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Dampgenerering i en solfanger

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Master i produktutvikling og produksjon

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Department of Energy
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MASTER THESIS

For

Harald Andreassen

Spring 2013

Steam generation in a solar collector

Dampgenerering i en solfanger

Background and objective

Solar salt (nitrate mixture) represents an attractive latent heat storage option (PCM) for frying, as the melting temperature is about 220 degrees C.
The solar heat can be collected and transferred from a solar concentrator to the storage by a self-circulating boiling–condensing system. Using water will then require a system pressure of 30-40 bar. The design of the system must therefore be made with care.

An experimental setup is being planned at the University of Mekelle, Ethiopia. The setup needs to be constructed and tested for steam generation and for heat transfer efficiency. The candidate will take part in this work. The objective is to demonstrate solar frying of injera (the national bread in Ethiopia).

The following tasks are to be considered:

1 Literature review of self-circulating steam based heat transfer systems

2 Construction of a polar mount solar dish with a solar tracking system

3 Testing and analysis of a steam based heat transfer loop

4 Documentation in a project report

Within 14 days of receiving the written text on the master thesis, the candidate shall submit a research plan for his project to the department.

When the thesis is evaluated, emphasis is put on processing of the results, and that they are presented in tabular and/or graphic form in a clear manner, and that they are analyzed carefully. The thesis should be formulated as a research report with summary both in English and Norwegian, conclusion, literature references, table of contents etc. During the preparation of the text, the candidate should make an effort to produce a well-structured and easily readable report. In order to ease the evaluation of the thesis, it is important that the cross-references are correct. In the making of the report, strong emphasis should be placed on both a thorough discussion of the results and an orderly presentation.

The candidate is requested to initiate and keep close contact with his/her academic supervisor(s) throughout the working period. The candidate must follow the rules and regulations of NTNU as well as passive directions given by the Department of Energy and Process Engineering.

Risk assessment of the candidate's work shall be carried out according to the department's procedures. The risk assessment must be documented and included as part of the final report. Events related to the candidate's work adversely affecting the health, safety or security, must be documented and included as part of the final report.

Pursuant to “Regulations concerning the supplementary provisions to the technology study program/Master of Science” at NTNU §20, the Department reserves the permission to utilize all the results and data for teaching and research purposes as well as in future publications.

The final report is to be submitted digitally in DAIM. An executive summary of the thesis including title, student’s name, supervisor's name, year, department name, and NTNU's logo and name, shall be submitted to the department as a separate pdf file. Based on an agreement with the supervisor, the final report and other material and documents may be given to the supervisor in digital format.

☒ Work to be done in lab (Mekelle University)
☐ Field work

Department of Energy and Process Engineering, 14 February 2013

Olav Bolland
Department Head

Ole Jørgen Nydal
Academic Supervisor

Co-supervisors: Mulu Bayray (Ass. Prof. Mekelle),
Asfafaw Hailesellassie (PhD NTNU)

Abstract

Due to practical and cultural aspects, the traditional direct solar cooker has not been implemented successfully in rural areas of African countries. In areas with a weak or non-existing electrical grid a lot of time is spent finding biofuels for cooking; time that could be used getting an education and a job. Woodland clearance has been a threat for many years, and apart from the direct environmental consequences the price of firewood is now very high.

By implementing a heat storage and automatic tracking to a solar cooker, the possibility of cooking in the evening - without sunlight or electricity - is exposed. By utilizing a circulating steam loop to charge a PCM (phase changing material) latent heat storage, the storage could possibly be placed indoors and serve as a stationary stove. To be able to leave the solar collector in order to go to school or work during the day, the system needs to track the sun automatically throughout the day. This can be done in many ways. A tracking system involving a small DC motor, an optical sensor and a PV-panel is described in this report.

The initial objective of this project was to demonstrate solar frying of injera on a simple test rig with a PCM latent heat storage in Ethiopia. Automatic tracking was implemented and tested to be reliable. Several factors caused the focal point to be imperfect, and the temperature in the system did not suffice to melt the PCM. A 60/40 (mol%) mix of $NaNO_3$ and KNO_3 respectively was used as medium for latent heat storage. This eutectic mixture has a melting point of about 220°C, which is quite suitable for baking and cooking.

Sammendrag

Av praktiske og kulturelle årsaker har ikke tradisjonelle solkokere blitt implementert i landlige områder i afrikanske land. I områder med dårlig eller ikke-eksisterende strømnett blir mye tid brukt på å finne biodrivstoff til matlaging; tid som kunne gått til å få en utdannelse og en jobb. Skogtynning har vært et problem i mange år, og bortsett fra de direkte miljøkonsekvensene dette har, er prisen på fyringsved nå svært høy.

Ved å implementere varmelagring og automatisk solfølging til en solfanger åpner muligheten for matlaging om kvelden seg, uten sollys eller elektrisitet. Ved å benytte et selvsirkulerende dampsystem til å smelte solsalt ved varmeoverføring kan varmelageret plasseres innendørs og fungere mer eller mindre som en stasjonær komfyr. For å kunne forlate solfangeren for å gå på skole eller jobb på dagtid, må systemet automatisk kunne følge solens bevegelse på himmelen. Dette kan gjøres på mange måter. Denne rapporten beskriver et solfølgingssystem som involverer en liten DC-motor, en optisk sensor og et solcellepanel.

Det opprinnelige målet med dette prosjektet var å demonstrere solsteking av injera på en enkel testrigg med et latent varmelager (solsalt) i Etiopia. Automatisk solfølging ble implementert og testet til å være pålitelig. Flere faktorer forårsaket et ufullkomment fokuspunkt, følgelig ble ikke smeltetemperaturen til solsaltet oppnådd. En 60/40 (mol%) blanding av $NaNO_3$ og KNO_3 (solsalt) ble brukt i varmelageret. Denne eutektiske blandingen smelter ved omtrent 220°C, noe som gjør den egnet til baking og steking.

Preface

This project report on the testing and analysis of a self-circulating steam based heat transfer system is part of a network project between Norwegian University of Science and Technology (Norway), Eduardo Mondlane University (Mozambique), Makerere University (Uganda), Addis Ababa Institute of Technology (Addis Ababa, Ethiopia), Ethiopian Institute of Technology (Mekelle, Ethiopia) and Bahir Dar Institute of Technology (Bahir Dar, Ethiopia) and has been conducted in the period from February to June 2013.

Through this project I have had the opportunity to be part of a large, exciting project, and to do practical testing outdoors during a most inspiring visit to Mekelle University, Ethiopia.

I would like to thank Ole Jørgen Nydal, Asfafaw Haileselassie, Jørgen Løvseth and Mulu Bayray for helpful supervision through the entire project. The practical work has been done in the workshop at the Mechanical Engineering department at Mekelle University, Ethiopia, and in the workshop at the thermal energy building at NTNU, Norway and had not been possible without their respective very helpful crew. Thanks to Paul Svendsen, Principal Engineer at Department of Energy and Process Engineering, NTNU for his speed lecture on how to correctly install Swagelok® connections. Thanks to the Swedes in Mekelle for lending me their compass, and to my family for great support.

HaraldAndreassen
Trondheim, June 10, 2013

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1. Introduction

Biomass is the primary source of energy for around three billion people today[i]. As a result of this, vast areas are now suffering from deforestation. In Nigeria alone, 43.4 million tons of fuel wood is consumed annually for cooking, and consequently the country lost approximately 61 450km^2 of forest between 2000 and 2005[ii]. Humans frequently exposed to the emissions from wooden fires experience high susceptibility to respiratory deceases, and annually nearly two million people die prematurely from illness attributable to indoor air pollution from household solid fuel use[iii].

In rural areas women are usually responsible for preparing the food and fire needed to cook. From a study done by Edwin Adkins et.al[iv], households of Sub-Saharan African villages consume on average 2.2kg of wood per capita per day, with women and girls mainly collecting the firewood. Collection of wood is a tedious task, requiring on average six hours of walking, a distance of almost 13km every week.

Figure 1 - Three boys gathering firewood in the rural highlands of Tigray region, Ethiopia

As a consequence of women usually preparing the food, and children naturally staying close to their mother, exposure is exceptionally high among these two groups[v].

Burns can be directly related to the use of biomass and fossil fuels, and it is believed that as much as 4000 deaths related to burns could be prevented yearly by improving cooking conditions in rural households[vi]. Implementing solar cookers in every day cooking would hopefully contribute to improving these statistics.

Figure 2 - A woman baking injera on a traditional clay stove in Mekelle, Ethiopia

There are many ways of improving cooking conditions. Use of stoves as opposed to open fires, use of more efficient cooking stoves as opposed to leaky ones, and use of alternative sources of energy as opposed to biomass are some.

Almost all forms of energy have been directly or indirectly obtained from the sun, and so the sun is considered the main source of energy on this planet. The use of solar energy for preparing food is an old idea and many concepts have been conceived.

Solar cookers can be used to cook food and pasteurize water, and their efficiency, practical solutions and range of applications are continually being developed. Numerous factors including access to materials, availability of traditional cooking fuels, climate, food preferences, cultural factors and technical capabilities affect people's approach to solar cooking.

Unfortunately it has never really caught on as a major method of cooking. An obvious reason for this is the dependence on direct sunlight. Once clouds appear on the sky or the sun sets in the evening, the typical solar cooker becomes useless. However, solutions have been conducted to meet these challenges. E.g. the solar box cooker, or oven type cooker, which also works when the sky is partially cloudy, as it is not dependant on direct beam radiation such as a parabolic reflective sun collector. By storing solar heat, the possibility of cooking when the sun is not shining, e.g. in the evening, is exposed.

Types of storage include vessels containing rock, water, oil, or solar salt. The latter is ideal for baking and frying as it melts at a high temperature and retains a constant temperature through its solidifying process. A eutectic mixture of 60% sodium nitrate and 40% potassium nitrate (solar salt) represents an attractive latent heat storage option for frying, as the melting temperature is about 220°C.

A challenge related to the use of solar salt is that it should not be heated from below, as the melting and thus expansion of the matter at the bottom of a container in theory would cause high pressure, introducing an explosion risk (even though this has not yet been verified by testing). To make use of solar salt it is therefore believed that one is dependent on heat transfer from a fluid passing through pipes or channels from top to bottom, or heating the storage from the top. (Side-illumination is believed to be a possibility and experiments on that matter have been planned at Mekelle University). A circulating steam or oil-loop can be used to transfer heat from the focal point to the heat storage. Top-side illumination can be achieved with a double-reflector, while illumination from the side can be done by using an offset-type reflector. Another advantage from utilizing a heat transfer system such as a self-circulating boiling-condensing steam system is that the heat storage can be placed elsewhere than directly in the focal point of a solar reflector. To reach melting temperature of the solar salt with steam, a pressure of approximately 40bar is required in the system.

This study is a sub-project of the larger network project *Small scale concentrating solar energy system with heat storage*[vii]. This paper reflects upon the functionality of a pressurized self-circulating steam loop with automatic tracking and a heat storage containing solar salt.

The testing has been done mainly at Mekelle University, Ethiopia. Some additional testing has also been done at NTNU, Trondheim, Norway. The experimental setup in Mekelle was constructed and tested with the help from six technicians at Mekelle University.

2. Background

2.1 The parabolic shape

A parabolic solar reflector is used to collect solar energy and bring it into a focal point. The energy available in the area of the aperture of the reflector, that is the area enclosed by the outer edge of the parabolic reflector, will theoretically be focused into one single point when the reflector is pointed directly towards the sun. Several factors will make the focal point somewhat imperfect in real life. Irregularities in the reflective surface, imperfect alignment to the sun and an application not perfectly placed in the focal point are some factors. The intensity related to a "perfectly" focused parabolic reflector focal point is also practically inconvenient. By applying theory to practical testing, solar cooking applications can be optimized.

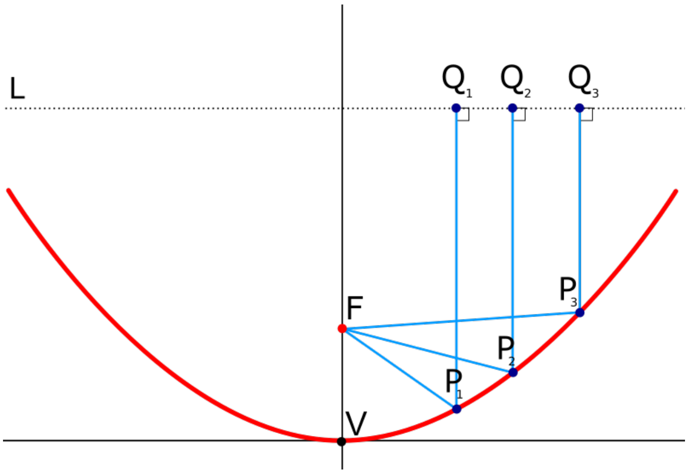


Figure 3 – Parallel sun beams focused into one point[viii]

The shape of a parabola is constant. No matter if it looks blunt or pointed; the shape will always be a part of the same basic shape, which is equal to the trajectory of a projectile fired into the air and falling naturally, air resistance neglected. The equation for the parabolic shape is

$$y = x^2$$

By rotating the parabola about its centre axis, the three dimensional parabolic dish shape (also called a paraboloid of revolution) is obtained. In this text it will be referred to as a parabola, parabolic dish or parabolic reflector.

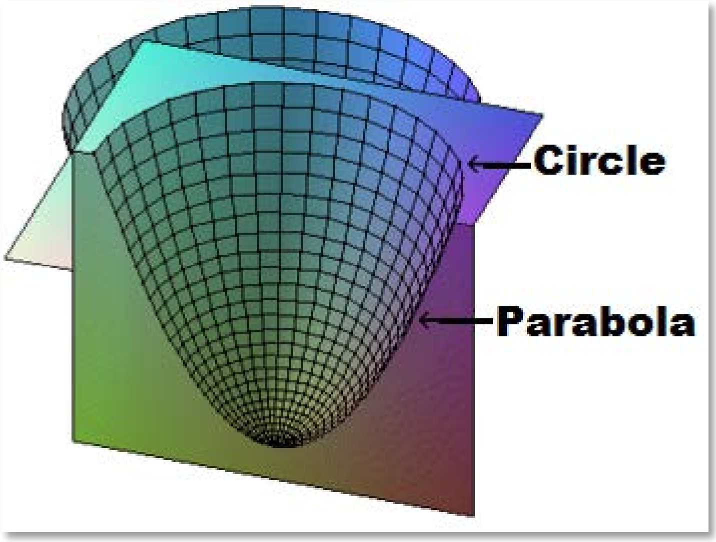


Figure 4 – 3D parabolic shape

Any horizontal intersection with the vertically aligned three dimensional parabola will project a circle, and any vertical intersection will project a parabola. (See Figure 4).

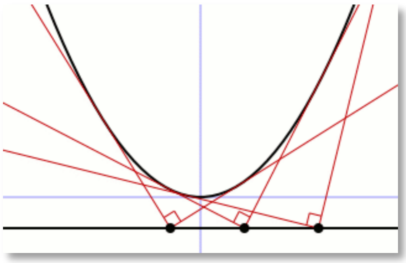


Figure 5 – Directrix

The directrix is the line consisting of the intersects of all perpendicular tangents to a parabola[ix]. This definition can make nice illustrations of infinity, although it has nothing to do with this master thesis.

2.2 Heat generating solar systems

There are many ways of generating heat by solar illumination. The reader might have felt the warm hood of a car left out in the sun on a summer day or sat down on a black bicycle seat heated by the sun. By implementing and utilizing basic physical laws, heat generation from solar energy can be optimized and utilized.

2.2.1 Direct illumination systems

The traditional solar cooker is made by the principles of reflection or minimizing convective losses. Arranging reflective surfaces in a way so that they focus their reflected sunbeams onto a pot, putting a pot inside a black box with a translucent top to reduce convective and radiation losses, or a combination of these, are basic ideas that have been subjects to optimization.

Figure 6 – A foldable cardboard reflector and box cookers at Mekelle University

Box cooker

A box cooker utilizes the principle of collecting solar energy with an absorber inside a box to reduce convection losses and inducing the greenhouse effect. Sunlight enters through a translucent top and heat gets absorbed by dark absorber pots and plates within the box. The long wave radiation from the dark surfaces cannot pass back out through the glass in the top of the box cooker, and the heat is trapped within the closed box. The heat input causes the temperature inside the box to increase until the heat loss of the cooker is equal to the solar heat gain[x]. By increasing the amount of sunlight or the intensity of the sunlight by adding reflectors, or by reducing heat loss with insulation, higher temperatures will be reached. A simple box cooker can reach temperatures sufficient for cooking food and pasteurizing water.

Direct illumination parabolic cooker

Food can be cooked by placing a cooking vessel directly in the focal point of a parabolic dish. The smoothness, reflectivity and size of the parabolic reflector determine the intensity at the focal point. A simple type of a directly illuminated parabolic cooker is the commercially available SK-14.

Figure 7 - SK-14

Figure 7 shows an SK-14 assembled at the Science Days in Oslo, Norway in September 2012. Even though the ambient temperature was not more than approximately 10°C and the sun was low on the autumn sky, soup was boiling in the pot when this picture was taken. The SK-14 is a collapsible reflector, made from thin aluminum rods and many reflective circle sectors.

The parabolic cooker is delicate to solar tracking as the focal point is very small relative to the reflector surface aperture. This also causes the focal point intensity to be high. The focal point intensity is related to the concentration ratio, which is defined as the ratio of the average energy on the receiver to that on the aperture[xi]:

$$C = \frac{A_{aperture}}{A_{reciever}}$$

2.2.2 Heat transferring systems

A heat transfer system is able to circulate naturally due to potential gradient between ascending and descending pipes. Natural circulation (or free convective) solar heat systems presents some advantages compared to forced-circulation, such as simple construction, wide adjustability, easier control and heat transfer ability at low temperature differences etc[xii]. When using water/steam as heat transfer fluid, the steam temperature is dependent on the system pressure.

Flat plate solar collector

A reflector can be made from a curved surface or flat plates. A simple design is a flat plate solar oven with reflective side panels such as described by Klemens Schwarzer[xiii]. The flat plate collector is a type of diffuse radiation collector, which consists of an absorbing plate with a special coating, usually covered by a transparent material to keep the long-wave radiation inside. The system in consideration consists of one or more flat plate collectors with absorbers and double glazed covering. Heat is transferred through a heat transfer fluid inside pipes located in the collector plates. The system is often used for domestic hot water, as the temperatures reached with such a design will not suffice for boiling purposes etc. Domestic water systems can be open or closed circuits. Open circuits use the hot water as the heat transferring fluid directly, whereas the closed circuit makes use of an additional heat exchanger between the heat transfer fluid and the hot water. By fitting reflectors to the side of the collector plate, temperatures suited for food cooking purposes can be reached.

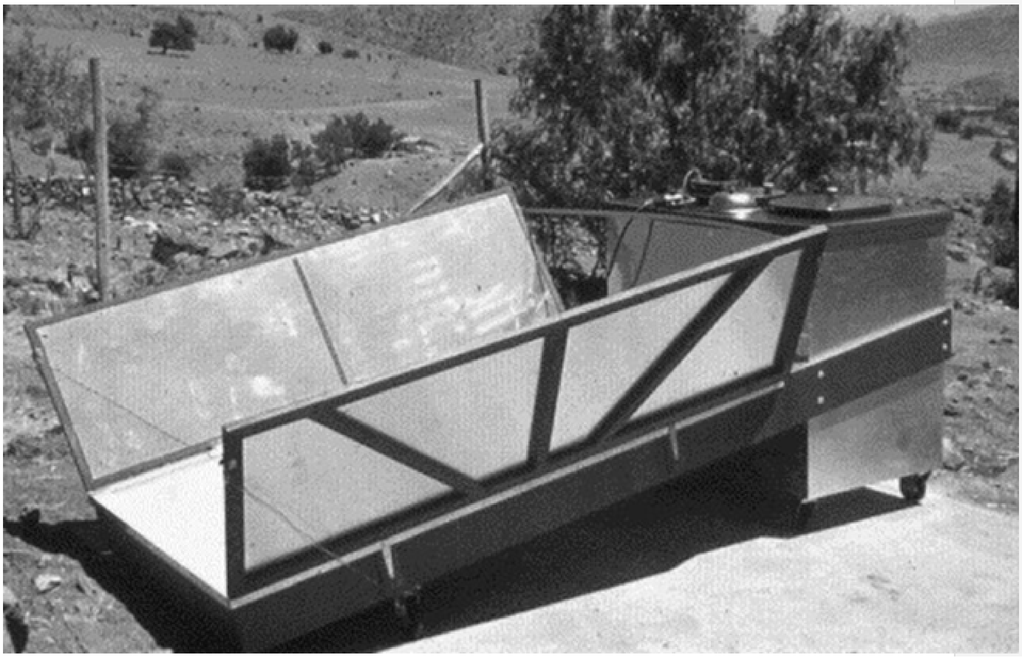


Figure 8 – Flat plate collector with reflectors for cooking purposes

The side reflectors improve radiation intensity at the collector plate. Oil is used as heat transferring fluid, and circulates naturally due to change in density from temperature change. This design is simple, efficient, and requires little maintenance.

Trough reflector

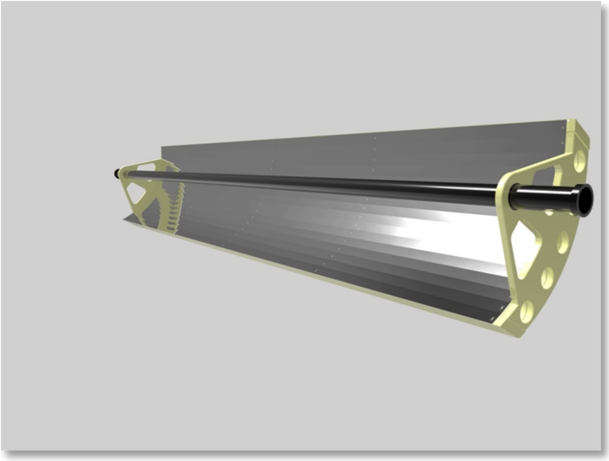


Figure 9 – Trough reflector

A more advanced version of the flat plate collector with reflectors is the parabolic through reflector. The trough reflector will obtain higher intensity at the desired focal area as it utilizes the parabolic shape as described earlier in this chapter. Due to its trough shape, however, the focal area will not be a point, but a line.

This design requires only one axis of rotation to track the sun, which makes for simple operation. Normally a tube will be located in the focal line, running the entire length of the trough and carrying a heat transfer fluid[xiv]. The last years there has been a strong development of direct steam generation systems using parabolic trough reflectors, and accordingly the use for storage systems adaptable to the two-phase fluid water/steam characteristics has been, and is, increasing[xv].

2.2.3 Heat storage

By implementing heat storage to a solar cooker, one is no longer dependant on cooking the food when and where there is sun. A heat storage can be thought of as a thermal battery. It is charged by solar power through a solar collector and can be utilized at a different location at a later time, say indoors after sunset. Sensible or latent heat storages can be used for solar heat storage, or a combination of the two[xvi].

Sensible heat storage

Thermal energy can be stored by raising the temperature of a solid or liquid material. The physical properties of the heat capacity and change in temperature of a material are utilized. The sensible heat storage capacity is dependent on the temperature change, the specific heat and the amount of storage material[xvii]. Sensible heat storage can be used for preheating and superheating of a water/steam system.

PCM

Phase changing materials (PCM) are latent heat storage materials, which means that heat is transferred (absorbed or released) at constant temperature as a material undergoes a phase change, that is when it changes from solid to liquid, liquid to gas or the other way round. An advantage of the PCM heat storage as opposed to the conventional (sensible) heat storage is that it absorbs and release heat at nearly constant temperature. In addition, they store 5-14 times more heat per unit volume than sensible heat storage materials like water, rock or masonry[xviii]. Furthermore, PCM storage systems have the advantage to operate with small temperature differences between charging and discharging[xix]. Sodium nitrate and potassium nitrate have melting temperatures of 310°C and 330°C respectively[xx]. When in a eutectic mixture, the melting point is lowered to about 220°C. One challenge related to PCM applications is the low thermal conductivity of PCMs. Measures have been done in order to increase the thermal conductivity, such as impregnating porous graphite matrices with the PCM[xxi]. The use of heat conductive metal fins within the PCM storage has been implemented in various ways[xxii],[xxiii].

2.3 Tracking

Solar tracking is essential to most solar cookers in order to obtain high efficiency and high temperatures, and it can be done using motors, weight systems or manual labour. Calibrated weight or clock systems, and motors together with sensors both offer the possibility of automatic tracking. The higher the desired temperature of the energy to be delivered, the higher must be the concentration ratio of the reflective system and the more delicate is the system to precise tracking[xxiv].

A weight system for solar tracking can be made in numerous ways. Brian White has designed a water clock, a tracking system with dripping water for a parabolic reflector[xxv].

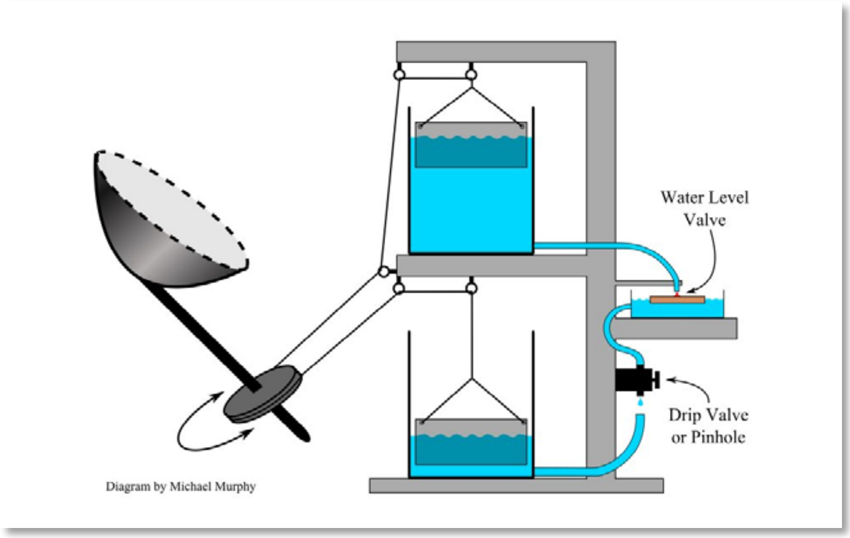


Figure 10 – Brian White's water clock

The system involves a series of pulley wheels, three water containers, two valves and two weights. The construction is somewhat complex, but in return quite accurate tracking can be achieved by calibrating the drip valve.

A box cooker is not as sensitive to sun alignment as a parabolic reflector as it does not have a small focal point. Nevertheless; it does require tracking.

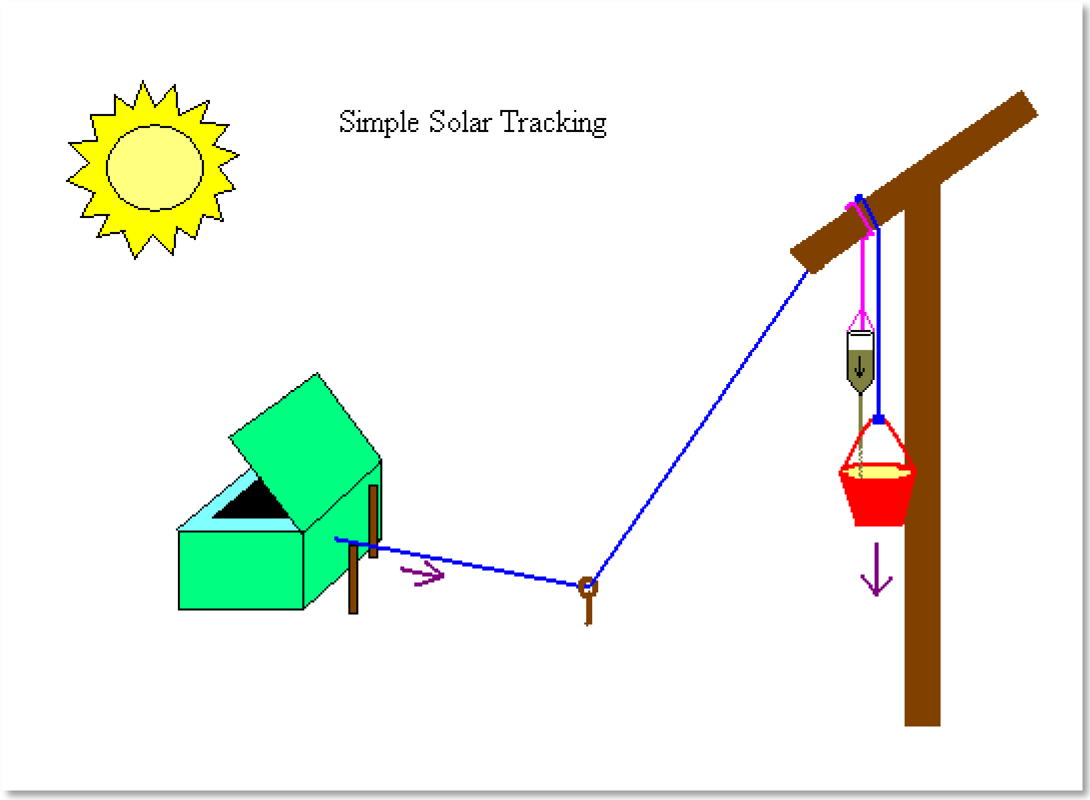


Figure 11 – Box cooker tracking system

Figure 11 illustrates a simple weight system with an inverted plastic bottle filled with sand filling a bucket through a small hole in the bottle cap[xxvi]. As the amount of sand in the bucket increases, the pulley system pulls one corner of the box cooker backwards until it is stopped by an object such as a pole in the ground. This is a rough tracking system, as the pull from the bucket will increase constantly. With a box cooker this system could be sufficient, however. By adjusting the bottle cap opening so that the pull from the bucket will not cause the box cooker to move until a given time, this pulley system works more like a timer. After a certain amount of time, the box cooker will rotate from initial position to a given end position. If your box cooker maintains desired temperature by being rotated once an hour, this system could give you two hours of time to do other things than watching the food heat up.

Not all weight-based tracking systems are capable of tracking the sun throughout an entire day, but have to be reset one or several times during the day. By utilizing a motor and an optical sensor, the system could theoretically be left alone all day long. There are several ways of implementing an optical sensor in a tracking system, but most use the idea of sunbeams being parallel and thus exploit the shadow cast by an object pointed directly towards the sun. Two sensors can be used as a switch and send an "on" signal to a control unit when for instance both sensors receive sunlight, or to directly turn a motor by registering whether both sensors are under the same illumination level[xxvii]. This concept can be programmed for two-axis tracking as well (usually utilizing four sensors).

When working with parabolic reflectors, a counterweight system is preferable when introducing automatic solar tracking. By balancing the torque around the pivoting axis, the force required to rotate the reflector with the suns movement will be minimized. This is favourable since it makes tracking possible with small weights or small motors, e.g. a small electric motor powered by a solar panel.

2.4 Previous work

A test rig was constructed at Mekelle University in January of 2013. It was designed to have the reflector rotate about the polar axis (to render possible one-axis tracking), with a self-circulating steam loop of which the purpose was to heat a cooking plate suitable for baking injera.

Injera was successfully baked on the steam heated cooking plate in February 2013. This work was led by Asfafaw Haileselassie.

Figure 12 – Injera baked on solar powered steam heated stove

The temperature at the focal point was measured with a hand held thermometer to be 585-630°C. The steam temperature was measured to be 250-260°C, and injera was baked on a clay stove with a surface temperature of 135-160°C. The report from that work was not yet published when this thesis was written, and these numbers are from conversations with Mr. Haileselassie.

3 Methods

3.1 Introduction

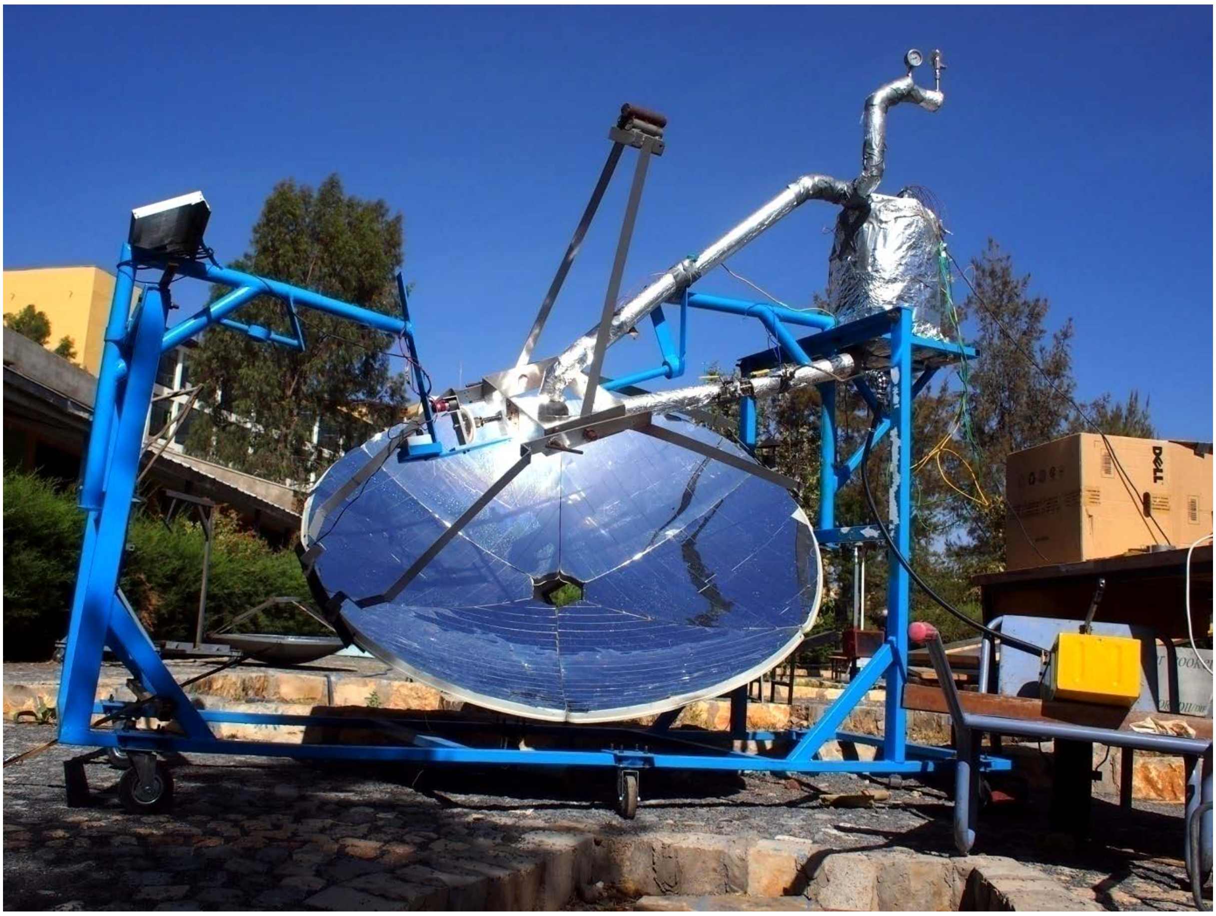


Figure 13 – The final test rig setup in Mekelle

One can say that Ethiopia receives thirteen months of sunlight, as the Ethiopian calendar has twelve months of exactly thirty days, and a thirteenth month called Pagume with five or six days[xxviii]. With fairly low annual precipitation[xxix] and thus small amounts of clouds, and a location close to the equator at 3° north to 15° north, it is exposed to strong radiation from the sun. This climate and the collaboration between NTNU, Trondheim, Norway and Mekelle University, Mekelle, Ethiopia made a visit to Mekelle feasible during the winter months in Norway.

The first part of this project included getting flight tickets and vaccines and actually going to Ethiopia.

Upon arrival in Ethiopia a warm welcome was given by students and staff at Mekelle University. A test rig for baking injera with a self-circulating steam loop was already constructed, and injera was successfully baked on the stove. The next task was to modify the rig to implement and test automatic tracking of the reflector and a heat storage in the steam loop instead of a direct cooking stove.

3.2 Heat storage

The piping needed for the heat storage had already been prepared, and a heat storage cylinder had been constructed at the Mechanical Engineering department workshop at Mekelle University. Inside the cylinder a pipe wound within a quadratic aluminum cast was used to transfer the heat from the steam to a phase changing material. This heat exchanger was fabricated partially at the department workshop, partially at a workshop in Mekelle city. The phase changing material was a mix of 60% Sodium Nitrate and 40% Potassium Nitrate, so-called solar salt[xxx]. Unfortunately these ingredients – especially Sodium Nitrate – are difficult to get a hold of in Ethiopia, so some was brought from Norway. After calculating the volume of the storage, it became clear that the available salt would not fill the heat storage. As constructing a new storage would require a lot of time, it was decided to continue with the existing heat storage and fill in as much solar salt as there was available. When well insulated, the losses from the heat storage should still be small, and it should theoretically be possible to melt the salt with the super-heated steam in the pipes within the aluminum cast of the heat storage.

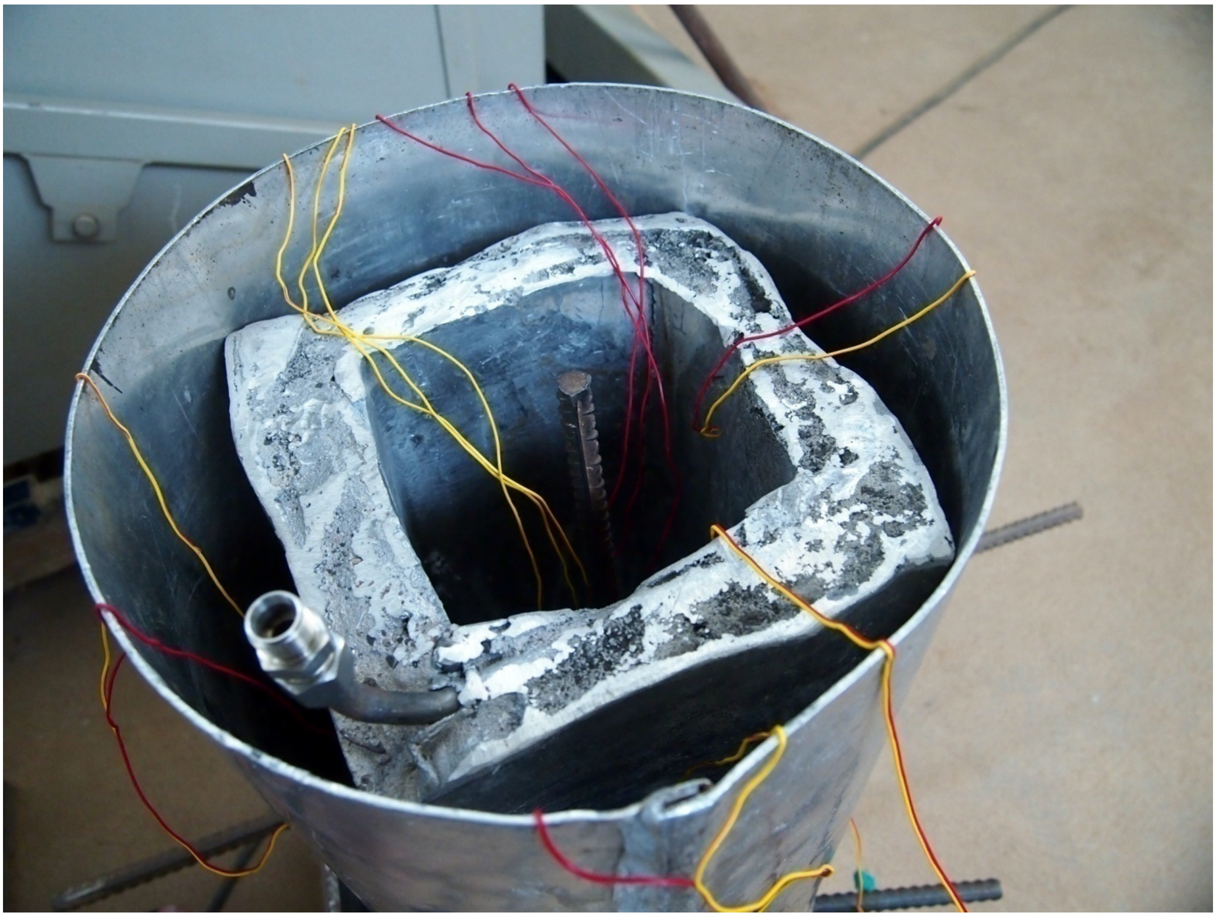


Figure 14 – The inside of the heat storage cylinder, with the inlet pipe, aluminum cast, center rod and thermocouple wires visible

The cylinder measured 50cm tall, 30cm in diameter. The square aluminum cast measured 45cm tall, with an average wall thickness of 4cm.

Before filling the storage with the nitrate mix, the two salts had to be pre-melted to reach a common, lower melting point. Potassium nitrate has a melting point of 334 °C[xxxi], and sodium nitrate has a boiling point of 306 °C[xxxii]. As the test rig was designed for 40bar and 250°C, the temperature of the steam in the system would not be high enough to melt these materials. When melted together, however, the eutectic mixture will have a melting point of approx. 220°C. Consequently premixing of the PCM was done in a furnace. The Mechanical Engineering Department at Mekelle University was at the time in possession of two suitable furnaces. Unfortunately, none of them were working. After some troubleshooting, the error was found and corrected and the melting was started. Due to the size of the furnace, the solar salt had to be melted in two batches. While the first batch was melting, the placement of the thermocouples was planned and a rod was placed in the center of the cylinder, in order to be able to read the temperatures at different depths in the center of the heat storage (see Figure 14).

A thermocouple is a sensor for measuring temperature. It works by measuring the voltage produced from heating or cooling a junction between two dissimilar metals[xxxiii]. The thermocouples used in this project were wire, with the two metals separated by standard electrical insulation. To cope with the possibility of getting several contact points on the thermocouples, as the insulation could dissolve in contact with the molten salt, the two wires on each thermocouple were separated (yellow and red wires in Figure 14). Now there would be only one contact point on each thermocouple, placed at desired locations. The first batch of molten salt was successfully poured into the storage, and as expected, the insulation around the thermocouple wires did melt in contact with the salt. Great care was taken, wearing protective gear when pouring the melt into the cylinder, as the temperature of the mix was approximately 350°C. The next day the second batch was melted

(16.7kg in total), and the first batch of solar salt had solidified in the heat storage. Some bubbles were visible at the surface of the salt, possibly due to impurities caused by the dissolving of the wire insulation. This is shown in Figure 15.

Figure 15 – Bubbles possibly due to impurities in the melt

The storage was insulated with all the Rockwool found available for purchase in Mekelle, tracked down at a factory producing ovens. In a city where the lowest average monthly temperature is 18°C[xxxiv], house insulation is not common merchandise. The insulation layer thickness was about 6cm. The Rockwool was clad with two layers of aluminum cooking foil bought at a super market.

3.3 Tracking

To be able to implement automatic tracking to the test rig, some modifications had to be done to the structure. It was desirable to use a small electric motor powered by a 10W PV-panel. Such a PV-panel and a plastic sprocket compatible with the small motor bought from Germany had already been provided by the author's co-supervisor.

The motor connected to the gear box was also wired through a fuse in order to keep it from burning in the case of an overload. To make the small motor able to rotate the reflector about its polar axis, and to prevent the teeth on the plastic sprocket to break, the system had to be well-balanced.

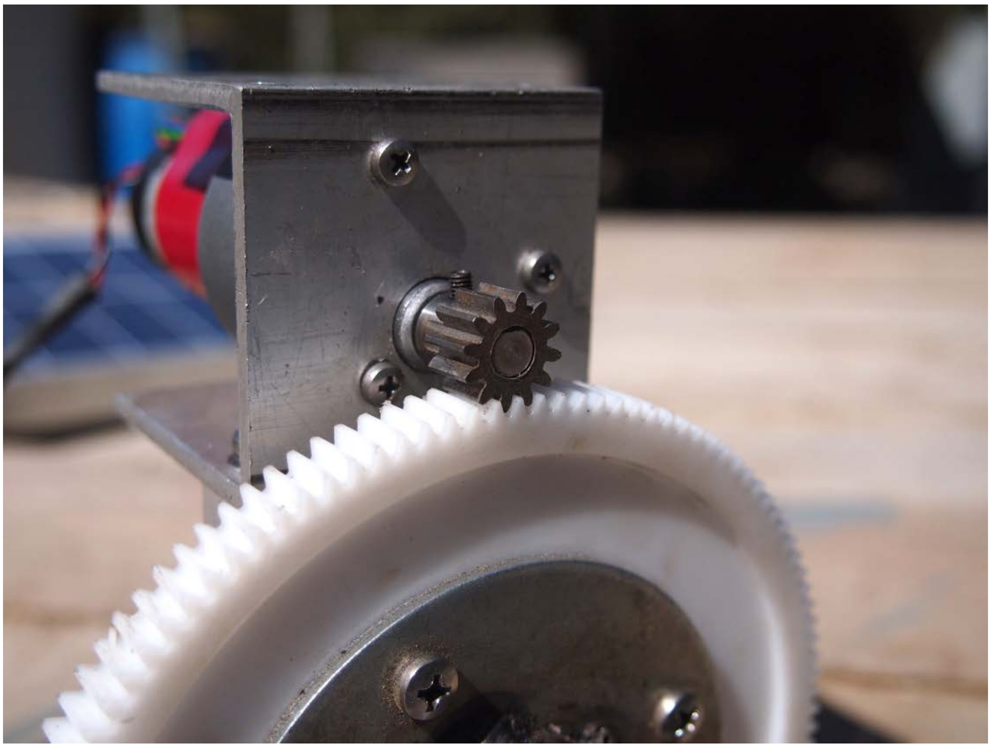


Figure 16- Motor, gear and fragile plastic sprocket

The better the balance of the system, the less torque would be required to rotate the reflector. To balance the torque around the rotating axis, a counterweight was constructed. As the weight of the reflector and its supporting frame was unknown and a scale was not to be found, the counterweight was made adjustable with several sections of solid steel rods. The counterweight design is showed in Figure 17.

Figure 17- Counterweight

The original test rig was designed to keep the reflector parallel to the polar axis in order to be able to track the sun in only one axis during the day. The declination of the sun throughout the year has to be compensated for regularly to keep the reflector plane normal to the incoming sunbeams. The “neutral” position of the solar declination is normal to the polar axis, which in Mekelle is 13.29° relative to the ground. When the angle was measured on the actual rig, however, the angle was around 23°. Due to this small, but significant error, one-axis tracking was not possible. A large, wooden triangle with a 13° angle was constructed in order to measure the angle of the parabola more easily. A steel frame around the boiler worked as a connection between the polar mount and the framework suspending the reflector. The counter weight was mounted on this frame, and the reflector could be rotated north/south about the frame due to their connection points being centered on either side of the boiler. The suspending framework was equipped with set screws, making it possible to fix the “polar angle” at the desired position. (Still, this would not cope with the problem of the rotational axis not being parallel to the polar axis).

Several factors need to be in place in order to theoretically be able to obtain a good focal point throughout the day with one-axis tracking on a parabolic reflector dish. As already described, the plane of the reflector must be normal to the incoming sunbeams. To obtain this when rotating the reflector from east to west with a stationary framework, the rotational axis must be facing straight towards north. In the beginning the rig was pointing towards what was believed to be true north. However, due to the absence of a compass this was likely to be wrong. When tracking the sun throughout the day, the reflector had to be adjusted quite a lot in the north/south direction, not only in the east/west direction. This suggested that the rotational axis was indeed not pointing towards north, as well as the angle of the polar mount was known to be incorrect. After some days and the use of a hand held GPS, the position of the sun at mid-day and the GPS-function on a mobile phone to correct the orientation of the test rig, the reflector required only minor adjustments in the north/south direction throughout the day.

Reasons for still having to do adjustments include the already mentioned polar mount and the fact that the framework supporting the reflector was flexing as the parabola was rotated to either side in the morning and afternoon hours. Even though it was not unlikely that the rig was off by a couple of degrees compared to true north due to some inaccuracy from the GPS-devices, the polar mount and the flexing structure were probably the main sources of error. Figure 18 shows the structure flexing in the afternoon.

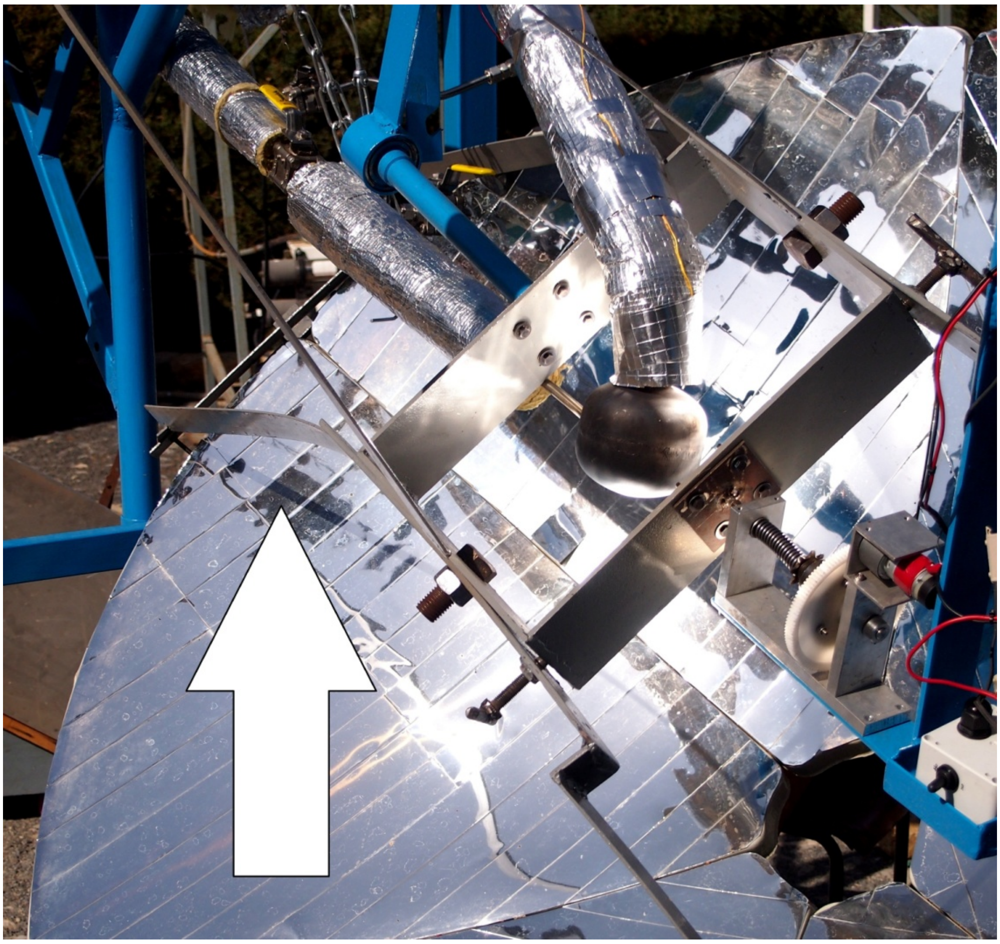


Figure 18- Flexing framework

To have the reflector follow the movement of the sun during the day, a typical optical sensor used for solar reflector was used. This one was made from two square optical sensors mounted parallel to each other on a square piece of metal and separated by approximately 1mm. This configuration was attached to a box made with a flange exactly the size of half the sensor plate. When the surface of the two sensors were normal to the incoming sun beams, the flange would cast shadow with its edge directly between the two sensors, leaving one sensor in the sunlight, the other in the shadow. The two sensors were connected to a control box, which again was connected to the PV panel and the electric motor. When only one of the sensors was receiving sunlight, the motor would be off. As soon as the sun moved far enough to indulge the other sensor with its beams, the control unit would tell the motor to turn until only one sensor was receiving sunlight again.

Figure 19- Top: Sensor box setup. Bottom left: Neutral position. Bottom right: Engaged position.

This way the tracking system would make sure the reflector was following the suns movement throughout the day.

The sensor box naturally needs to be mounted normal to the reflector plane, so that the surface of the sensors and the reflector plane is parallel to each other. In this way the reflector will be facing directly towards the sun as the sensor is following the suns movement throughout the day. The sensor box was therefore mounted on the side of the reflector dish, normal to the reflector plane.

The tracking was monitored by controlling the focal point with long wooden sticks. This method had been used for the previous setup, so the rig operators were well accustomed to it.

Figure 20 – Controlling the focal point

The method might seem inaccurate, but the intuition established by the test personnel on this matter is not to be underestimated. After controlling the focal point several hundred times, the time it takes for the wooden stick to start to emit smoke or catch on fire and the type of smoke emitted at first when exposed to a well-focused focal point, is well known to the rig operators. A difference in one or more of the parameters mentioned, unnoticeable to the untrained spectator, could indicate an imperfect focal point to the rig operators. Imperfect relative to the optimal focal point obtainable with the reflector in use, that is.

3.4 Piping

The piping used for the steam loop was Swagelok®[xxxv], a system capable of high pressure fluids. It is important that the pipes, with valves and fittings, are connected correctly. If not fitted the right way, a connection might burst open when subject to high pressure. As this system had an intended pressure of around 40bar and accordingly water steam at 250°C[xxxvi], such an incident was highly unwanted. Insulation of the pipes is crucial to minimize convective and radiation heat loss.

Figure 21- Boiler and steam pipe with insulation

The piping was well-insulated with thick Rockwool®[xxxvii] insulation made for pipes. The return pipe was also insulated, in order to minimize the amount of energy needed to re-heat the returning water to its boiling point and to avoid two-phase working condition.

3.5 Pipeline setup

To test the performance of the heat storage and the automatic tracking, necessities are water in the boiler and sun in the sky. To be able to reach high pressure in the steam loop, proper bleeding of the pipes is essential. If there was to be air in any part of the pipe loop, this air would work as a sort of cushion, as it is compressible. Then, instead of reaching high pressure as the water boils in the boiler, the air would compress and cause the pressure increase to be small. Also, air in the pipeline could act as an air lock, hindering or blocking the circulating flow. To bleed the system properly, the air had to be purged out, as there were both upward and downward bends in the pipe loop.

On a car or a bicycle with hydraulic brakes, the system consists of a brake fluid reservoir at the top and a brake cylinder at the bottom of the system. As the steam system constructed and tested in this project was a complete loop, an inlet and outlet valve and a middle valve between them was needed to assure flow through the entire pipeline. A sketch of the pipeline and its valves is illustrated in Figure 22.

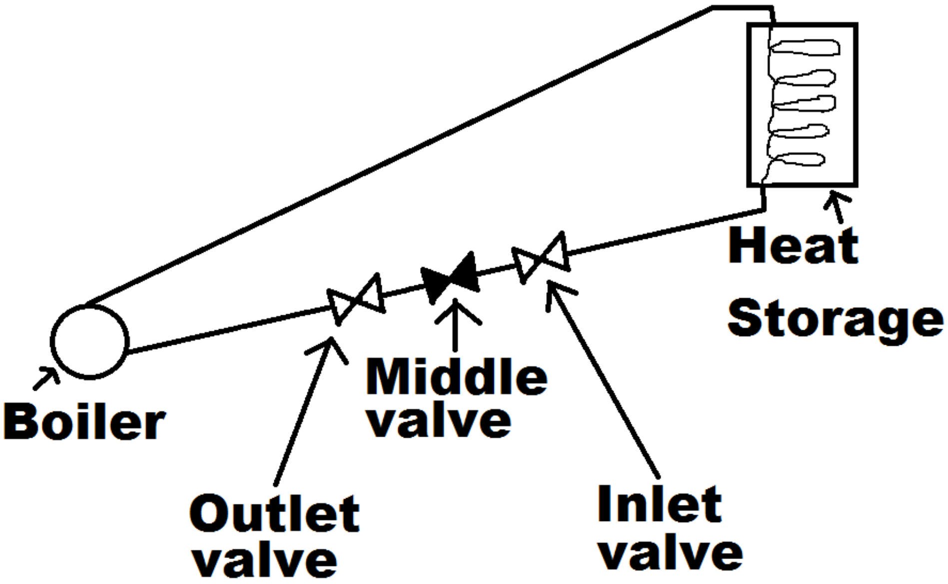


Figure 22- Valves

As the inner diameter of the pipes was 8mm, the bleeding was initially done with a manual pump with a fairly small pumping chamber. Because of the small cross-section area of the pipes this pump gave a relatively high flow rate, which is needed to bleed the loop. If there is air trapped in an upwards bend, high flow rate is needed to purge the air out.

From the first day of testing, there were problems with reaching high enough pressure. In order to obtain temperatures high enough to melt the solar salt, the steam loop has to reach a pressure of about 40 bar[xxxviii], but the pressure gauge on the test rig was showing only 8 bar.

When initiating the test at the beginning of the day, the system was bled of air and ultimately the pipeline should have been full of water. The outlet valve was closed, then the middle valve was opened and the pump was given a slight pump so that the pressure increased slightly, and finally the inlet valve was closed. When the reflector was put into position, aiming its focal point onto the boiler, the pressure would increase immediately as there was no room for the water to expand.

When the pressure is increased one can start extracting water from the outlet valve. It is essential that there is overpressure inside the pipes when extracting water. If the pressure within the pipes drops to atmospheric pressure with the outlet valve open, equilibrium will cause air to freely enter the pipe if the water flow ceases, and the system must be bled again. Two thirds of the total volume should be extracted in order to achieve good circulation and let all the water within the system to be able to fully vaporize as the volume ratio of water in liquid and gas state is 1/3.

At first, the total volume of the pipeline was not known, as the exact volume of the boiler and the length of the coiled pipe within the heat storage was unknown. The length of the coiled pipe was estimated after consulting the author's co-supervisor who had been involved in making the heat storage. The coiled pipe was made from a section of a 6 meter long pipeline, and the remaining section had also been coiled but was not cast in aluminum. The remaining coil was found and measured. The volume of the boiler was estimated by measuring its outer dimensions and assuming its wall thickness. The total volume of the pipeline was calculated to be 997cm^3, which meant that about 660ml of water should be extracted. A few days later the weather was cloudy, so no tests were carried out. The pipeline was therefore disassembled and the volume was measured to be exactly 900ml, which meant that 600ml should be extracted.

One should flush the system regularly in order to remove debris from the pipeline and to obtain pure water in the system and accordingly the desired properties of water. The following picture illustrates the difference between water that has been in the system for a long time and re-used several times (clearly contaminated) and clean water extracted from the system after a proper flushing.

Figure 23- Water samples illustrating the importance of flushing the system regularly

The tap water in Mekelle is very hard. The salt in the water would after some time scale inside the pipes. To avoid this, bottled water was used for the experiments.

Seven thermocouples were located at different positions inside the heat storage. Two at the inner wall of the cylinder, two at the inner wall of the aluminum cast, and three at the center of the cylinder, mounted on an iron rod. In addition to these, one thermocouple was mounted directly on the steam pipe, close to the boiler, one was mounted directly on the steam pipe right at the inlet to the heat storage, and one was mounted directly on the return pipe, right at the outlet of the heat storage. In the software Labview the thermocouples were named as showed in this sketch.

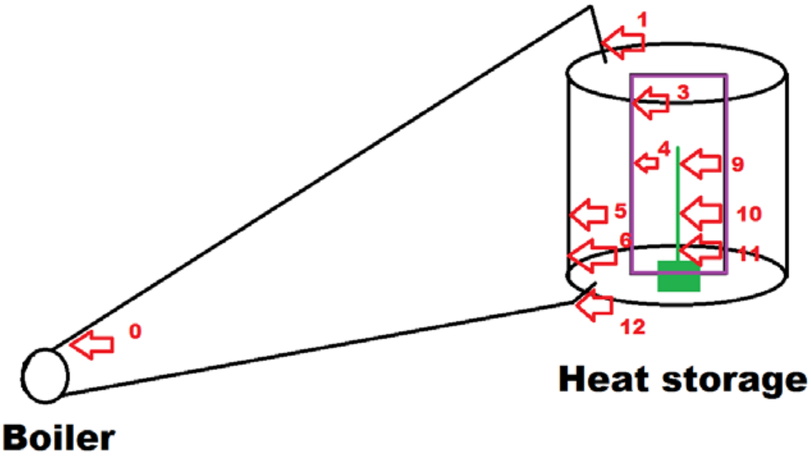


Figure 24- Thermocouple distribution sketch

Thermocouple 2 on the data logger was not working, and thermocouples 7 and 8 were reading ambient temperature. The distribution of the seven thermocouples inside the storage was as follows:

Thermocouple #	Location
3	5cm from the top of the aluminum cast, touching the inner aluminum wall
4	18cm from the bottom of the aluminum cast, touching the inner aluminum wall
5	13cm from the bottom of the cylinder, touching the cylinder inner wall
6	2cm from the bottom of the cylinder, touching the cylinder inner wall
9	18cm from the bottom of the cylinder, mounted on the center rod
10	13cm from the bottom of the cylinder, mounted on

	the center rod
11	2cm from the bottom of the cylinder, mounted on the center rod

Table 1 – Thermocouple distribution

3.6 Experiments

Experiments made it clear that circulation was present. The first day of testing a small amount of water was extracted when the pressure increased after bleeding the pipeline. The pressure didn't seem to rise above 8bar, so extracting more water was postponed while letting the pressure increase. Due to a power cut, the logging stopped at 10:40 that day. The power came back approx. at noon, but due to a mistake the data logging was not started until 13:50. Experiment notes were taken, however, and 50ml more was extracted at 12:10, followed by a slight temperature increase (Labview was running, but not recording). Pressure had dropped to 6bar after the extraction, but the system temperature was increasing as a result of steam circulation.

The pressure stayed constant at 8bar for more than one hour, and the temperatures inside the storage did not increase much. More water was extracted to improve circulation, even though the pressure was not more than 8bar. A total of 250ml was extracted, and temperatures started increasing. At around 14:20 the maximum temperature was reached that day, with close to 200°C at the steam pipe and 190°C at one point on the aluminum cast. With a better focal point, these temperatures would have been reached earlier, and the maximum temperature would have been higher. The second day a steady temperature of about 170°C was reached inside the storage, even though there were some clouds present. After the second day the entire rig was mounted on the back of a truck and taken on an exhibition parade. The setup was probably inflicted some damage during this transportation, as the temperatures reached after the exhibition was generally lower than prior to it, despite improved test procedures.

With a small amount of water extracted, the pressure would stay high, but the temperature inside the storage would be low, and the temperature at the outlet of the heat storage would be equal to the ambient temperature, indicating no circulation. When extracting more water, the process of steam rising through the steam pipe, transferring its heat to the solar salt by condensing on its way through the heat storage, and returning as water through the return pipe was initiated. A clear indicator of the circulation process was the thermocouple at the outlet of

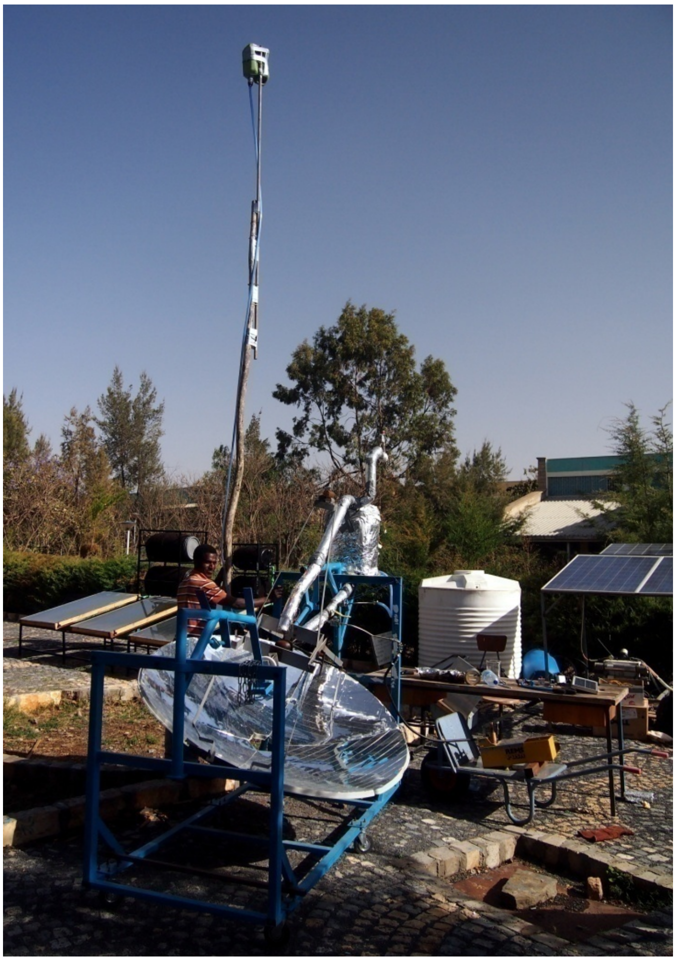


Figure 25 – 7m water tower

the storage. This thermocouple was sensitive to temperature change as it was placed directly on the pipe, as opposed to the ones inside the heat storage.

Air was a suspect, possibly trapped within the pipeline and causing the pressure to remain low. After consulting Ole Jørgen Nydal through e-mail, a water tower was constructed to increase the flow rate when flushing the system, thus improving the bleeding procedure. A ten liter water tank connected to a water hose was mounted on a steel pipe, which again was mounted onto a long, wooden pole, making the total height of the erected water tower 7 meters.

Regarding that the outlet valve was 1.4m above the ground, a water head of 5.6m was obtained. The pressure of the water at this head is given by

$$P = \rho g H = 998 \, {}^{kg}\!/_{m^3} * 9.8 \, {}^{m}\!/_{s^2} * 5.6m = 54.77kPa = 0.5477bar$$

Mekelle University is located at approximately 2200m above sea level, and accordingly the atmospheric pressure is 0.79bar[xxxix]. The fluid velocity of the water caused by the water tower can be calculated using Bernoulli's equation. Point 1 is at the water tank, point 2 at the outlet of the system:

$$P + \frac{\rho V^2}{2} + \rho g h = constant$$

$$V_1 \ll V_2$$

$$P_1 = P_{atm,2200m} = 0.79bar$$

$$h_2 = 0$$

$$V_2 = \sqrt{\frac{2(P_1 + \rho g h_1 - P_{Head,tot})}{\rho}} = 10.48\, {}^{m}/_{s}$$

Flow rate:

$$Q = VA$$

$$Q = 10.48\, {}^{m}/_{s} * \frac{100cm}{1m} * \pi \frac{(0.8cm)^2}{4} = 526.78\, {}^{cm^3}/_{s} = 0.53\, {}^{l}/_{s}$$

The water flow through the pipes was now strongly increased. However, the water flow was somewhat decreased by making its way through the entire pipe loop. The coiled pipe manufactured for the heat storage would to some degree obstruct the water flow at high velocity. To remove potential air trapped between the outlet/inlet valve and the middle valve, the middle valve was opened rapidly while the water from the water tower was flushing through the pipeline. This caused the water flow through the outlet valve to increase noticeably, proving that the flow was indeed hindered on its way through the entire loop. However, steam circulation should not be affected in the same way, as the velocities related to natural circulation are very low.

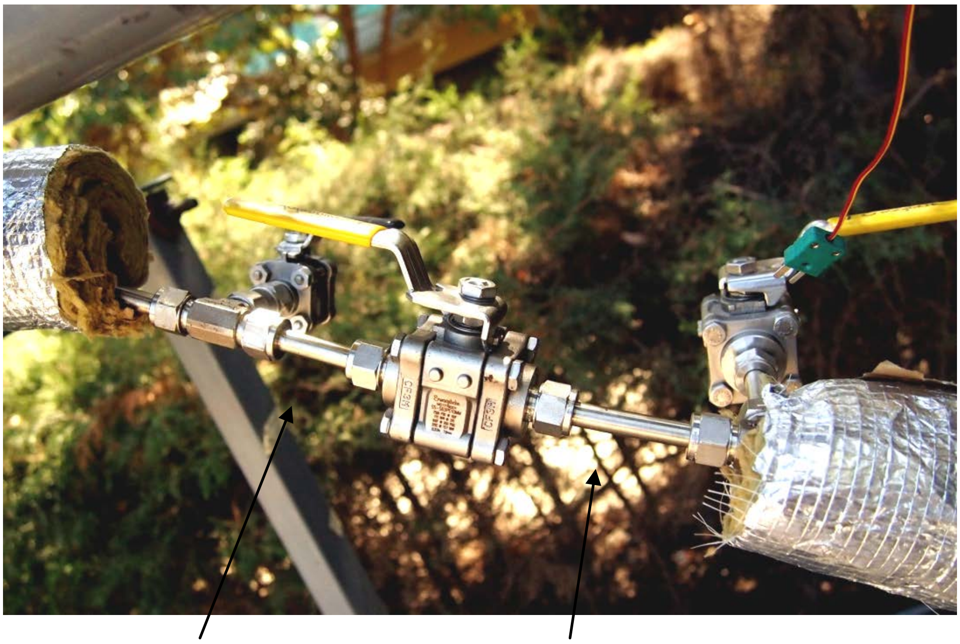


Figure 26- Possible air trap

After flushing 6 liters through the pipeline, the outlet valve was closed, and the pump was connected to the inlet to slightly increase the pressure and verify that the system was free of air. While fastening the connection from the pump to the inlet valve, constant pressure was put on the pump lever, so that there was a small, continuous flow of water from the pump into the closed inlet valve. Doing so, the connection between the pump and the inlet valve was kept airless while fastening the connector. Still there were problems reaching high pressure during tests. Small amounts of water were extracted at a time to keep overpressure in the system. Early in the day, when the system was fairly full of water, extracting 50ml could cause the pressure to drop from 50bar to atmospheric pressure. After letting out 660ml and letting the system heat up throughout the day with a clear sky and good tracking, the pressure was still struggling to reach 10bar. To try and improve the bleeding procedure even more, the pump was connected to the outlet while flushing with the water tower. The pump had an outlet valve as well, so the flushing was done through the pipeline, through the connection to the pump, and out through the pump's outlet valve, into its water chamber. Then the outlet valve on the pump was closed, and the water was pumped back up through the pipeline and up the water tower.

As the valves on the pipeline now were working as both inlets and outlets, they will in this text be referred to as in Figure 22 to avoid confusion.

Because the hose between the water tank on the tower and the inlet on the pipeline was see-through, bubbles were observed exiting the pipeline when pumping the water back up. This was at first suspected to be because of a defect in the pump, drawing dilution air through a leak gasket or the like. This suspicion was disproved, however, after repeating the process of flushing and pumping back up three or four times. At last there would be no air exiting when pumping the water back up the water tower. One last repetition was executed to make sure there was no water in the system. The outlet valve on the pump was closed, and then the inlet valve on the pipeline was closed before the middle valve on the system was opened. Then a slight movement of the pump handle caused the pressure in the system to increase instantly, and the outlet valve was closed. The first day this method was used, clouds appeared and testing was aborted. The next day the system was flushed and bled in the same manner, but the pressure would not reach more than 4bar. There were some clouds present this day, which could have been the reason for the pressure being that low. This also suggested that the temperature in the system and thus the pressure in general was delicate to the intensity of the focal point, and thus sensitive to the shape of the reflector.

An analogue compass was acquired towards the end of the stay in Mekelle. When the position of the test rig was compared to the true north provided by the analogue compass, it became evident that the rig was only approximately two degrees off. Still the tracking sensor had to be slightly adjusted in the morning and the afternoon. As described in section 3.3, the explanation to this was the damaged reflector, incorrect polar mount and the flexing framework suspending the reflector dish. At its outermost positions that are in the morning and the afternoon, the flexing caused the reflector to hang down to one side, providing a focal point above the boiler.

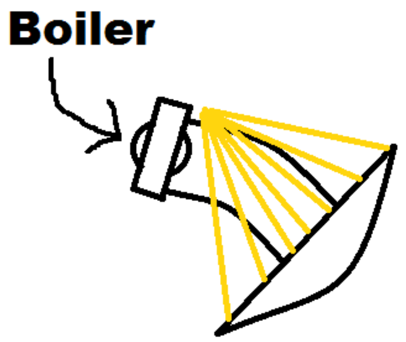


Figure 27- Heightened focal point (exaggerated sketch)

The sensor was mounted on the western side of the reflector, with its shadowing flange on the eastern half of the box. It therefore had to be adjusted slightly towards east in the morning and slightly towards west in the afternoon, so that the focal point again would be well-focused on the boiler.

The test procedure was the same for the rest of the stay, and fairly uniform results were obtained. Clouds and thus varying radiation factors together with human errors concerning orientation of the test rig, bleeding and monitoring of the tracking made the temperatures slightly different for every day of testing.

Some testing was carried out at NTNU, Norway after returning from Mekelle University. A similar rig was constructed in April 2012, with a much more rigid reflector and framework.

Figure 28 - Steam generating, self-circuklating rig at NTNU

Testing in Trondheim can be a challenge, as clouds are frequent. Some tests were obtained, however. The experience from these tests was that the temperature is indeed very sensitive to fluctuating radiation. “Blue skies” in Trondheim in May usually mean that there are *almost* no clouds. With shifting clouds in the sky, melting of the solar salt was not accomplished, reaching a maximum temperature of approximately 135°C in the storage.

4 Results

The thermocouple readings were essential to indicate the performance of the heat storage. Ten thermocouples were distributed throughout the heat storage and pipeline, which gave a good image of how the system was behaving.

The graphical displays of the thermocouple readings show how the temperatures in the entire system are developing through the day.

Figure 29 – Illustrative temperature increase, readings from 25.03.2013

The problem of reaching high enough temperature to melt the solar salt was consistent. At the end of the stay at Mekelle University the early rainy season was starting off, and the shifting cloudy weather was causing the focal point to fluctuate accordingly. The manufacturing of the modified structure was more time-consuming than first estimated, giving less time for testing than initially hoped for. Nevertheless, consistent results were obtained, and good ideas for further work were established.

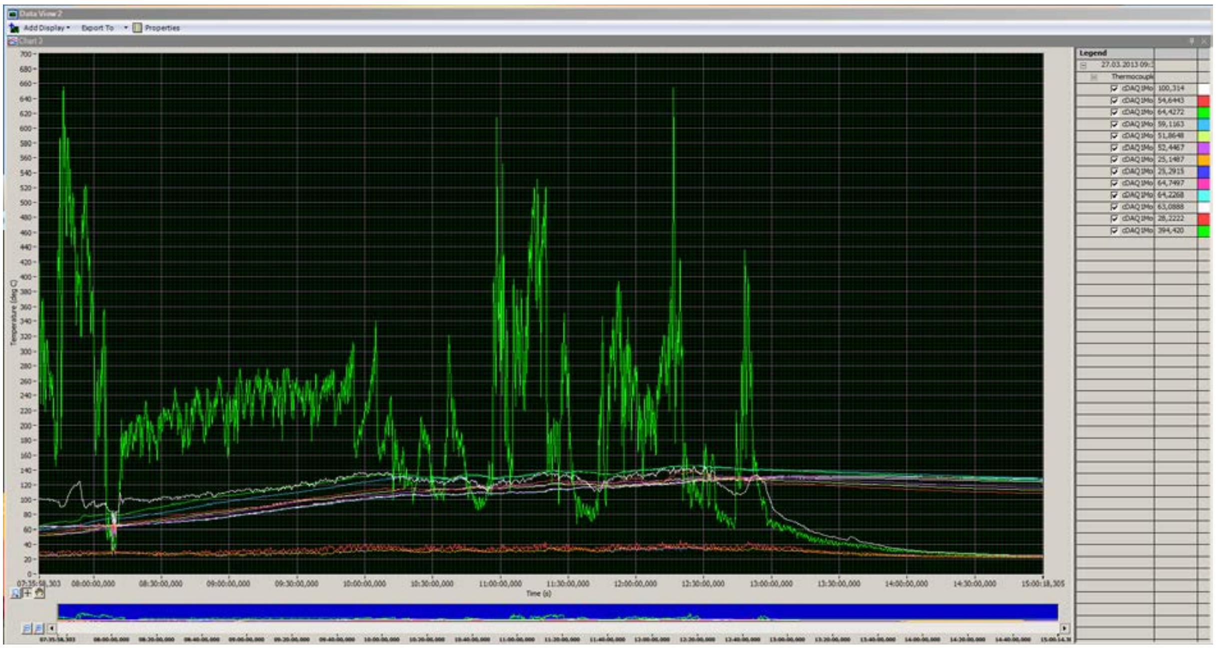
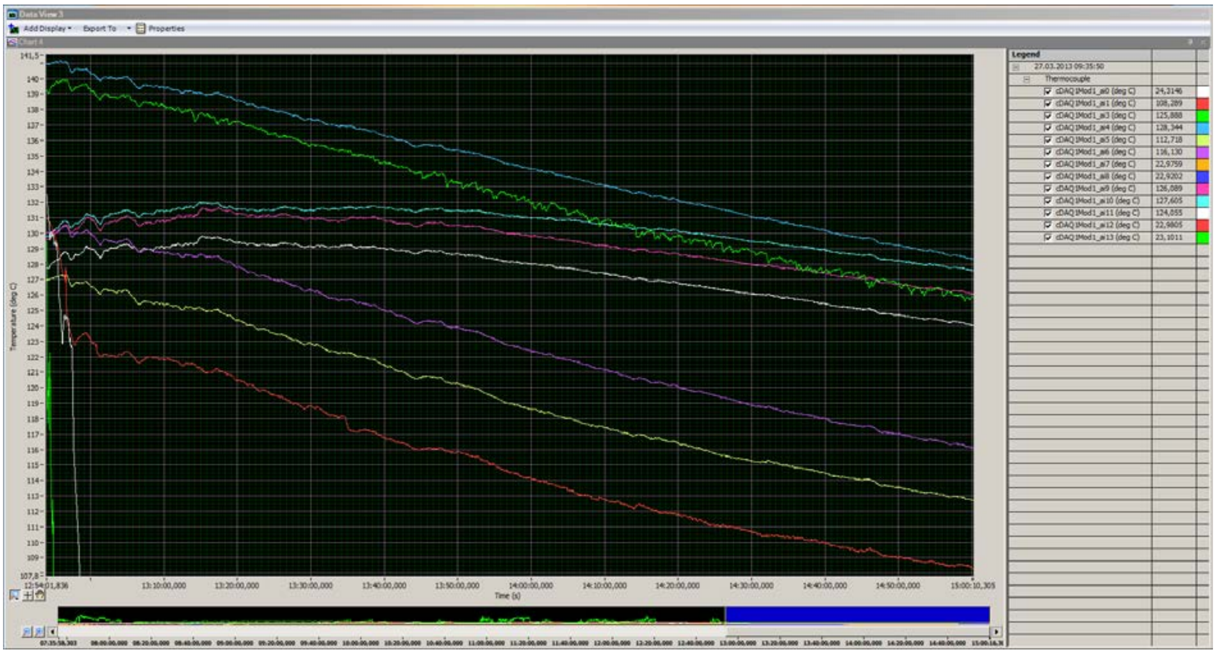


Figure 30 – Fluctating temperature due to clouds

As seen in Figure 30, the temperature at the focal point fluctuates (seen as the green line) significantly due to heavy clouds. The highest peaks are at almost 660°C, but these were caused by the wooden sticks used to manually control the focal point catching on fire directly underneath the thermocouple. The highest temperature from solar radiation measured by the thermocouple mounted in the focal point was about 500°C, but the intensity of the focal point was uneven, giving a representative average temperature of around 340°C. The bottom red line in the graph shows ambient temperature, at around 30°C. The right side of the graph shows how the temperature decreased after turning the reflector away from the sun and emptying the pipeline of steam. Due to constant clouds on the sky, tracking was aborted and the temperatures inside the storage were logged for two hours. The temperatures read in the storage are represented by the cluster of lines seen as fairly stable on the graph. When magnified, their development over two hours without steam supply can be studied.



Legend		
27.03.2013 09:35:50		
Thermocouple		
☑ cDAQ1Mod1_ai0 (deg C)	24,3146	⬜
☑ cDAQ1Mod1_ai1 (deg C)	108,289	🟥
☑ cDAQ1Mod1_ai3 (deg C)	125,888	🟩
☑ cDAQ1Mod1_ai4 (deg C)	128,344	🟦
☑ cDAQ1Mod1_ai5 (deg C)	112,718	🟨
☑ cDAQ1Mod1_ai6 (deg C)	116,130	🟪
☑ cDAQ1Mod1_ai7 (deg C)	22,9759	🟧
☑ cDAQ1Mod1_ai8 (deg C)	22,9202	🟦
☑ cDAQ1Mod1_ai9 (deg C)	126,089	🟪
☑ cDAQ1Mod1_ai10 (deg C)	127,605	🟦
☑ cDAQ1Mod1_ai11 (deg C)	124,055	⬜
☑ cDAQ1Mod1_ai12 (deg C)	22,9805	🟥
☑ cDAQ1Mod1_ai13 (deg C)	23,1011	🟩

Figure 31 – Temperature development in heat storage after aborting solar tracking

Three of the middle lines suggest a small increase in temperature before decreasing slowly. These lines are from thermocouples located at the bottom at the center pole, at the aluminum cast wall and at the cylinder wall. Due to indolence in the heat storage temperature distribution, these parts of the heat storage received heat from the center of the aluminum cast (the highest temperature in the heat storage was where the steam pipe was located) even after the steam was emptied from the system. After 45 minutes, the temperature started to decrease also in these places. After two hours, the average temperature decrease inside the storage was 9.4°C, from 132.3°C to 122.9°C. The red line (bottom) on the graph represents the temperature at the outlet, outside the heat storage and is left out from the calculation. The energy inside the storage is given by

$$E_{PCM} = \int_{23}^{109} mC_p dT + \int_{110}^{120} mC_p dT + \int_{121}^{T_{max}} mC_p dT$$

With heat capacity found through a differential scanning calorimeter (DSC) study[xl].

$$C_p(\mathrm{kJ/kg}) = \begin{cases} 0.75 & T < 110\,^{\circ}\mathrm{C} \\ 4.1 & 110\,^{\circ}\mathrm{C} \le T \le 120\,^{\circ}\mathrm{C} \\ 1.4 & 120\,^{\circ}\mathrm{C} < T < 210\,^{\circ}\mathrm{C} \\ 12 & 210\,^{\circ}\mathrm{C} \le T \le 220\,^{\circ}\mathrm{C} \\ 1.6 & T > 220\,^{\circ}\mathrm{C} \end{cases}$$

Figure 32 - PCM heat capacity

The reason for a higher heat capacity at 110-120°C is a solid-solid phase change where the PCM expands. At 210-220°C the PCM will undergo a phase change between solid and liquid. To achieve such phase changes (both ways), large amounts of heat transfer is needed. That is also why a PCM is preferable when cooking or baking – it will stay hot much longer than the equivalent mass at the same initial temperature in a conventional sensible heat storage system.

Consequently the energy loss from 132.3°C to 122.9°C with 16.7kg of solar salt was

$$\begin{aligned} E_{Loss} = {} & \left(\int_{23}^{109} 16.7kg * 0.75\, {}^{kJ}\!/_{kgK}\, dT + \int_{110}^{120} 16.7kg * 4.1\, {}^{kJ}\!/_{kgK}\, dT \right. \\ & \left. + \int_{121}^{132.3} 16.7kg * 1.4\, {}^{kJ}\!/_{kgK}\, dT \right) \\ & - \left(\int_{23}^{109} 16.7kg * 0.75\, {}^{kJ}\!/_{kgK}\, dT + \int_{110}^{120} 16.7kg * 4.1\, {}^{kJ}\!/_{kgK}\, dT \right. \\ & \left. + \int_{121}^{122.9} 16.7kg * 1.4\, {}^{kJ}\!/_{kgK}\, dT \right) = 219.8kJ \end{aligned}$$

At a rate of

$$\frac{219800J}{2h * 60min * 60sec} = 30.5W$$

The heat storage insulation could clearly be better, even though the scarce insulation acquired did quite a good job.

The energy stored at 150°C, which was a regular temperature to reach in the storage during testing, with 16.7kg of solar salt is

$$E_{PCM,150°C} = \int_{23}^{109} 16.7kg * 0.75 \, {}^{kJ}/_{kgK} \, dT + \int_{110}^{120} 16.7kg * 4.1 \, {}^{kJ}/_{kgK} \, dT + \int_{121}^{150} 16.7kg * 1.4 \, {}^{kJ}/_{kgK} \, dT = 9286.9kJ$$

Adding the energy stored in the aluminum cast given by

$$E_{Cast,150°C} = \int_{23}^{150} 27kg * 0.883 \, {}^{kJ}/_{kgK} \, dT = 3027.8kJ$$

gives a total stored energy of 12314.7kJ within the heat storage with a uniform temperature of 150°C. This heat, and consequently its temperature, will decrease rapidly compared to the heat stored at liquid state, due to the heat capacity as described above. When entering liquid state, say by being heated by water steam at 250°C (desired temperature in this system), the energy stored will be as follows:

$$E_{PCM,250°C} = \int_{23}^{109} 16.7kg * 0.75\, {}^{kJ}/_{kgK}\, dT + \int_{110}^{120} 16.7kg * 4.1\, {}^{kJ}/_{kgK}\, dT + \int_{121}^{209} 16.7kg * 1.4\, {}^{kJ}/_{kgK}\, dT + \int_{210}^{220} 16.7kg * 12\, {}^{kJ}/_{kgK}\, dT + \int_{221}^{250} 16.7kg * 1.6\, {}^{kJ}/_{kgK}\, dT = 33485.1kJ$$

In words, the total energy within the storage will be almost tripled when heated from 150°C to 250°C.

New findings done by Asfafaw Haileselassie (Ph.D, NTNU) proves that baking of injera is possible at temperatures above 120°C, and that the amount of energy required to bake one injera is 364.04-386.61kJ (The report on that study was not yet published when this report was written).

That means that the energy within the storage cannot be utilized for baking injera when the PCM temperature drops below 120°C. Accordingly, the energy available for injera baking is a lot less than the total energy of the storage at a uniform 150°C

$$E_{Available} = \int_{120}^{150} 16.7kg * 1.4\, {}^{kJ}/_{kgK}\, dT + \int_{120}^{150} 27kg * 0.883\, {}^{kJ}/_{kgK}\, dT = 1416.6kJ$$

$$\frac{1416.6kJ}{386.61kJ} = 3.66$$

$$\frac{1416.3kJ}{364.04kJ} = 3.89$$

Accordingly, the heat storage can theoretically bake about 3 injeras at 150°C, regarding losses.

The energy not applicable for injera baking is

$$12314.7\text{kJ} - 1416.6\text{kJ} = 10898.1kJ$$

However, this energy can be used for boiling and pasteurization of water and cooking other foods, so it is not useless.

If heated to 250°C, the heat storage is theoretically capable of baking

$$33485.1kJ + 3027.8kJ - 10898kJ = 25614.8kJ$$
$$\frac{25614.8kJ}{386.61kJ} = 66$$
$$\frac{25614.8kJ}{364.04kJ} = 70$$

between 66 and 70 injeras. Discussions with residents revealed that a regular Ethiopian family consumes around 30-40 injeras over a four day period, and bakes approximately every fourth day. Therefore this heat storage could provide approximately four days' worth of food for two families when fully charged.

Another advantage with reaching liquid state is that the temperature will stay more or less constant at melting temperature until the PCM is fully solidified, as described in chapter 2. Constant temperature of the cooking plate is desirable when making food.

The temperature at the bottom of the boiler was measured towards the end of the stay in Mekelle, when an extra thermocouple was located and mounted on the bottom surface of the boiler. It became evident that the focal point only reached around 340°C when the sun was shining (in between shifting clouds). With the steam temperature measured to be approximately 175°C, this gives an efficiency of about 51%. Boiler temperature readings were not consistent as the intensity of the focal point was not uniform and clouds were frequent at the end of the testing period, when the boiler thermocouple was introduced.

All thermocouple readings and their respective descriptions are presented in Appendix A.

5 Discussion

5.1 Introduction

The initial objective of the experiments carried out through this project was to demonstrate solar baking of injera on a PCM heat storage heated by a self-circulating steam system. This was not achieved, however. The main problem with the experiments carried out in Mekelle was reaching the desired temperature in the heat storage. As a result, the solar salt was never melted with solar energy, and the heat storage was not suitable for injera baking. The reasons for the insufficiently high temperature could originate from the tracking, the pipeline or the focal point, related to the reflector and the reflector setup. The automatic tracking was working well, and was continuously monitored manually so that the focal point could not be much better with the setup used. The pipeline was constructed with care – all connections were leakage free (evidential through pressure tests), the pipeline inside the heat storage was made from a continuous pipe bent with a uniform downward decline, and the decline continued all the way back to the boiler. There could still be air bubbles trapped in the pipeline somewhere, causing the flow to be held back. As circulation clearly was present, as described in Chapter 3, air in the system was evidently not a big problem, even though there could have been some air present. As the pipeline theoretically and experimentally was working the way it should, and tracking was working well, the remaining sinner was the temperature in the boiler, provided by the focal point from the reflector which was supported by its framework or suspension bracket. As illustrated in

Figure 18, the framework suspending the reflector was flexing when the reflector was not hanging straight down. At midday the sun is at its strongest, the framework is not flexing, and the focal point was significantly better than in the early morning and afternoon. Due to some indolence of the system however, temperature rise is not instant, and maximum temperatures were usually not achieved until around 14:00. Although the framework was not sufficiently rigid, the reflector itself was also a source of an imperfect focal point. Due to transport, damages from construction and assembly/disassembly and lack of rigidity, the reflector shape was imperfect. Even though the focal point was as good as it could be with the setup used, the concentration ratio could have been better. It was clear that not all sunbeams were reflected onto the boiler.

Figure 33 – Scattering of reflected sunbeams

As seen in Figure 33, sunlight was being reflected not only onto the boiler, but also on the grey framework around the boiler and even the blue support in the upper left corner of the picture. The smoke seen in this photo is coming from the wooden stick used to evaluate the intensity of the focal point. By holding a larger wooden plate under the boiler, one could also see the dispersion of the sunbeams well. There was an area clearly more intense than the rest, but the total area illuminated by reflected sunbeams was an irregular shape of approximately 30cm by 20cm.

5.2 Concentration ratio

If it is assumed that the focal point obtained during these tests was the best achievable for the slightly damaged and flexing reflector dish, the optimal concentration ratio for this setup can be calculated. If the focal shape reflected onto the wooden plate is simplified to an ellipse, its area is given by A=πab, where a and b are one-half of the ellipse's major and minor axes respectively. The diameter of the circular reflector was 1.8m.

$$A_f = \pi ab = \pi * 15cm * 10cm = 471.2cm^2$$

$$A_r = \pi r^2 = \pi 90\mathrm{cm}^2 = 25446.9\mathrm{cm}^2$$

$$C = \frac{A_r}{A_f} = 54.0$$

As expected, the concentration ratio was low. If an assumed perfect focal point of circular shape with a diameter of 6cm is taken into consideration, the concentration ratio is significantly improved:

$$C = \frac{A_r}{A_f} = \frac{25446.9cm^2}{28.3cm^2} = 899.2$$

The direct radiation was measured to vary between 900W/m^2 to 1260W/m^2. The software for logging the radiation on the computer was unfortunately not working, but the increase in the morning and decrease in the afternoon was very consistent, so one can assume that the average radiation factor is equal to the mean of the maximum and minimum value. That implies that the average power submitted by the focal point is equal to:

$$P_f = radiation\ intensity * aperture = 1080\,{}^{W}\!/_{m^2} * 2.69m^2 = 2743.2W$$

Which gives the intensity at the focal point:

$$I_f = \frac{2743.2W}{0.047m^2} = 58366.0\,{}^{W}\!/_{m^2} = 5.8\,{}^{W}\!/_{cm^2}$$

As previously described, the intensity at the focal point was not uniform. If it is assumed that 70% of the power was concentrated on 40% of the focal point area, the intensity increases to

$$I_{f,max} = \frac{2743.2W * 0.7}{0.047m^2 * 0.4} = 102140.4\,{}^{W}\!/_{m^2} = 10.2\,{}^{W}\!/_{cm^2}$$

which is an increase by a factor of 1.8. By assuming a theoretical perfect focal point of 6cm in diameter, the theoretical optimal intensity would be

$$I_{f,theoretical} = \frac{2743.2W}{0.003m^2} = 914400\,{}^{W}\!/_{m^2} = 91.4\,{}^{W}\!/_{cm^2}$$

This is an increase by a factor 15.8 from I_f.

5.3 Tracking

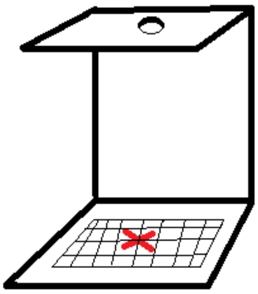


Figure 34–Tracking calibration device

The tracking could be monitored by making a simple calibrating unit mounted to the reflector. With two plates mounted parallel to each other and to the reflector plane, the top plate with a small hole, the lower one with a grid or similar to measure the offset of the sunlight emitted through the top hole relative to a center mark. Making and implementing such a device was considered, but the existing method of monitoring tracking was evaluated to be adequate. The fact that the reflector and its framework was flexing would make this kind of tracking device somewhat imprecise, as the optimal focal point in practice was not obtained when the reflector was 100% aligned to the sun in the morning and afternoon.

5.4 Sources of errors

As sufficiently high temperatures were reached with the previous setup, the reason for not achieving the same results with the heat storage pipeline was believed to be related to the pipeline and air trapped in it, as this was the only part that had been changed. The rig operators were the same and their methods likewise. Improvements were made to the pipeline with regards to flushing, bleeding, alignment and positioning of the boiler. The ends of the cut pipes were inspected and assured not to choke and obstruct circulation. It finally became more likely that the error lied with the reflector and the focal point, as the bleeding procedure was optimized and that circulation was evidently present.

Had it been discovered at an earlier stage, or would there have been more time for experiments, improvements to this area of the setup would have been made. The reflector was examined and found to be damaged. Its shape may have gotten bent and damaged during disassembly and assembly when modifying the construction. Also, the transportation associated with the exhibition was likely to inflict damage to the setup as it was fully assembled on the back of the truck and the trailer had no suspension. Another reason could be that when manual tracking was practiced (before the counter weight system was manufactured and automatic tracking implemented), the reflector was suspended not only by its framework, but also by external supporting rods and chains moved around as the tracking was carried out. This would cause the framework to flex less than when carrying the reflector's entire weight itself.

The temperature at the bottom of the boiler was measured towards the end of the stay in Mekelle. It became evident that the focal point only reached an effective temperature of around 340°C when the sun was shining (i.e. in between shifting clouds). With a steam temperature measured to be approximately 175°C that gives an efficiency of about 51%. With a better focal point the temperature should reach 500°C easily, and the steam temperature would accordingly be expected to reach around 250°C (as it did with the previous setup), enough to melt the solar salt. The use of a self-circulating boiling-condensing system to melt solar salt in a latent heat storage is evidently feasible. By obtaining an optimal focal point on the boiler, the intensity could theoretically be approximately 16 times higher and the temperature in the boiler would increase significantly. By changing the reflector to one without damages and possibly larger in size, melting temperature in the storage is certainly be possible to achieve (as was done with the previous setup).

6 Further work

To melt the PCM already present in the heat storage and to actually verify that the pipeline and heat storage design is working properly, a gas burner, wooden fire or similar can be used to heat the boiler instead of a solar reflector. If desired temperature and pressure is achieved by using this method together with the procedure of flushing and bleeding described in Chapter 3, it is obvious that the problem lies at the heat generated at the boiler, and the reflector must be optimized, either in rigidity, size or both. With a new, undamaged and possibly larger reflector, suspended by a rigid framework, the system should be flushed and bled in the same manner as before, and tracking should also be done in the same way. If the reflector is changed to one of different design and weight, the counterweight needs to be alternated in order to obtain balance of torque about the pivoting point. Steel rods can be removed easily from the existing counterweight with the use of an angle grinder, as they are spot welded to each other. To add more weight, additional steel rods can be spot welded to the existing ones. The framework's rigidity can be improved by adding supporting beams in the east-west direction, as the existing ones are only located north-south. A lattice design could be implemented to the original design, but this would cause more shade to be cast onto the reflector. A support ring could be manufactured to enclose the reflector's outer edge, retaining the reflector itself from flexing.

If using an alternative source of heat to generate steam and changing the reflector does not increase the temperature sufficiently, the steam loop needs to be considered. Perhaps there has been a production error when making the pipeline or bending the pipe for the heat storage. Even though the design was well thought of and a Swagelok® pipe bender was used to make the bends, there could possibly be an air trap in the pipeline somewhere. In that case, the solar salt within the storage could be melted by an alternative heat source, poured into one or two containers (small enough to fit in the furnace for later melting) for storage, and the pipeline and aluminum cast for the heat storage could be remade. Alternatively, a smaller heat storage could be made, as the solar salt is only filling one-half of the current storage, and the melted PCM can be poured directly over into the smaller storage. As mentioned in chapter 4, new findings suggest that temperatures as low as 120°C is sufficient to bake injera. By using a PCM with a lower melting point than the solar salt used in this project, the system would not be as delicate to a high concentration ratio and a good focal point. With a melting point at 150°C, PCM could be melted with the existing setup – damaged reflector and flexing framework aside.

To improve tracking, it is utterly necessary to improve the rigidity of the framework suspending the reflector. With a flexing framework, the reflector will hang down to the side in the morning and afternoon, as illustrated in Figure 27. Consider that the deflection of a beam is related to the height of the beams cross-section by a power of three[xli]. With a sufficiently rigid reflector and framework, a tracking monitoring device as illustrated in Figure 34 can be utilized. When the system is able to melt the PCM, cooking experiments on the heat storage can be conducted.

Future applications for the steam generating solar collector are many. With an automatic tracking system, the reflector and boiler can be placed outside a bakery, hospital or the like to provide steam for baking, sterilization etc. To take care of safety in these applications as the system is pressurized and at high temperature, one or several technicians should be educated for operation of the system. A fence could be built around the reflector and boiler outside the building to prevent unwanted persons, such as children, to come near the setup. Technicians should be responsible for supervision during tracking, as well as operation and maintenance.

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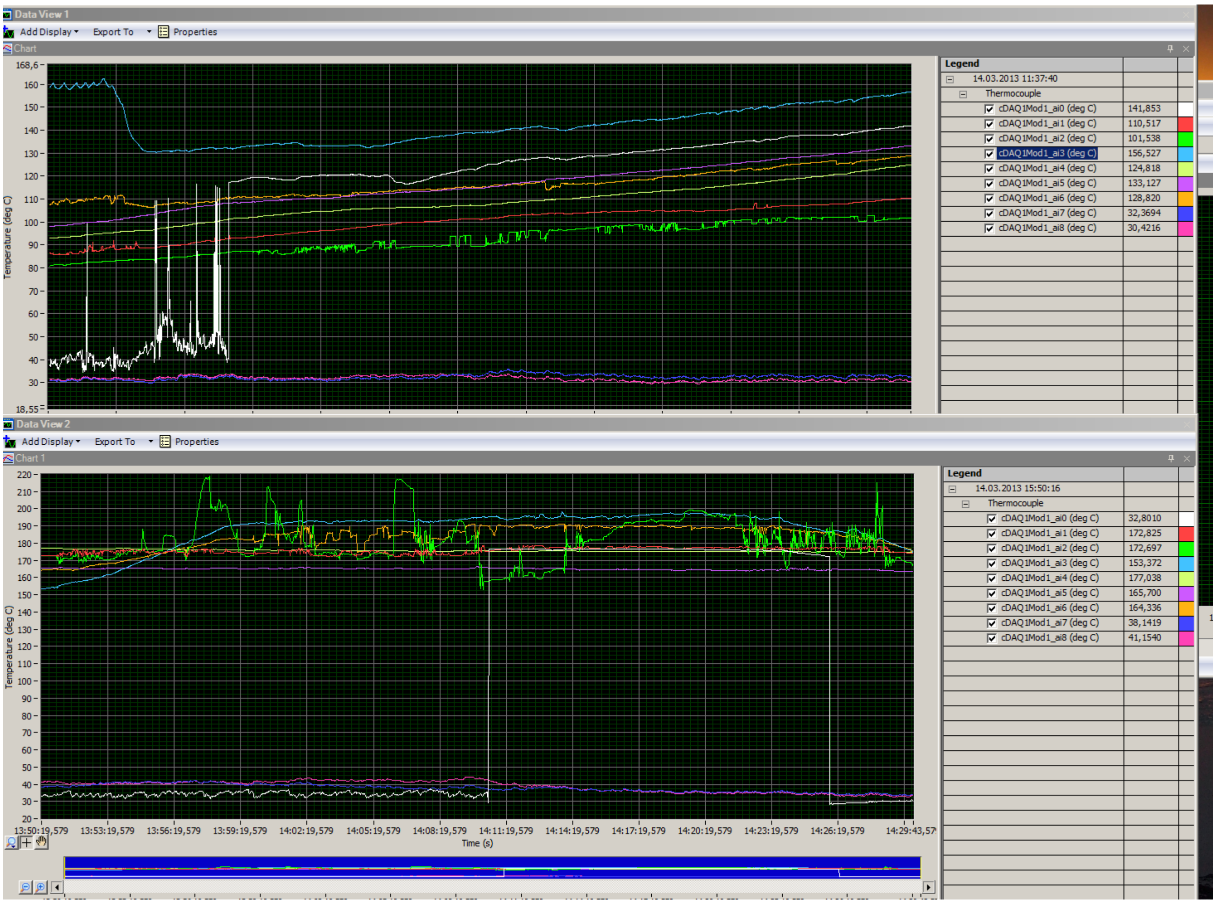
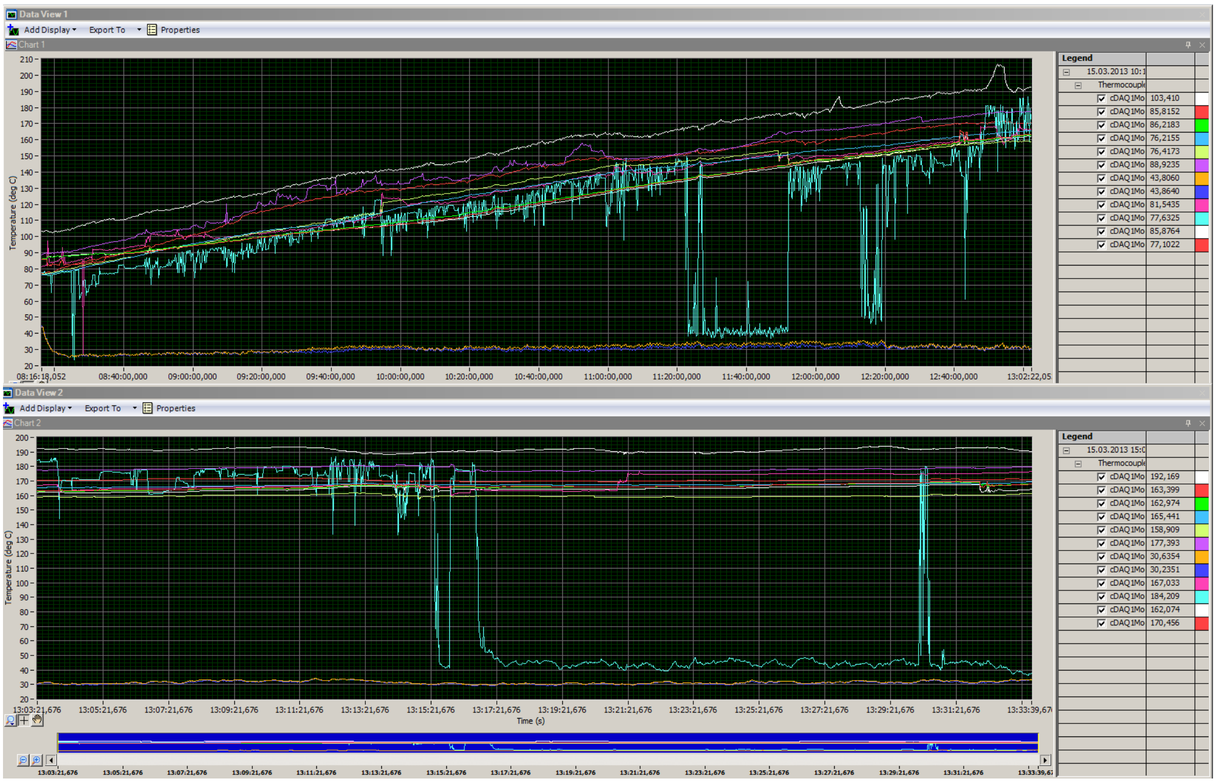
Appendix A – Thermocouple readings



Legend		
⊟ 14.03.2013 11:37:40		
⊟ Thermocouple		
☑ cDAQ1Mod1_ai0 (deg C)	141,853	⬜
☑ cDAQ1Mod1_ai1 (deg C)	110,517	🟥
☑ cDAQ1Mod1_ai2 (deg C)	101,538	🟩
☑ cDAQ1Mod1_ai3 (deg C)	156,527	🟦
☑ cDAQ1Mod1_ai4 (deg C)	124,818	🟨
☑ cDAQ1Mod1_ai5 (deg C)	133,127	🟪
☑ cDAQ1Mod1_ai6 (deg C)	128,820	🟧
☑ cDAQ1Mod1_ai7 (deg C)	32,3694	🟦
☑ cDAQ1Mod1_ai8 (deg C)	30,4216	🟪

Legend		
⊟ 14.03.2013 15:50:16		
⊟ Thermocouple		
☑ cDAQ1Mod1_ai0 (deg C)	32,8010	⬜
☑ cDAQ1Mod1_ai1 (deg C)	172,825	🟥
☑ cDAQ1Mod1_ai2 (deg C)	172,697	🟩
☑ cDAQ1Mod1_ai3 (deg C)	153,372	🟦
☑ cDAQ1Mod1_ai4 (deg C)	177,038	🟨
☑ cDAQ1Mod1_ai5 (deg C)	165,700	🟪
☑ cDAQ1Mod1_ai6 (deg C)	164,336	🟧
☑ cDAQ1Mod1_ai7 (deg C)	38,1419	🟦
☑ cDAQ1Mod1_ai8 (deg C)	41,1540	🟪

14.03.2013: Quite high temperature achieved, almost 220°C for one minute on the steampipe at 12:06. The reflector was probably not that damaged at this time. The storage reached a steady temperature at around 180°C. Two readings due to a power cut.

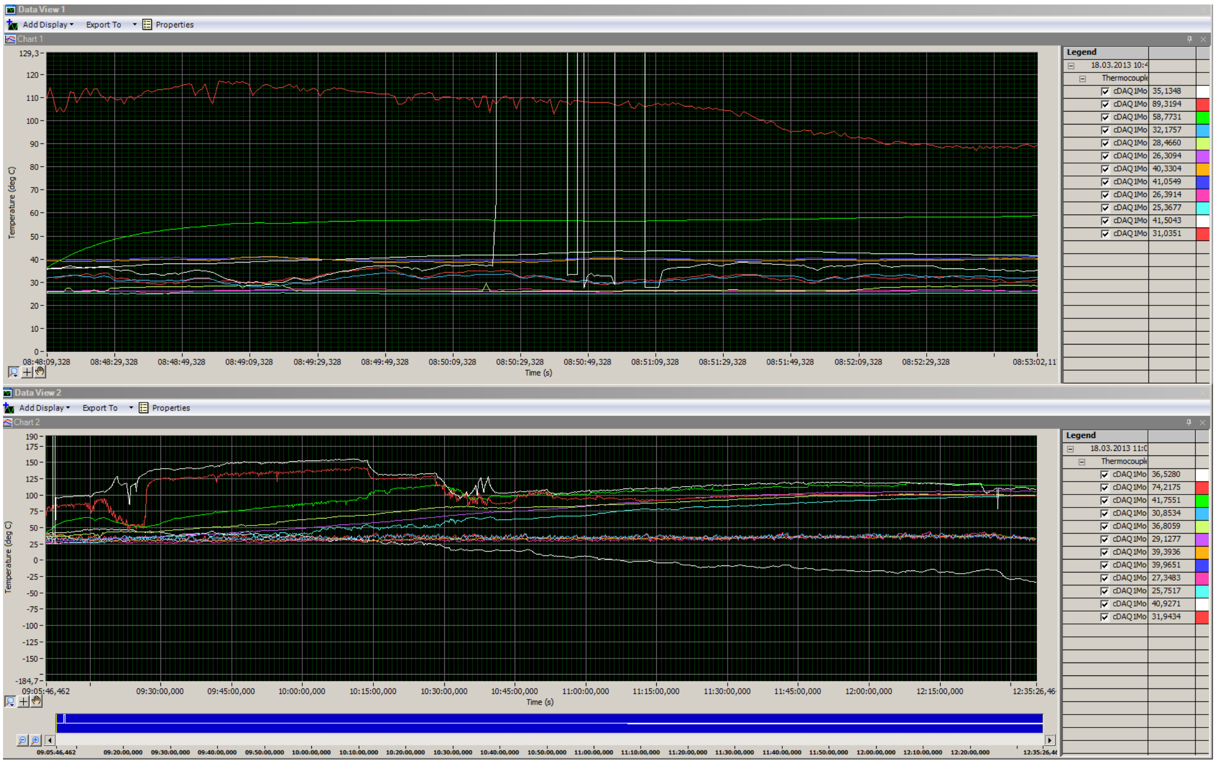


Legend		
⊟ 15.03.2013 10:1		
⊟ Thermocouple		
☑ cDAQ1Mo	103,410	⬜
☑ cDAQ1Mo	85,8152	🟥
☑ cDAQ1Mo	86,2183	🟩
☑ cDAQ1Mo	76,2155	🟦
☑ cDAQ1Mo	76,4173	🟨
☑ cDAQ1Mo	88,9235	🟪
☑ cDAQ1Mo	43,8060	🟧
☑ cDAQ1Mo	43,8640	🟦
☑ cDAQ1Mo	81,5435	🟪
☑ cDAQ1Mo	77,6325	🟦
☑ cDAQ1Mo	85,8764	⬜
☑ cDAQ1Mo	77,1022	🟥

Legend		
⊟ 15.03.2013 15:0		
⊟ Thermocouple		
☑ cDAQ1Mo	192,169	⬜
☑ cDAQ1Mo	163,399	🟥
☑ cDAQ1Mo	162,974	🟩
☑ cDAQ1Mo	165,441	🟦
☑ cDAQ1Mo	158,909	🟨
☑ cDAQ1Mo	177,393	🟪
☑ cDAQ1Mo	30,6354	🟧
☑ cDAQ1Mo	30,2351	🟦
☑ cDAQ1Mo	167,033	🟪
☑ cDAQ1Mo	184,209	🟦
☑ cDAQ1Mo	162,074	⬜
☑ cDAQ1Mo	170,456	🟥

15.03.2013: Steady temperature increase throughout the storage. A steady temperature of around 170°C in the storage was achieved. Some small clouds were present this day. The drops in the blue line is due to a bad connection on the thermocouple, causing it to read ambient temperature as a connection point between the two conductors in the thermocouple was established at the connection to the extension cable. Experiments were aborted at 15:33 due to clouds. Two readings due to a power cut.

The 16th and 17th of march there was an exhibition involving the solar test rig. No experiments were carried out.



Legend		
⊟ 18.03.2013 10:4		
⊟ Thermocouple		
☑ cDAQ1Mo	35,1348	⬜
☑ cDAQ1Mo	89,3194	🟥
☑ cDAQ1Mo	58,7731	🟩
☑ cDAQ1Mo	32,1757	🟦
☑ cDAQ1Mo	28,4660	🟨
☑ cDAQ1Mo	26,3094	🟪
☑ cDAQ1Mo	40,3304	🟧
☑ cDAQ1Mo	41,0549	🟦
☑ cDAQ1Mo	26,3914	🟪
☑ cDAQ1Mo	25,3677	🟦
☑ cDAQ1Mo	41,5043	⬜
☑ cDAQ1Mo	31,0351	🟥

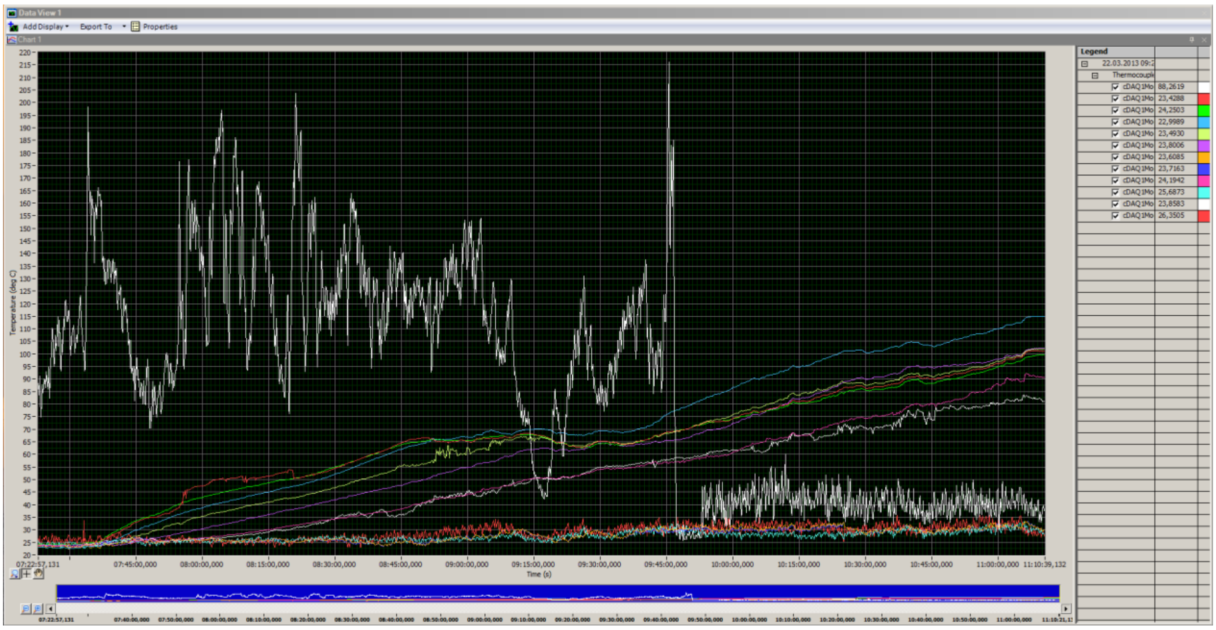
Legend		
⊟ 18.03.2013 11:0		
⊟ Thermocouple		
☑ cDAQ1Mo	36,5280	⬜
☑ cDAQ1Mo	74,2175	🟥
☑ cDAQ1Mo	41,7551	🟩
☑ cDAQ1Mo	30,8534	🟦
☑ cDAQ1Mo	36,8059	🟨
☑ cDAQ1Mo	29,1277	🟪
☑ cDAQ1Mo	39,3936	🟧
☑ cDAQ1Mo	39,9651	🟦
☑ cDAQ1Mo	27,3483	🟪
☑ cDAQ1Mo	25,7517	🟦
☑ cDAQ1Mo	40,9271	⬜
☑ cDAQ1Mo	31,9434	🟥

18:03:2013: The maximum temperature achieved this day was 152°C on the steam pipe. The vertical white lines seen on the upper graph is caused by a bad connection in one of the thermocouples, having it reading a temperature of 2200°C. Two readings due to a power cut.

Legend		
⊟ 19.03.2013 09:2		
⊟ Thermocouple		
☑ cDAQ1Mo	40,5095	⬜
☑ cDAQ1Mo	108,552	🟥
☑ cDAQ1Mo	122,788	🟩
☑ cDAQ1Mo	126,815	🟦
☑ cDAQ1Mo	106,880	🟨
☑ cDAQ1Mo	114,826	🟪
☑ cDAQ1Mo	23,6263	🟧
☑ cDAQ1Mo	23,9170	🟦
☑ cDAQ1Mo	126,344	🟪
☑ cDAQ1Mo	126,319	🟦
☑ cDAQ1Mo	124,876	⬜
☑ cDAQ1Mo	82,7621	🟥

19.03.2013: Somewhat steady increase in temperature. There were some shifting clouds this day. The steady increase up to the maximum temperature was a result of a slight adjustment in the focal point, suggesting the importance of a good focal point. The maximum temperature established was 140°C in the steam pipe and 139°C at one point in the storage, while the rest of the storage was ranging from 115°C to 130°C.

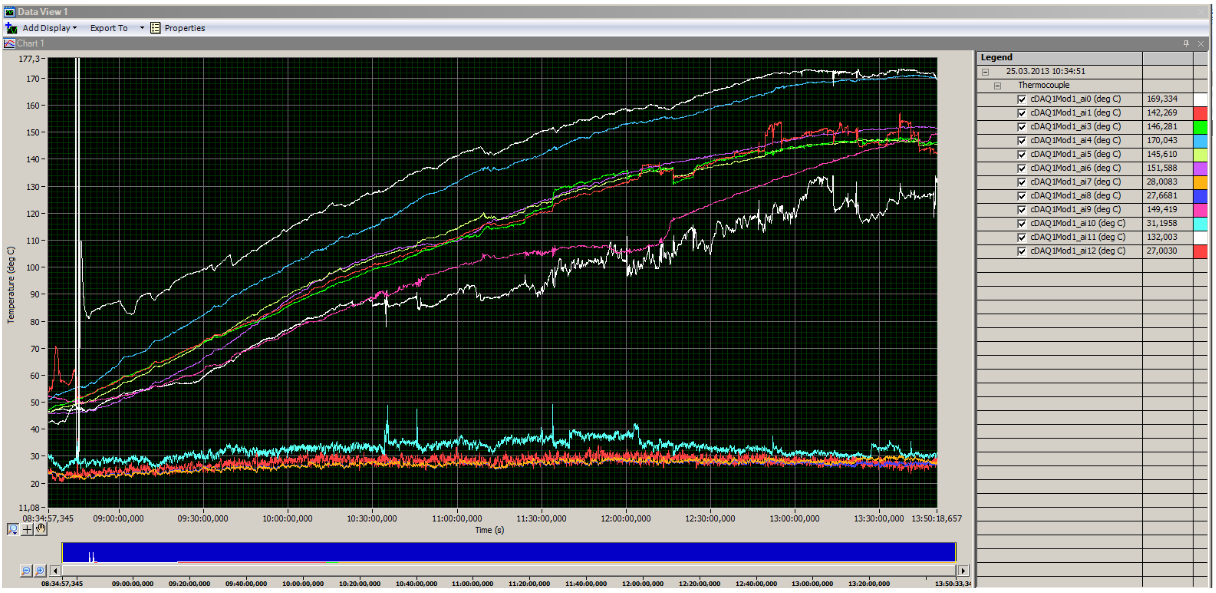
20th and 21st of March were cloudy and rainy. No experiments were carried out.



Legend		
⊟ 22.03.2013 09:2		
⊟ Thermocoupl		
☑ cDAQ1Mo	88,2619	⬜
☑ cDAQ1Mo	23,4288	🟥
☑ cDAQ1Mo	24,2503	🟩
☑ cDAQ1Mo	22,9989	🟦
☑ cDAQ1Mo	23,4930	🟨
☑ cDAQ1Mo	23,8006	🟪
☑ cDAQ1Mo	23,6085	🟧
☑ cDAQ1Mo	23,7163	🟦
☑ cDAQ1Mo	24,1942	🟪
☑ cDAQ1Mo	25,6873	🟦
☑ cDAQ1Mo	23,8583	⬜
☑ cDAQ1Mo	26,3505	🟥

22.03.2013: Some clouds this day. Temperature is fluctuating accordingly. The steam pipe reached a temperature of 216°C at one instant, but dropped to around 40°C immediately as thick clouds became consistent. Heat storage reached temperatures between 80°C-115°C.

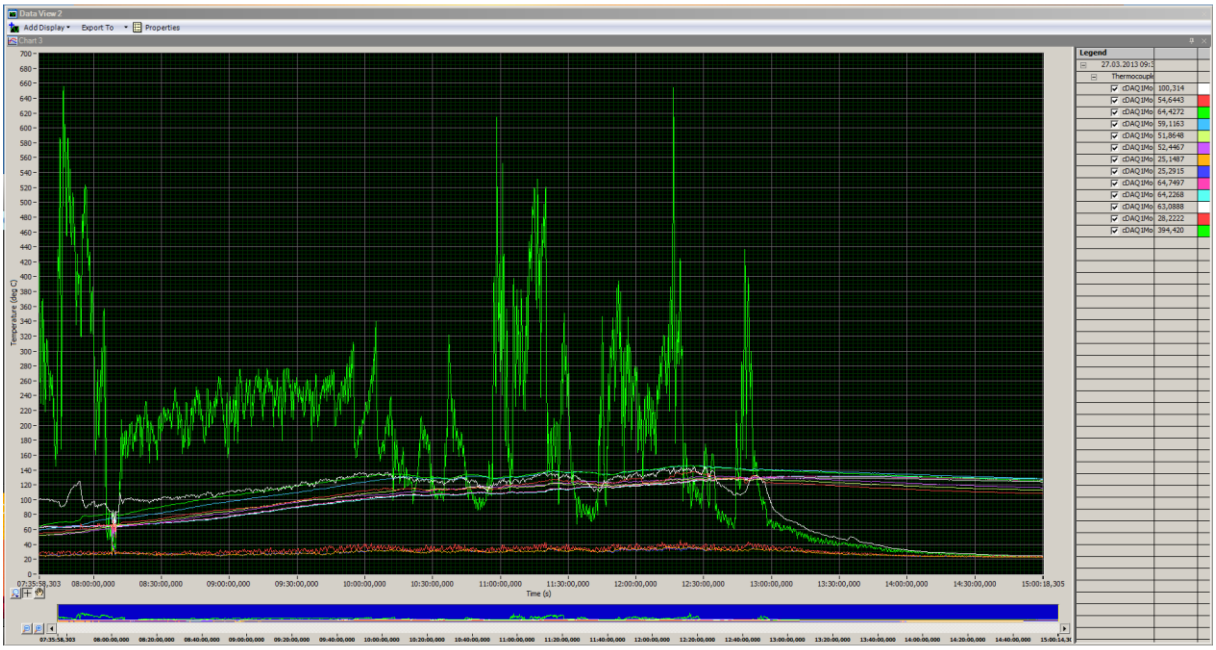
The 23rd of March was cloudy – no testing. The 24th was a Sunday, and the person carrying the key to the material lab with the logging equipment was not available.



Legend		
⊟ 25.03.2013 10:34:51		
⊟ Thermocouple		
☑ cDAQ1Mod1_ai0 (deg C)	169,334	⬜
☑ cDAQ1Mod1_ai1 (deg C)	142,269	🟥
☑ cDAQ1Mod1_ai3 (deg C)	146,281	🟩
☑ cDAQ1Mod1_ai4 (deg C)	170,043	🟦
☑ cDAQ1Mod1_ai5 (deg C)	145,610	🟨
☑ cDAQ1Mod1_ai6 (deg C)	151,588	🟪
☑ cDAQ1Mod1_ai7 (deg C)	28,0083	🟧
☑ cDAQ1Mod1_ai8 (deg C)	27,6681	🟦
☑ cDAQ1Mod1_ai9 (deg C)	149,419	🟪
☑ cDAQ1Mod1_ai10 (deg C)	31,1958	🟦
☑ cDAQ1Mod1_ai11 (deg C)	132,003	⬜
☑ cDAQ1Mod1_ai12 (deg C)	27,0030	🟥

25.03.2013: The first day of flushing with the 7m water tower. The steam pipe reached a temperature of 173°C at 15:45. The pressure reached 12bar. The storage held a temperature between 130°C and 170°C. The vertical white line was caused by adjusting thermocouple 0, having it read the imaginary 2200°C temperature at one point.

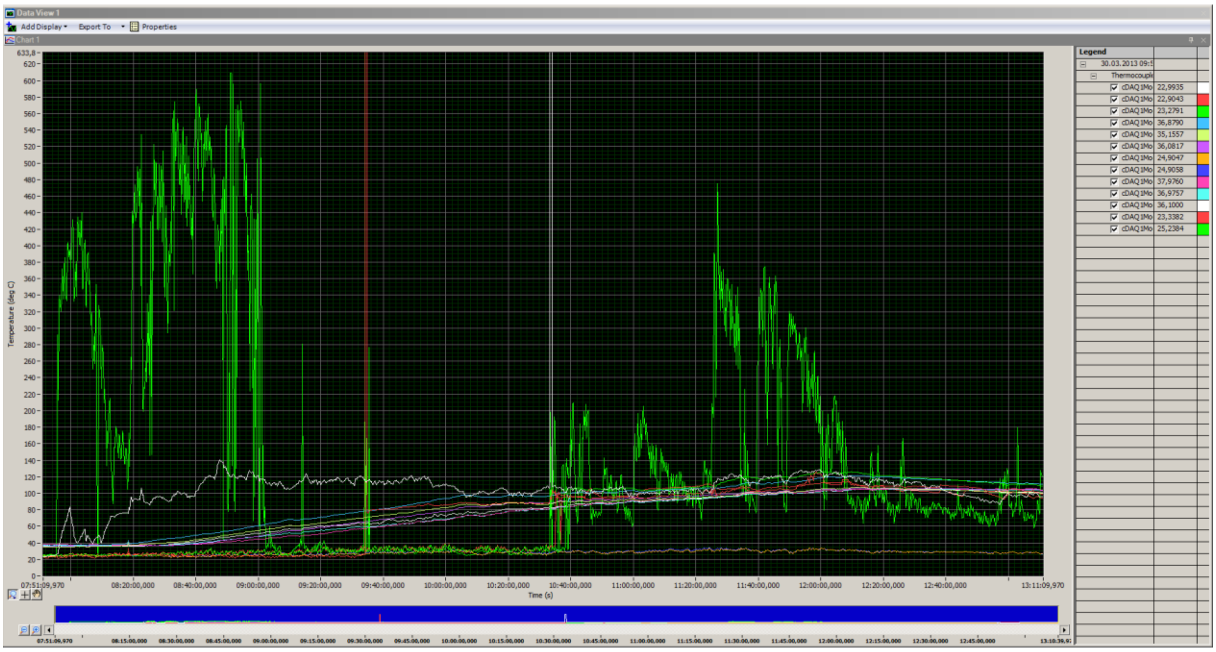
26.03.2013: The rig was adjusted slightly towards north by utilizing the analogue compass provided by the Swedes. The maximum temperature reached in the steampipe was 140°C.The storage reached between 115°C and 135°C. The vertical red lines were caused by adjusting thermocouple 13, having it read the imaginary 2200°C temperature at one point.



Legend		
⊟ 27.03.2013 09:3		
⊟ Thermocouple		
☑ cDAQ1Mo	100,314	⬜
☑ cDAQ1Mo	54,6443	🟥
☑ cDAQ1Mo	64,4272	🟩
☑ cDAQ1Mo	59,1163	🟦
☑ cDAQ1Mo	51,8648	🟨
☑ cDAQ1Mo	52,4467	🟪
☑ cDAQ1Mo	25,1487	🟧
☑ cDAQ1Mo	25,2915	🟦
☑ cDAQ1Mo	64,7497	🟪
☑ cDAQ1Mo	64,2268	🟦
☑ cDAQ1Mo	63,0888	⬜
☑ cDAQ1Mo	28,2222	🟥
☑ cDAQ1Mo	394,420	🟩

27.03.2013: Frequent clouds made the temperature fluctuate this day. A spear thermocouple was located and placed on the boiler in order to monitor the actual temperature at the focal point. The storage reached temperatures between 125°C and 145°C. The highest peaks on the graph (580°C-660°C) was caused by the wooden sticks used to monitor the location of the focal point catching on fire directly underneath the thermocouple placed on the boiler.

No experiments were carried out the 28th and 29th due to good old sightseeing.



Legend		
⊟ 30.03.2013 09:5		
⊟ Thermocoupl		
☑ cDAQ1Mo	22,9935	⬜
☑ cDAQ1Mo	22,9043	🟥
☑ cDAQ1Mo	23,2791	🟩
☑ cDAQ1Mo	36,8790	🟦
☑ cDAQ1Mo	35,1557	🟨
☑ cDAQ1Mo	36,0817	🟪
☑ cDAQ1Mo	24,9047	🟧
☑ cDAQ1Mo	24,9058	🟦
☑ cDAQ1Mo	37,9760	🟪
☑ cDAQ1Mo	36,9757	🟦
☑ cDAQ1Mo	36,1000	⬜
☑ cDAQ1Mo	23,3382	🟥
☑ cDAQ1Mo	25,2384	🟩

30.03.2013: The last day of testing there were also some clouds. The maximum temperature reached on the boiler was around 420°C. The significant decrease in temperature at the boiler (seen as the green line) was due to a consistent cloud cover. The storage reached temperatures between 120°C-140°C.