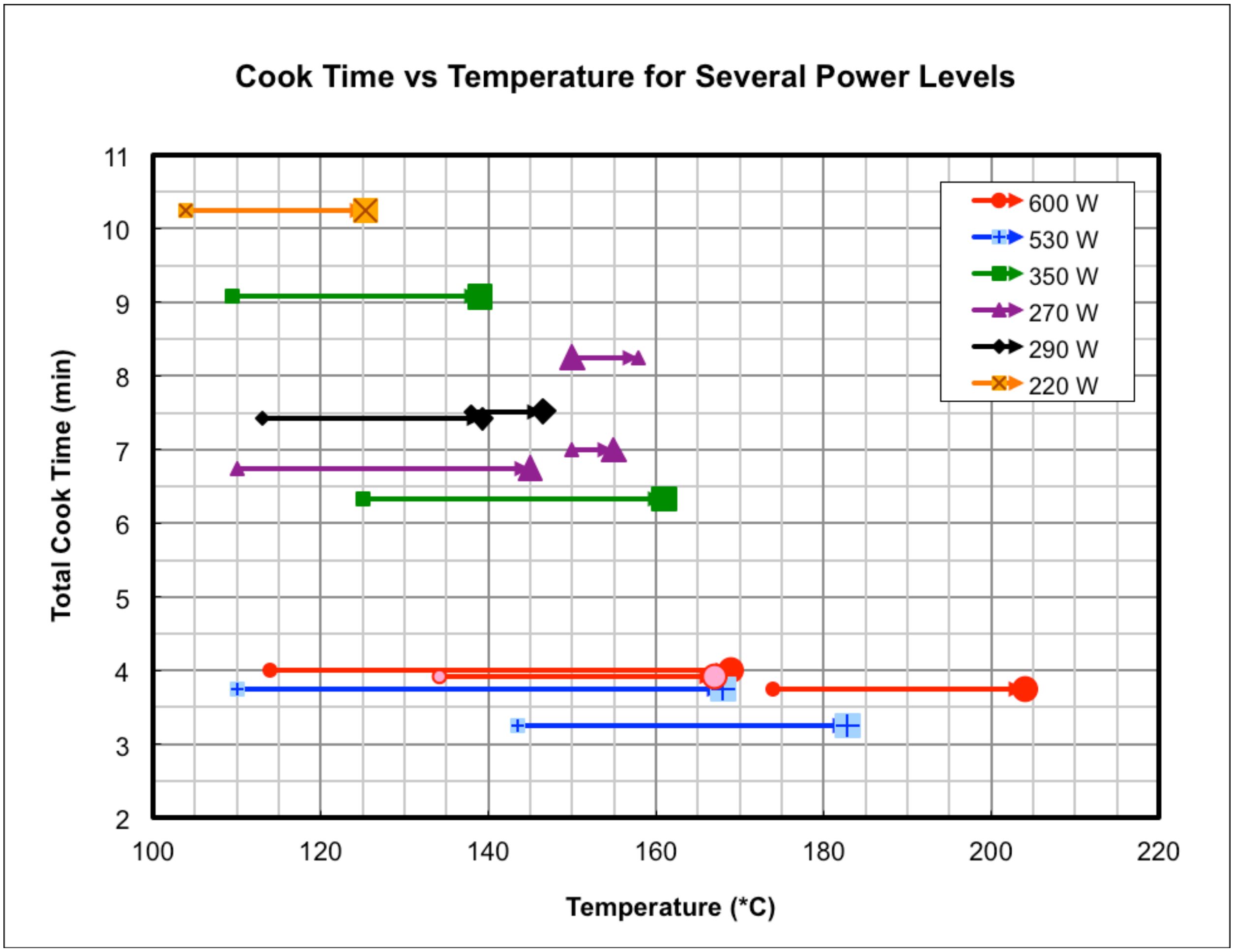

Figure 4.1: Cook times for roti at different power ratings and initial temperatures. Initial temperatures are denoted with small marks; final temperatures with large marks.

All roti cooked with at least ~530W finished in around four minutes with final temperatures of at least 165 °C. These were deemed ideal. At 270 to 350 W, cook times roughly double and the final temperature falls to 140-150 °C. These roti were passable (entirely cooked), but not ideal. At the lowest power, the stove proved unable to make an acceptable roti. Note that the total energy required is roughly equal for the ~600W and ~300W methods. That is, there is little motivation for making the less-favorable rotis from an energy budget standpoint. Based on these results, we have taken T=170 °C and P=500 W as our minimum design constraints. Since the storage media temperature would vary, a final design for the delivery system would also need a way to tune heat flow, to both provide the required heat when the storage media was at low temperatures and avoid waste when the media was hot.

4.4 Thermal Conduction Calculations

We first considered heat delivery through thermal conduction. Conductive heat flow is described by

$$P_x = kA\frac{\partial T}{\partial x}$$

where *P* is power, *k* is thermal conductivity [power/length/degree], *A* is cross-sectional area, *x* is flow direction, and *T* is temperature. We found that meeting our specifications with a 30 °C temperature drop and physical dimensions given by the Iowa team required very large cross-sections: 6.7 inch diameter in Cu or 8.4 inch diameter in Al. Aside from the technical difficulties of designing a mechanism to gradually bring that much surface area into thermal contact, the required metal prices (est. $125 for Al, $900 for Cu) put this solution outside of Climate Healers' per-stove budget. A worksheet for this analysis can be found in our team binder: "Conductor based Delivery Analysis v3.xlsx; Conductor Estimates."

5. Heat Siphon Design and Fabrication

We next considered energy delivery through a heat siphon. In a heat siphon, liquid at a lower hot reservoir is evaporates and rises as hot gas. This gas condenses at the colder top and flows down via gravity. While there is extensive literature on heat pipe and heat siphon design, very little focuses on designing in our temperature and power regimes. We therefore approached many of the design considerations from first principles. The phase-change fluids were evaluated based on vapor pressure and critical point. Energy transfer capabilities were evaluated for conduction through the pipe wall (1), at the phase change (2), through fluid flow (3), and through radial conduction at the burner (4). Additional considerations included thermal expansion at bimetal joints and optimizing the fill level.

5.1 Phase Change Fluid Considerations

Because the fluid is heated while captive in the sealed tube, pressure poses a serious safety concern. Vapor pressure can be determined by integrating the Clausius-Clapeyron (CC) relation:

$$\frac{dp}{dT} = \frac{L_e}{T\Delta V}$$

where p is pressure, T is temperature, L_e is the latent heat of evaporation [energy/mass] at the operating temperature, and ΔV is the change in volume between the states. For example, at 350 °C, water has a vapor pressure of ~16 MPa (158 atm). Ethylene glycol, a major constituent in antifreeze, proved to have the lowest pressures of readily available and affordable fluids examined. By comparison, it has a vapor pressure of only 1.6 MPa (16 atm) at 350 °C. Though we hope to operate the siphon between 170 and 230 °C, the storage system is designed to peak at 350 °C. Further, if the stove is not used, excess heat can build up in the media. The Iowa modeling team provided 550 °C as a conservative “worst-case” temperature for the media.

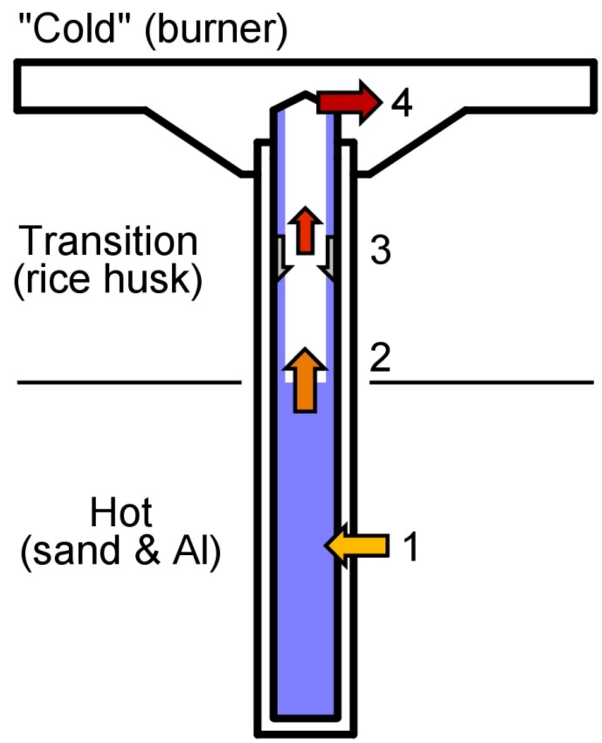

Figure 5.1 Diagram showing energy flow in a heat siphon.

Pressures estimations via CC are valid only while both phases exist and while the temperature and pressure remain below the fluid’s critical point. Above this point, the boundary between phases is lost and the fluid begins to behave more like a gas.

Though we believe CC still provides an upper bound for pressures, we have not researched the transition region between CC behavior and ideal gas law behavior. Therefore, we caution against operating the siphon above the critical point of ethylene glycol (447 °C) until this is fully characterized. As a comparison, the critical point of water is 374 °C. Note that the fill level will be important for ensuring both phases remain and for dictating behavior above the critical point.

5.2 Energy Path Calculations

We also calculated the temperature drop required to provide the specified 550 W of heat flow at each step. For radial conduction, power is given by

$$P = 2\pi rhk\frac{dT}{dr}$$

where h is height of the cylinder. We chose 1 inch stainless steel Swagelok tubing based on pressure ratings and an inner radius compatible with our fluid flow. For this tubing and 30 cm of exposure to the sand/Al, we expect a temperature drop of 2.8 °C, well within reasonable limits. A worksheet for this calculation can be found in our team binder: "Heat Siphon Calculations v4.xlsx; Wall Conduction."

The rate at which fluid must evaporate at the hot end (and condense at the cool end) can be found by

$$J = P/L_e$$

where J is the required vapor flow [mass/time]. The vapor flow will be crucial in the fluid dynamics estimations. A worksheet for these calculations can be found in our team binder: "Heat Siphon Calculations v4.xlsx; PC Material."

Fluid dynamics equations were required to determine what temperature differences would be required to provide sufficient vapor flow, *J,* given pressure-driven gas rise and gravity-driven liquid return. This problem was solved under laminar-flow assumptions, resulting in low temperature differences, but with Reynolds' numbers suggesting laminar liquid flow and turbulent vapor flow. It is possible that turbulent pipe flow solutions may be usefully applied to this problem for more rigorous results. Ultimately, however, empirical measurements may prove most useful here. Derivations for the relevant fluid mechanics equations can be found in Appendix B. Worksheets using those equations to estimate temperature differentials, pressure differentials, and velocity profiles can be found in our team binder: "Heat Siphon Calculations v4.xlsx; Fluid Dyn Basic 4."

Finally, we calculated thermal conduction outward across the burner. We aimed for conditions where losses from the burner (either to roti or to ambient air) were uniform across the burner plate, and solved for the temperature profile as a function of the burner thickness profile. Our final burner design was an aluminum disc with an approximated hyperbolic thickness profile. For this design, we expect less than 20 °C drop across the burner. The derivations for these equations can be found in

Appendix C?. Worksheets using those equations for linear and hyperbolic profiles can be found in "Heat Siphon Calculations v4.xlsx; Plate Conduction."

5.3 Other Considerations.

Given that an Al burner would be mated to a stainless steel tube and fittings, we considered differential thermal expansion. Using linear approximations and a conservative upper temperature of 350 °C, we found radial changes ~50 μm and socket depth changes ~125 μm. Based on these values, we chose a tapered pipe thread (NPT) and teflon tape for the connection. A worksheet for these calculations can be found in our team binder: "Heat Siphon Calculations v4.xlsx; Thermal Expansion."

Finally, we must consider the optimal fill volume. If too little ethylene glycol is included, all the liquid will vaporize as the siphon is heated. Once all liquid is gone, the evaporation-condensation heat transfer will become ineffective. If too much fluid is added, the volume fraction of liquid will increase (liquid densities fall as temperatures rise) until it takes up most of the volume. Again, this will lead to inefficient heat transfer. Additionally, behavior above the critical point approaches that of gasses, so pressure at very high temperatures is dependent on the total amount of ethylene glycol included. This parameter has not yet been addressed and should be evaluated before testing, especially at high temperatures.

5.4 Fabrication

Given the high pressures involved (estimated 16.8 MPa at 550 °C for ethylene glycol), we acquired most parts from vendors with published data on working pressures. The pipe, end-caps and NPT adapter were purchased from Swagelok. Of those parts, the pipe was most vulnerable to failure through internal pressure, with a working pressure rating of 21.5 MPa. The burner, however, required custom fabrication, and was completed in the UC Berkeley Etcheverry shop. Shop experts Mick and Gordon both gave crucial advice on how to machine for such high pressure applications. Images of the custom piece and of the completed heat siphon are available in Appendix D.

6. An Alternative Fluid Design

6.1 Introduction

As noted in our revised team goals, we think that it will be useful to present some further design concepts which reflect the scope of the stored solar cook stove problem.

The figure below encapsulates the input/output relationship for our stored thermal energy problem. The Sun and roti dough (time-delayed) are inputs to the system. Warm roti is the output, with required heat transfer characteristics specified by our earlier experiments.

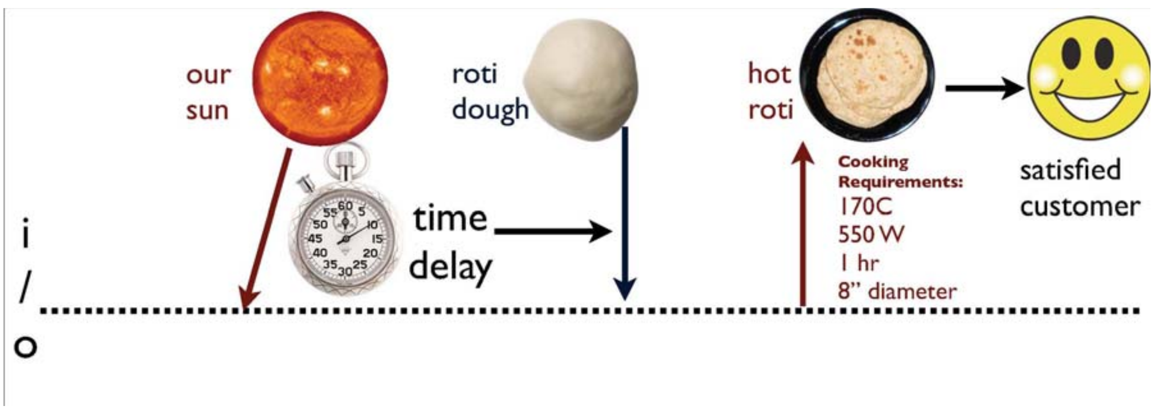

Figure 6.1. Input/Output Relationship of Stored Thermal Stove

The design discussed in this section is conceptual, and as such we do not provide detailed physical models or specifications. Rather, it is intended as a possible direction for further development.

6.2 A More Fluid Approach

Here we consider a design in which three fluids perform the roles of thermal collection, storage, and delivery. They are denoted as FC, FS, and FD, respectively and have temperatures of vaporization of TC, TS, and TD.

Before presenting the proposed concept, we discuss *heat exchangers,* important subcomponents of this design. Heat exchangers are modular components designed to transfer heat from one liquid to another. Kakac and Liu[21] note that the fluids can be allowed to mixed or physically separated, as will be the case with those that we

[21] Sadik Kakaç and Hongtan Liu (2002). Heat Exchangers: Selection, Rating and Thermal Design (2nd ed.). CRC Press.

consider here. Heat exchangers can transfer thermal energy between fluids of the same phase or used to evaporate or condense fluids, also. As far as building prototypes is concerned, an advantage of using heat exchangers is that they are commonly used in industrial applications such as car radiators and can therefore be purchased off-the-shelf.

The below figure is a diagram of a *shell and tube* heat exchanger, in which a tube-side fluid is to be heated or cooled. The shell-side fluid passes over the tubes, absorbing or transferring respectively its energy to the tube side fluid. [22]

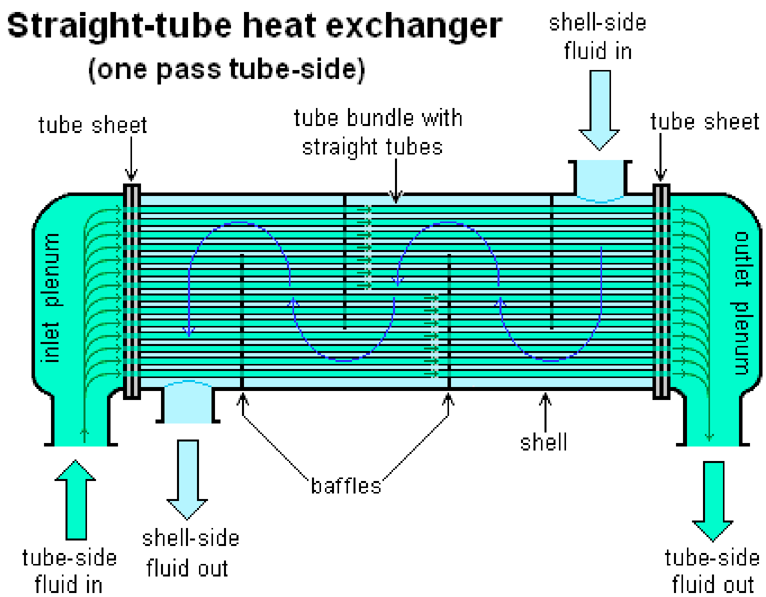

Figure 6.2. Shell and Tube Heat Exchanger, image taken from wikimedia[23]

In short, a heat exchanger is a device with through which two fluids pass (with two inputs and two outputs). One fluid is cooled, transferring its heat to the other fluid.

6.3 A Design Concept

The figure below presents a system-level overview of the all-fluid concept.

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[22] [W] http://en.wikipedia.org/wiki/Heat_exchanger

[23] [W] http://en.wikipedia.org/wiki/Heat_exchanger

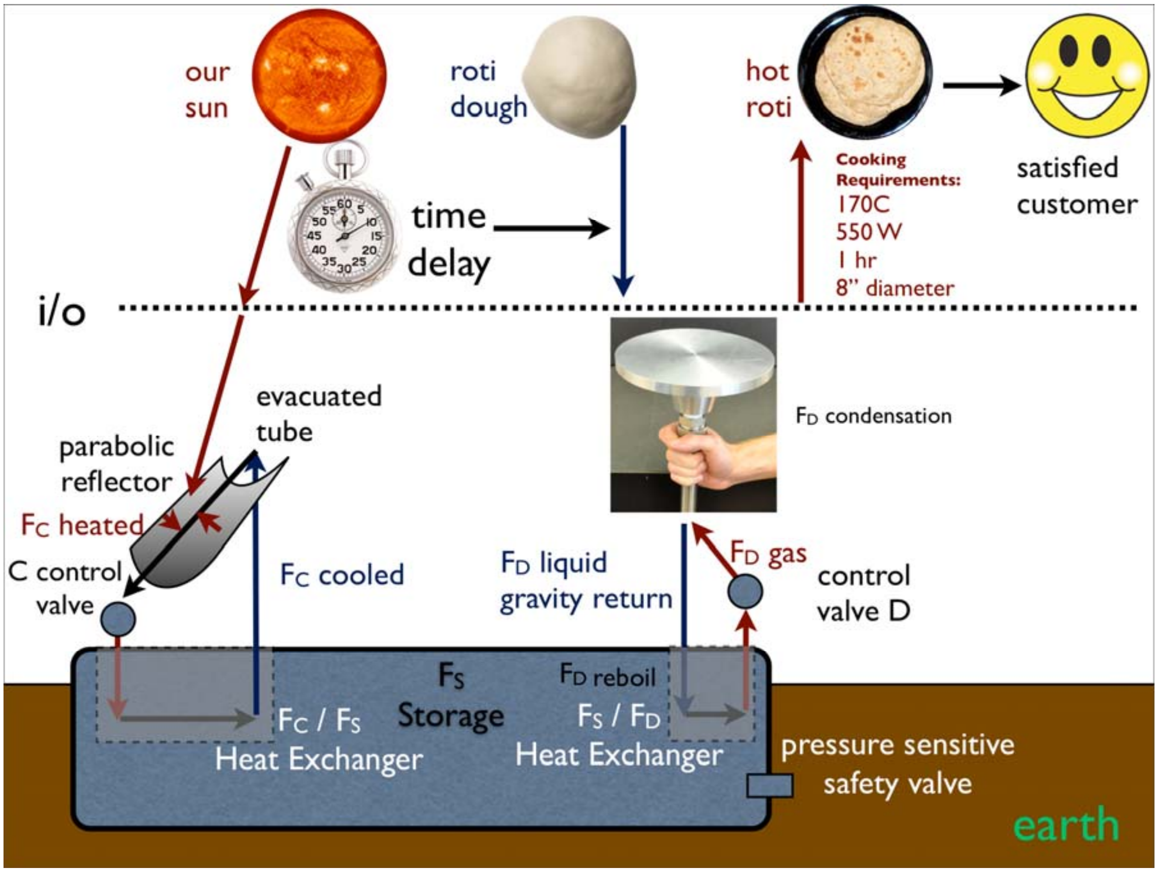

Figure 6.3. All-Fluid Design.

The process can be decomposed as follows:

- A tube containing FC runs along the line defining the focus of the parabolic collector.
- Reflected solar energy vaporizes the FC.
- FC gas enters the FC/FS heat exchanger, where it condenses, returning as a liquid to the parabolic collector. When the sun sets, a valve can be shut off to prevent energy loss.
- The heat exchanger absorbs the condensation energy of FC, heating FS. Until cooking begins, FS is stored at a temperature higher than TD (and lower than TS).
- To cook, the user turns on a valve regulating FD. FD liquid enters the FS/FD heat exchanger, where it is heated and exits as a vapor.
- Conceptually similar to our current design, the FD vapor condenses against the stove, releasing heat and cooking the roti before returning to the second heat exchanger.

Selection of the working fluids will inform the hardware design. Fluids should meet the following criteria:

- TC should be fairly high and must be larger than TD so that the final phase change can take place.
- TS should be higher than TC, as vapor in the storage container may create unsafe pressure.
- TD should be a little higher than the temperature required to cook the roti so that the temperature transfer to the stove
- Safety and evironmental impact. Fluids should be nontoxic.
- Affordability.

For example, candidates for FC, FS, and FD respectively are glycerine (290 C), mineral oil (330 C) and propelyne glycol (187 C), with boiling points parenthesized.[24]

6.4 Potential Benefits and Risks Compared to the Current Design

Generally speaking, the design process for this project was complicated by the many interactions and tradeoffs between various system components. A considerable benefit of an all-fluid design is that heat exchangers simplify specifications of the interfaces between collection, storage, and delivery processes. This should improve the modularity, making it easier to design and test a particular subsystem without completely redesigning the others, as well as easing the integration of outdoor solar collection and indoor cooking.

A specific concern with the current design is the interface between the parabolic collector and the sand storage unit. As the sun sets, the ambient temperature cools and if left open, the temperature of the sand will decrease. Therefore, just as the sand reaches its peak temperature, the aperture should close. This presents numerous challenges. In particular, it is difficult to size the aperture and time its closing. If not properly controlled, an open aperture will leak energy from the thermal storage unit. Closing the aperture manually requires additional human interaction while shuttering it automatically adds much greater design complexity. Such concerns might be lessened with the all-fluid design. The use of well-insulated off-the-shelf pipes (e.g. evacuated tubes) should reduce potential energy losses compared with the current design. Furthermore, when the sun sets, it is simpler to turn a valve to stop fluid flow than actuate the aperture shutter mechanism.

As well as the solar collection problem, sand as a thermal storage medium presents challenges in delivering heat for cooking. The primary advantage of sand is that it can reach high temperatures, has a fairly high specific heat, and is dirt cheap. However, it is a formidable challenge to design a robust conductive pathway throughout the sand into the thermosyphon. An advantage of using fluid to store

[24] www.engineeringtoolbox.com

thermal energy is that convection can be employed to our advantage, whereas doing so with sand is more of a challenge.

Another problem with the current design is the large mass of sand required to store the required cooking energy. Here too, fluids should perform better: the specific heat of sand is approximately .8 kJ/kg K, while that of mineral oil, a storage fluid candidate is 1.67 kJ/kg K. (For reference that of water is 4.19.)[25]

While there are some potential benefits, a number of risks are associated with the three fluid design:

- Repeated heating and cooling of the fluids may break them down, particularly organic oils.
- Safety measures should be taken to ensure that pressures are kept at safe levels for each fluid container. This may add additional significant complexity and be expensive.
- Heat exchangers are expensive components, being complex to both design and manufacture. While they can be bought off-the-shelf, there are many design parameters that determine its performance, such as material, diameter, thickness, length, and layout of the tubes.
- Fluid storage containers may be expensive.
- As with the previous design, insulation of the fluid at high temperatures for several hours is a challenge.

[25] www.engineeringtoolbox.com

7. Implementation and Evaluation

7.1 Implementation Strategy

To build on the trust that distribution of solar lights has won Climate Healers in the village of Karech, we recommend a multi-staged approach to introduce cookstoves to the village. This will increase the likelihood of adoption and allow for more feedback during the design process.

First, we recommend that instead of bringing a second stored energy solar cookstove prototype to the village, a field-proven woodburning cookstove of higher efficiency than a 3-stone fire be introduced next. This has several advantages:

- The Namaste prototype was overwhelmingly rejected by the village and perhaps decreased the village's confidence in Climate Healers. A field-proven high efficiency stove would demonstrate the ability of new stove technology to decrease wood use. This could be demonstrated in the village with a side-by-side comparison of a 3-stone fire and a high efficiency woodstove. Following the demonstration, the high efficiency stove could be offered for a small price (subsidized by Climate Healers) with the promise that it could be traded for a home-built stored energy solar cookstove in the future. The Darfur Stoves Project provides a great model for this type of technology introduction.[1]
- A fuel-efficient stove would allow for further feedback and information on the needs and desires of the women of Karech without the distraction of development issues of a design-in-progress. Ultimately the fuel-efficient stove would also provide an alternative for comparison once the stored energy solar cookstove is introduced.
- A number of fuel-efficient stoves are already developed and could be quickly implemented. Some suggestions are available at these references.[2,3]

Second, we recommend further testing and evaluation of the stove before deployment. Durability of the stove in both dry and monsoon conditions may be tested by simply leaving the stove outdoors for a week, temperature cycling, and drenching the stove with a hose to simulate monsoons. While not all effects will be immediately obvious, implications of wet or dirty sand and overheating should be evident.

Finally, we recommend introduction of the stored energy solar cookstove prototype in a more urban setting prior to introduction to the village. For example, prototypes may be provided to small cooking businesses in India for initial testing and feedback. Similarly, sale of the stove prototype to middle-class communities would

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[1] Darfur Stoves Project Initial Fact-finding Mission Field Trip Report by C Galitsky, A Gadgil, M Jacobs, Y Lee. Available at: http://darfurstoves.org/our-solution/scale/
[2] http://www.aprovecho.org/lab/index.php
[3] http://kammen.berkeley.edu//cookstoves.html

provide a venue for feedback and trouble-shooting while potentially raising money for further development and subsidizing of stove distribution in impoverished villages.[4]

7.2 Desirability

Overall desirability of a stored energy solar cookstove remains high as the village of Karech is well aware of the need to decrease wood usage, as discussed in section 1. Time saved not collecting wood may be spent crafting products for sale (for example currently villagers fashion plates out of leaves) or studying.[5] Furthermore, FES works closely with the village to emphasize the need for change to save the forest. Finally, if the stoves are manufactured in the village, the villagers will have an additional investment of pride.

The current prototype has several undesirable factors that should be fixed before introduction to the village:

- Convenience. The current prototype is too large and will be unstable on the hilly terrain of the village. Furthermore, it is too heavy to be moved to and from the house for cooking as suggested and adjustment of collector on a daily basis is not optimal. A modular design has been suggested to help address these issues.
- Safety. The current design requires building to extreme temperature and pressure requirements, which will always present a safety issue as long as the potential for the storage reaching 550°C remains. Prototypes must certainly be tested extensively before being brought to India and we recommend a mechanism for heat dissipation. Alternatively a non-fluid design or better heat transfer efficiency allowing for lower overall temperatures would address this issue.

These issues will certainly be addressed in future iterations and we note that the current prototype does meet the main concern of the original Namaste prototype in that it allows cooking when sunlight is not available.

7.3 Technical Feasibility

Theoretical calculations suggest that the current design is capable of cooking roti and experiments have confirmed that evening cooking is possible. Energy storage to allow cooking of roti in the morning remains a very difficult problem and may either be achieved in future iterations or, alternatively, a more efficient stove may be used in the morning as an alternative to a 3-stone fire. A second technical hurdle remains in the ability to manufacture the stove in the village out of local materials. Full

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[4] Implementation strategy ideas were developed in brainstorming with Susan Addy, ECAR Project Lead, 2011.

[5] Personal communication with Sailesh Rao of Climate Healers.

manufacturing of the current design is simply not feasible in the village. However technically challenging manufacturing steps (such as heat pipe assembly) may be outsourced allowing for assembly of the stove in the village, which would still provide projects for the National Rural Employment Guarantee. Furthermore, future modular iterations of the design may be tailored to allow more local manufacturing.

7.4 Financial Viability

The current design is certainly not affordable by the inhabitants of Karech due to the use of expensive materials and large volumes of materials. Cost will certainly be reduced in future iterations and furthermore, two options exist for subsidizing the price presented to villagers:

- Climate Healers is currently in negotiation with the Indian government (specifically the Minister of the Environment and Rural Employment Board) to discuss the manufacturing of stored energy solar cookstoves as part of the National Rural Employment Guarantee. This would subsidize labor costs and increase desirability as the villagers themselves would manufacture their own stoves. Moreover, the Indian government would also cover material costs.
- Carbon credits have been successfully demonstrated to offset the costs of stoves by other organizations and therefore should be easily implemented by Climate Healers as well. Examples of previous carbon credit implementation for stoves can be found here.[6] Examples of successful use of carbon credits to offset new technology implementation can also be found here.[7]

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[6] http://stovetec.net/us/images/stories/pdfs/GoldStandardCarbonCreditProtocols.pdf
[7] http://www.fastcompany.com/1749253/can-a-swiss-textile-company-help-cure-guinea-worm-by-trading-carbon-for-water

8. Concluding Remarks

Ultimately, a defining feature of our work was the challenge of designing a single component in isolation from the rest of the system. In some respects, this was beneficial because it focused our energy (no pun intended) -- making us think deeply about the heat transfer principles and many design tradeoffs within a single module.

Yet, we also came to appreciate that any successful design requires a holistic plan. The complex interfaces between the thermal collection, storage, and delivery components of the solar cooker demonstrate the need for a more modular strategy. Although any number of concepts appear feasible, we expect that the three-fluid approach will be both modular and affordable. We have not yet undertaken a comprehensive analysis of it, and as such we are unable to say with certainty that such an approach is even viable. However, we do think that it warrants further consideration by future engineering teams who consider this worthy yet challenging problem of designing a stored solar energy cookstove.

Appendices

Appendix A. Potential materials for thermal storage

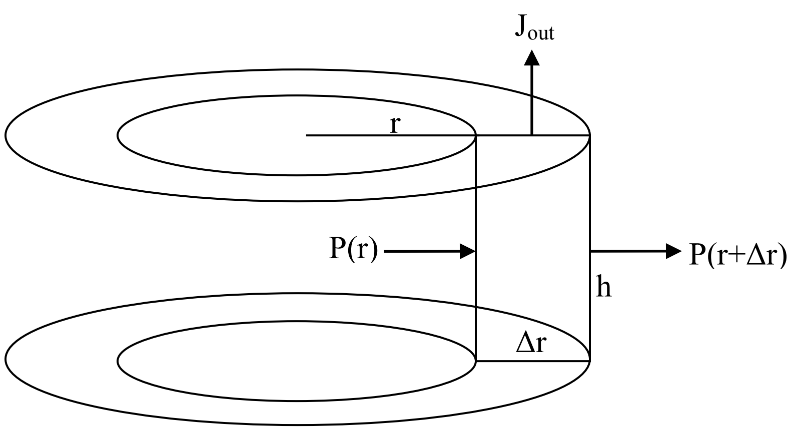
Material	T_m (°C)	L_f (kJ/kg)	c_p (kJ/kg K)	Safety	Cost ($/kg)
Pure metals[a]					
Bismuth	271.40	**X**[c] (54.1)	0.122		**X**[c] (~22)
Cadmium	321.07	213	0.232	***X*** *(toxic)*	
Indium	156.60	28.6	0.233		**X** (~4,500)
Lead	327.46	23.0	0.129	***X*** *(toxic)*	
Litium	180.5	432	3.582	**X** (combustible)	
Polonium	254	-	-	**X** (radioactive)	
Thallium	304	20.3	0.129	**X** (toxic)	
Tin	231.93	**X**[c] (59.2)	0.228		**X**[c] (~11)
"Fusable"alloys[b]					
5:3 Bi:Sn	202	**X**[c]			**X**[c]
1:1 Bi:Sn	286	**X**[c]			**X**[c]
Waxes					
Typical	60-70		2.14-2.9	**X**[d] (combustible)	
Paraffin	47-64		2.9	**X**[d] (combustible)	
Beeswax	62-64		3.4	**X**[d] (combustible)	
Specialty	up to 180				**X**
Salt	**X** (~800)		0.88-0.92		
Glasses		**X** (~0)	0.5-0.9		
Rubbers					
Typical			2.0		
India Rubber			1.13-4.1		
Sand			0.8		

Table A1: Potential phase change and temperature change materials. X's indicate incompatibility with our design. **a:** For pure metals, only those with phase changes between

150-400 °C shown; physical properties are from CRC. **b:** Alloys include only those without cadmium or lead for toxicity issues, or indium for cost. Data is from http://www.gizmology.net/fusiblemetals.htm. **c:** Bismuth, tin, and their alloys are cheaper than most, but still cost-prohibitive when combined with their specific heat capacities. **d:** Liquid waxes would be promising as temperature-change materials, except that they flash at 200-250 °C. Data for waxes, rubber, glass from http://www.engineeringtoolbox.com/specific-heat-solids-d_154.html.

Appendix B. Conductive Radial Heat Flow

This seeks to derive the equations for radial heat flow over a finite circular domain with no-flow boundaries at the outer edge and an axial source or sink. The mathematics are expected to be analogous to groundwater flow through porous media around a well or injection site.



Ring shaped control volume, where J_{out} is any loss uniform over the disk with dimensions [Energy/Area/Time]:

Conservation of energy:

(1) $E(t + \Delta t) = E(t) + P(r)\Delta t - P(r + \Delta r)\Delta t - J_{out} Area \Delta t$

Rearranging, (U ≡ energy density [Energy/Volume]):

(2) $VU(t + \Delta t) - VU(t) + P(r + \Delta r)\Delta t - P(r)\Delta t = -J_{out} 2\pi r \Delta r \Delta t$

Dividing by unit:

(3) $\frac{V}{2\pi r h \Delta r}\frac{U(t+\Delta t)-U(t)}{\Delta t} + \frac{P(r+\Delta r)\Delta t - P(r)}{2\pi r h \Delta r} = \frac{-J_{out}}{h}$

Pass to limits as Δr→0, Δt→0:

(4) $\frac{\partial U}{\partial t} + \frac{1}{2\pi r h}\frac{\partial P}{\partial r} = \frac{-J_{out}}{h}$

Thermal energy (density, heat capacity, temperature, and volume):

(5) $U = \rho c_p T = \rho c_p T$

Power through conduction (thermal conductivity, area)

(6) $P = JA = -kA\frac{\partial T}{\partial r} = -k2\pi rh\frac{\partial T}{\partial r}$

Combining (4), (5), and (6):

(7) $\frac{\partial}{\partial t}(\rho c_p T) + \frac{1}{2\pi rh}\frac{\partial}{\partial r}\left(-k2\pi rh\frac{\partial T}{\partial r}\right) = \frac{-J_{out}}{h}$

For constant density, heat capacity, height, and delta, and for uniform thermal conductivity:

(8) $\rho c_p\frac{\partial T}{\partial t} - \frac{k}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right) = \frac{-J_{out}}{h}$

We will now consider 2 possibilities: (A) No outside losses and uniform fall of T, (B) total losses through J_{out} = total input power.

(A9) $\rho c_p\frac{\partial T}{\partial t} - \frac{k}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right) = 0$

So total power in at the inner radius will correspond to a uniform temperature rise:

(A10) $P_{total} = \pi r_{out}^2 h\rho c_p\frac{\partial T}{\partial t}$

Combining (A9) and (A10):

(A11) $\frac{P_{total}}{\pi r_{out}^2 hk} = \frac{1}{r}\frac{d}{dr}\left(r\frac{dT}{dr}\right)$

(A12) $\left(\frac{P_{total}}{\pi r_{out}^2 hk}\right) rdr = d\left(r\frac{dT}{dr}\right)$

Integrating (recall that no-flow at the perimeter):

(A13) $\left(\frac{P_{total}}{\pi r_{out}^2 hk}\right)\int_{r_{out}}^{r} r'dr' = \int_0^{r\frac{dT}{dr}} d\left(r'\frac{dT'}{dr}\right)$

(A14) $\left(\frac{P_{total}}{2\pi r_{out}^2 hk}\right)(r^2 - r_{out}^2) = r\frac{dT}{dr}$

(A15) $\left(\frac{P_{total}}{2\pi hk}\right)\left(\frac{r}{r_{out}^2} - \frac{1}{r}\right) = \frac{dT}{dr}$

(A16) $\left(\frac{P_{total}}{2\pi hk}\right)\int_{r_1}^{r_2}\left(\frac{r}{{r_{out}}^2}-\frac{1}{r}\right)dr=\int_{T_1}^{T_2}dT$

(A17) $\left(\frac{P_{total}}{2\pi hk}\right)\left(\frac{{r_2}^2-{r_1}^2}{2{r_{out}}^2}-ln\frac{r_2}{r_1}\right)=T_2-T_1$

(B9) $\frac{J_{out}}{h}=\frac{k}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right)$

Here, total power will be the Jout over the entire top area:

(B10) $P_{total}=J_{out}\,\pi {r_{out}}^2$

Combining (B9) and (B10):

(B11) $\frac{P_{total}}{\pi {r_{out}}^2 hk}=\frac{1}{r}\frac{d}{dr}\left(r\frac{dT}{dr}\right)$ which is identical to (A11) and solution follows from there

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This result A/B can be applied to the sand mixture delivering heat to the siphon as it removes it from the center. It also applies to heat distribution to the edges of the burner as it is delivered to the center by the siphon.

In the case of a conductor where height varies with r, the analysis holds until equation (7). From there, it progresses as follows:

(C8) $\rho c_p\frac{\partial T}{\partial t}-\frac{k}{rh}\frac{\partial}{\partial r}\left(rh\frac{\partial T}{\partial r}\right)=\frac{-J_{out}}{h}$

From here, we take the case where J_{out} = total input power.

(C9) $\frac{J_{out}}{h}=\frac{k}{rh}\frac{\partial}{\partial r}\left(rh\frac{\partial T}{\partial r}\right)$

With (B10), we have:

(C11) $\frac{P_{total}}{\pi {r_{out}}^2 k}=\frac{1}{r}\frac{d}{\partial r}\left(rh\frac{dT}{dr}\right)$

(C12) $\left(\frac{P_{total}}{\pi {r_{out}}^2 k}\right)rdr=d\left(rh\frac{dT}{dr}\right)$

(C13) $\left(\frac{P_{total}}{\pi {r_{out}}^2 k}\right)\int_{r_{out}}^{r}r'dr'=\int_0^{rh\frac{dT}{dr}}d\left(r'h\frac{dT'}{dr}\right)$

(C14) $\left(\frac{P_{total}}{2\pi {r_{out}}^2 k}\right)(r^2-{r_{out}}^2)=rh\frac{dT}{dr}$

(C15) $\left(\frac{P_{total}}{2\pi k}\right)\left(\frac{r}{r_{out}{}^2 h} - \frac{1}{rh}\right) = \frac{dT}{dr}$

(C16) $\left(\frac{P_{total}}{2\pi k}\right)\int_{r_1}^{r_2}\left(\frac{r}{r_{out}{}^2 h} - \frac{1}{rh}\right) dr = \int_{T_1}^{T_2} dT$

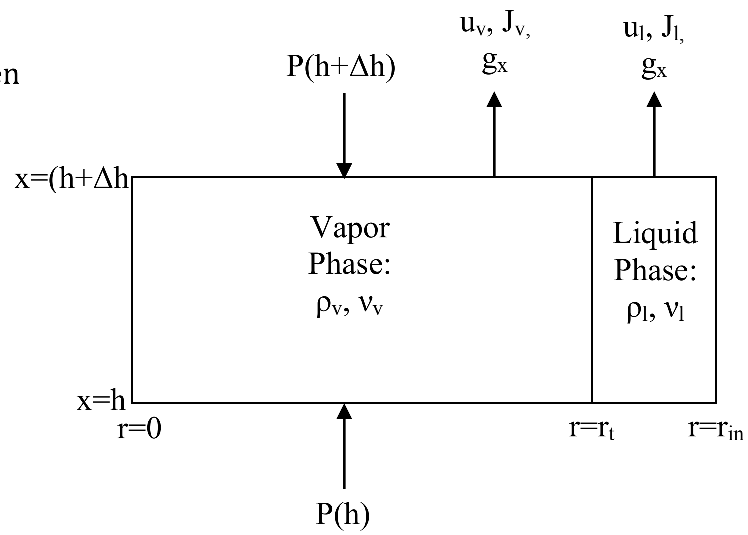
At this point, the specific function h(r) must be known. As an example, we take h=a/r for uniform, constant a:

(C17) $\left(\frac{P_{total}}{2\pi ka}\right)\left(\frac{r_2{}^3 - r_1{}^3}{3r_{out}{}^2} - (r_2 - r_1)\right) = T_2 - T_1$

Appendix C. Fluid Flow in a Simple Heat Siphon (basic model)

This seeks to derive relationships that can be used to quantify performance of a gravity-driven cylindrical heat siphon. In this device, the liquid phase flows down the interior edges of a sealed tube, while the vapor phase rises up the middle.

At right shows a "slice" of the tube, within the transition region between hot and cold temperatures.



Assumptions:

$u_r = u_\theta = 0$

$\frac{\partial u_x}{\partial \theta} = 0$ (symmetry)

$\frac{\partial u_x}{\partial t} = 0$ (steady state)

Incompressible

No phase change in transition

No heat exchange in transition

Navier-Stokes (cylindrical coordinates)

(1) $\frac{\partial u_x}{\partial x} = 0$ (from continuity equation and assumptions)

(2) $0 = -\frac{1}{\rho}\frac{dp}{dx} + g_x + \vartheta\left[\frac{1}{r}\frac{d}{dr}\left(r\frac{du}{dr}\right)\right]$ (from u_x component of Navier-Stokes)

For vapor region:

(3) define $A_v \equiv \frac{1}{\rho_v \vartheta_v}\frac{dp}{dx} - \frac{g_x}{\vartheta_v}; \left(\frac{1}{ms}\right)$

(4) $A_v = \left[\frac{1}{r}\frac{d}{dr}\left(r\frac{du_v}{dr}\right)\right]; \left(\frac{1}{ms}\right)$

(5) $A_v r dr = d\left(r\frac{du_v}{dr}\right); \left(\frac{m}{s}\right)$

(6) $\frac{A_v r^2}{2} + C_v = r\frac{du_v}{dr}; \left(\frac{m}{s}\right)$

(7) $\frac{A_v r dr}{2} + C_v \frac{dr}{r} = du_v \; ; \left(\frac{m}{s}\right)$

(8) $u_v = \frac{A_v}{4} r^2 + C_v ln(r) + \; B_v \; ; \left(\frac{m}{s}\right)$

Boundary condition 1

(12) $\frac{du_v(0)}{dr} = 0$ (no discontinuity at center)

(13) $C_v = 0$ (from 12, 6)

(14) $u_v(r) = \frac{A_v}{4} r^2 + B_v$

Boundary condition 2

(15) $u_v(r_t) = u_l(r_t)$ (no slip at fluid boundary)

(16) $\frac{A_v}{4} {r_t}^2 + B_v = u_l(r_t)$ (no slip at fluid boundary)

Total flux condition

(17) $J = \rho_v \int_0^{2\pi} \int_0^{r_t} u_v r dr \, d\theta$

(18) $J = 2\pi\rho_v \int_0^{r_t} \left(\frac{A_v}{4} r^2 + B_v\right) r dr$

(19) $J = 2\pi\rho_v \left(\frac{A_v}{16} {r_t}^4 + \frac{B_v}{2} {r_t}^2\right)$

Getting u_v as a function of $u_l(r_t)$, r_t, and J:

(20) $J = 2\pi\rho_v \left(\frac{A_v}{16} {r_t}^4 + \frac{u_l(r_t)}{2} {r_t}^2 - \frac{A_v}{8} {r_t}^4\right)$ (16 into 19)

(21) $J = \frac{\pi\rho_v}{8} \left(8u_l(r_t){r_t}^2 - A_v {r_t}^4\right)$

(22) $A_v = \frac{8u_l(r_t)}{{r_t}^2} - \frac{8J}{\pi\rho_v {r_t}^4}$

(23) $2u_l(r_t) - \frac{2J}{\pi\rho_v {r_t}^2} + B_v = u_l(r_t)$ (22 into 16)

(24) $B_v = \frac{2J}{\pi\rho_v {r_t}^2} - u_l(r_t)$

(25) $u_v(r) = \frac{\frac{8u_l(r_t)}{{r_t}^2} - \frac{8J}{\pi\rho_v {r_t}^4}}{4} r^2 + \frac{2J}{\pi\rho_v {r_t}^2} - u_l(r_t)$ (22 and 24 into 14)

(26) $u_v(r) = u_l(r_t)2\frac{r^2}{{r_t}^2} - u_l(r_t) + \frac{2J}{\pi\rho_v {r_t}^2} - \frac{2J}{\pi\rho_v {r_t}^2}\frac{r^2}{{r_t}^2}$

(27) $\boldsymbol{u_v(r) = u_l(r_t)\left(2\frac{r^2}{{r_t}^2} - 1\right) + \frac{2J}{\pi\rho_v {r_t}^2}\left(1 - \frac{r^2}{{r_t}^2}\right)}$

Getting dp/dx as a function of $u_l(r_t)$, r_t, and J:

(28) $\frac{1}{\rho_v\vartheta_v}\frac{dp}{dx} - \frac{g_x}{\vartheta_v} = \frac{8u_l(r_t)}{{r_t}^2} - \frac{8J}{\pi\rho_v {r_t}^4}$ (3 and 22)

(29) $\boldsymbol{\frac{dp}{dx} = \frac{8\rho_v\vartheta_v u_l(r_t)}{{r_t}^2} - \frac{8J\vartheta_v}{\pi {r_t}^4} + \rho_v g_x}$

For liquid region:

(30) $0 = g_x + \vartheta_l\left[\frac{1}{r}\frac{d}{dr}\left(r\frac{du_l}{dr}\right)\right]$ (from 3, assuming gravity >> pressure difference)

(31) define $A_l \equiv -\frac{g_x}{\vartheta_l}$

through similar logic (see 4-8):

(32) $u_l = \frac{A_l}{4}r^2 + C_l ln(r) + B_l$

Boundary condition 1 (no flow at wall):

(33) $u_l(r_{in}) = 0 = \frac{A_l}{4}{r_{in}}^2 + C_l ln(r_{in}) + B_l$

(34) $B_l = -\frac{A_l}{4}{r_{in}}^2 - C_l ln(r_{in})$

(35) $u_l = \frac{A_l}{4}(r^2 - {r_{in}}^2) + C_l ln\left(\frac{r}{r_{in}}\right)$

Boundary condition 2 (no transfer at interface):

(36) $\frac{du_l}{dr}(r_t) = 0 = \frac{A_l}{2}r_t + \frac{C_l}{r_t}$

(37) $C_l = -\frac{A_l}{2}{r_t}^2$

(38) $u_l = \frac{A_l}{4}(r^2 - {r_{in}}^2) - \frac{A_l}{2}{r_t}^2 ln\left(\frac{r}{r_{in}}\right)$ (37 into 35)

(39) $\boldsymbol{u_l = \frac{A_l}{4}\left[(r^2 - {r_{in}}^2) - 2{r_t}^2 ln\left(\frac{r}{r_{in}}\right)\right]}$

Total flux condition

(40) $$J = \rho_v \int_0^{2\pi} \int_{r_t}^{r_{in}} u_v r dr\, d\theta$$

(41) $$J = 2\pi\rho_v \int_{r_t}^{r_{in}} \frac{A_l}{4}\left[(r^2 - r_{in}{}^2) - 2r_t{}^2 ln\left(\frac{r}{r_{in}}\right)\right] r dr$$

(42) $$J = \frac{A_l}{2}\pi\rho_v \int_{r_t}^{r_{in}} (r^3 - r r_{in}{}^2 - 2r r_t{}^2 ln\, r + 2r r_t{}^2 ln\, r_{in}) dr$$

(43) $$J = \frac{A_l}{2}\pi\rho_v \left[\begin{matrix}\left(\frac{r_{in}{}^4}{4} - \frac{r_{in}{}^2}{2} r_{in}{}^2 - 2r_t{}^2 \frac{r_{in}{}^2}{4}(2ln\, r_{in} - 1) + r_{in}{}^2 r_t{}^2 ln\, r_{in}\right) - \\ \left(\frac{r_t{}^4}{4} - \frac{r_t{}^2}{2} r_{in}{}^2 - 2r_t{}^2 \frac{r_t{}^2}{4}(2ln\, r_t - 1) + r_t{}^2 r_t{}^2 ln\, r_{in}\right)\end{matrix}\right]$$

(44) $$J = \frac{A_l}{2}\pi\rho_v \left[\begin{matrix}\frac{r_{in}{}^4}{4} - \frac{r_{in}{}^4}{2} - \frac{r_{in}{}^2 r_t{}^2}{2} 2ln\, r_{in} + \frac{r_{in}{}^2 r_t{}^2}{2} + r_{in}{}^2 r_t{}^2 ln\, r_{in} \\ -\frac{r_t{}^4}{4} + \frac{r_{in}{}^2 r_t{}^2}{2} + \frac{r_t{}^4}{2} 2ln\, r_t - \frac{r_t{}^4}{2} - r_t{}^4 ln\, r_{in}\end{matrix}\right]$$

(45) $$J = \frac{A_l}{8}\pi\rho_v \left[-r_{in}{}^4 + 4r_{in}{}^2 r_t{}^2 - 3r_t{}^4 + 4r_t{}^4 ln\left(\frac{r_t}{r_{in}}\right)\right]$$

(46) $$\boldsymbol{J = \frac{\pi\rho_l g_x}{8\vartheta_l}\left[r_{in}{}^4 - 4r_{in}{}^2 r_t{}^2 + 3r_t{}^4 - 4r_t{}^4 ln\left(\frac{r_t}{r_{in}}\right)\right]}$$

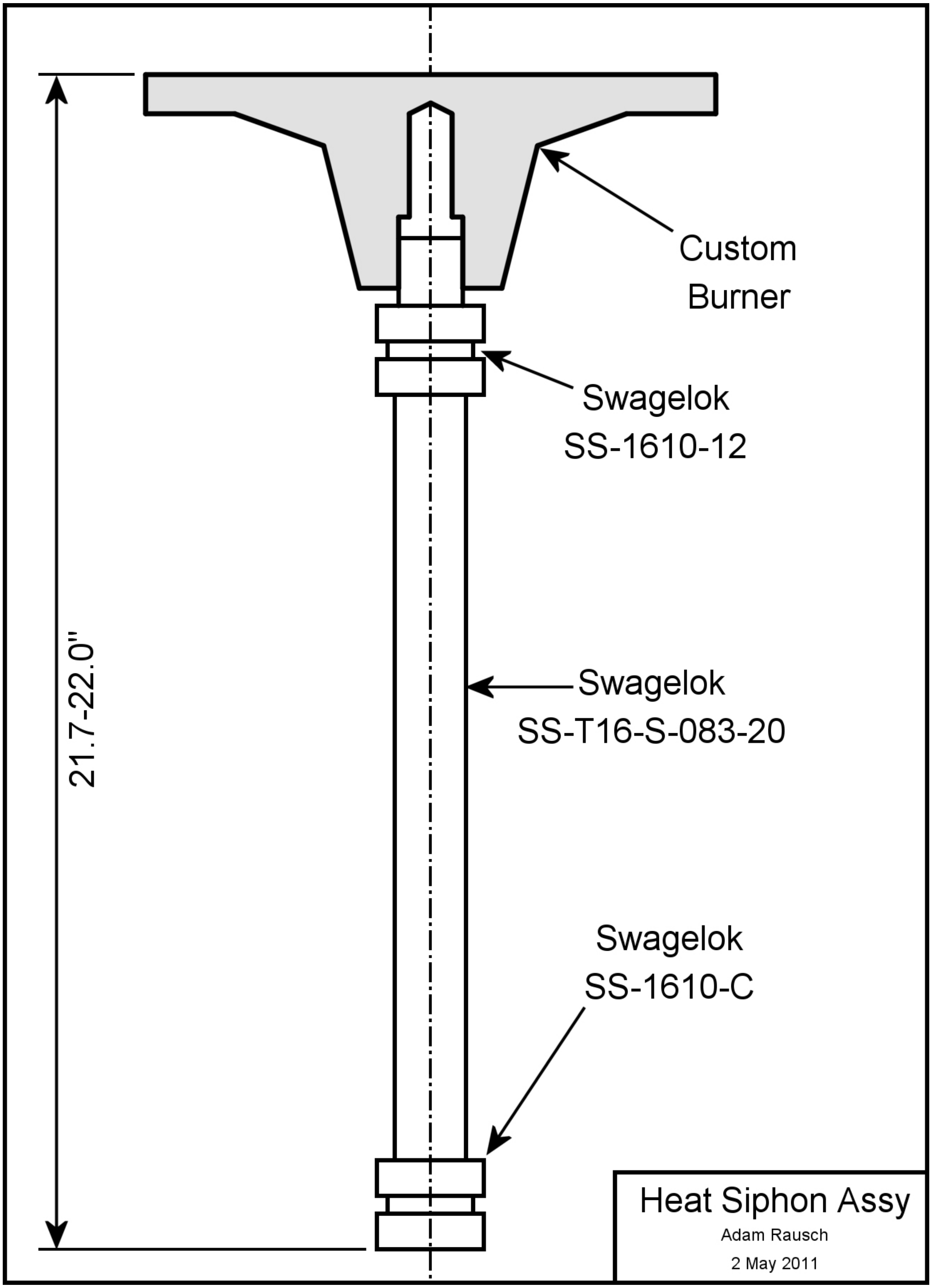
This gives us r_t for a given J and r_{in}.

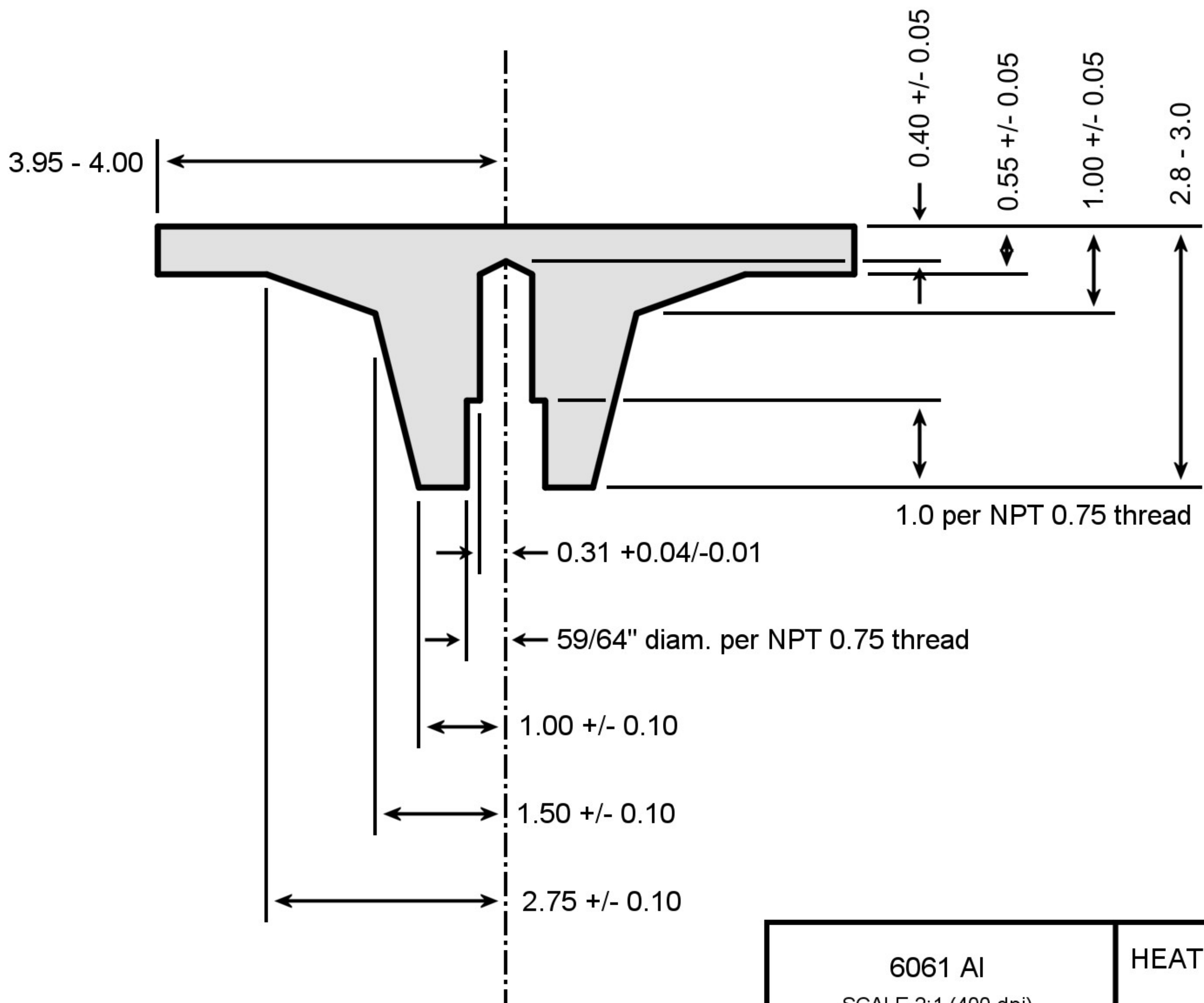
With r_t known, we can solve for u_l (39).

With r_t and $u_l(r_t)$ known, we can solve for dp/dx (29) and u_v (27).

With dp/dx known, we can solve for the dT/dx via the Clausius-Clapyron equation for the phase-change fluid.

Appendix D: Design drawings and prototype images





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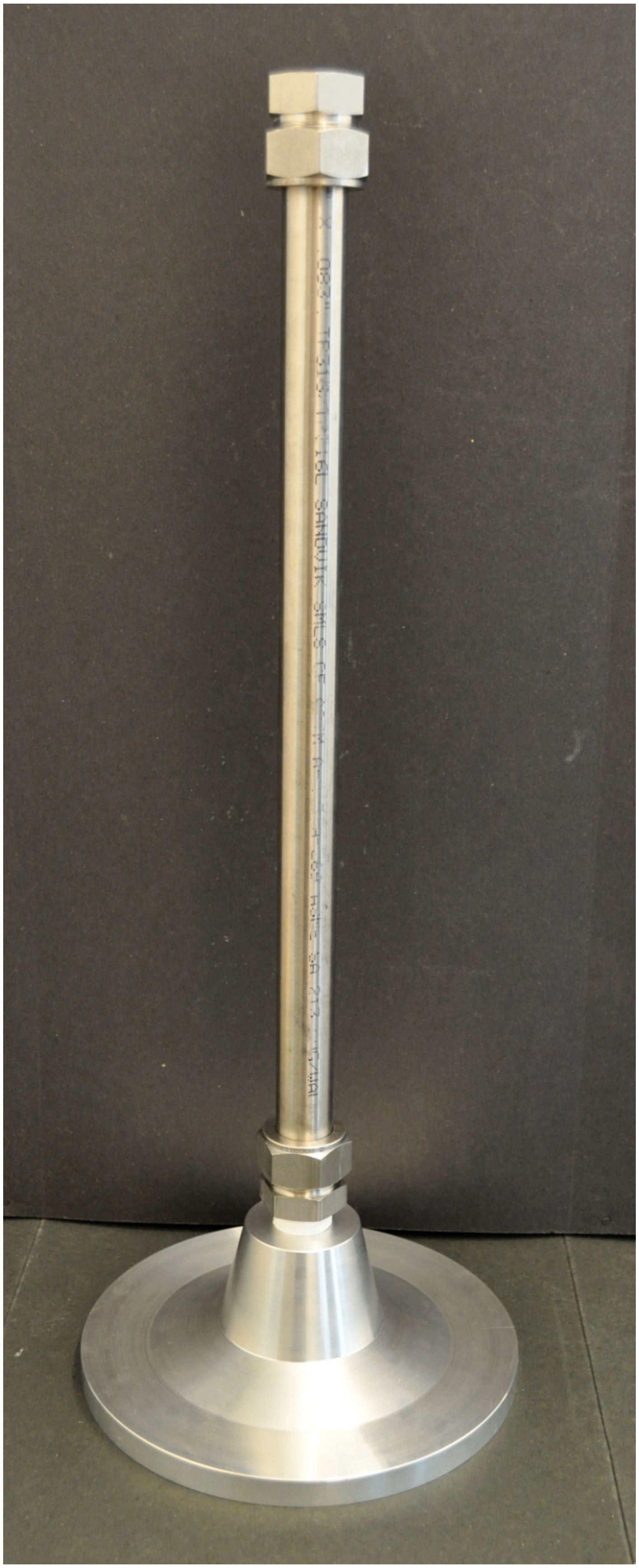
SCALE 2:1 (400 dpi)
DIMENSIONS IN INCHES

HEAT SIPHON BURNER
ADAM RAUSCH
V. 2.1
2 MAY 2011


SANDVIK