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Evaluation of Thermal Energy Storage Materials for Solar Cooker

Helsinki Metropolia University of Applied Sciences

Degree Bachelor of Engineering

Degree Programme Environmental Engineering

Thesis

Date 05.12.2014

Author(s) Title Number of Pages Date	Solomon Abate Evaluation of Thermal Energy Storage Materials for Solar Cooker 26 pages + 7 appendices 05 December 2014
Degree	Bachelor of Engineering
Degree Programme	Environmental Engineering
Specialisation option	Renewable and Energy
Instructor(s)	Antti Tohka, Senior lecture.

The performance of a solar thermal energy storage system using Lapland granite rock fragments 2-4 cm in diameter were assessed using a scaled-down model. The thesis deals with a selected medium that absorbs and stores solar heat during the day time and releases it when the sun was not shining. A storage rock bed of 5.89 kg with 30 cm x 30 cm base area and 6 cm thickness was placed at the bottom of a solar cooker and painted with black color to increase thermal absorption. The overall performance of a solar cooker i.e. the temperature with and without thermal energy storage (TES) materials was monitored for 20 hours. Solar energy is collected for 4 hours and the solar cooker temperature change was studied while solar radiation was zero. When TES materials were used the temperature was above 40°C for 3 hours and 30 minutes; however, without TES materials the solar cooker retain the heat for only 45 minutes. The average of solar radiation received over a specified period of time during 13:00 to 17:00 was estimated 798KJ. The average heat gained by TES material was 7.67W.The efficiency of the solar cooker with a storage system made of is about 14%.

Keywords	solar cooker ,solar radiation and TES, Thermal storage material, packed-bed rocks

Acknowledgements

I would like to offer my deepest gratitude to my thesis supervisor Lic. Sc. (Tech) Antti Tohka for his support and devoted valuable time to my thesis project. And I would also like to thank to my language supervisor Minna Paananen-Porkka for her cooperation.

Nomenclature

A	cross-sectional area, m^2; surface area, m^2
C	specific heat at constant, kJ/kg K
d	diameter, m
D	diameter, m
E	energy, J or kJ
EX	exergy, J
P	energy rate, W or kW
g	acceleration due to gravity, 9.81 m/s)
h	specific enthalpy, kJ/kg
h_r	overall heat transfer coefficient, W/m^2°C
k	thermal conductivity, W/m °C
Kr	thermal diffusivity, m^2/s
L	thickness, m
m	mass, kg
Nu	Nusselt number
P *	constant-pressure gradient, Pa or kPa
Pe	Peclet number
Pr	Prandtl number
q	heat rate per unit area, W/m^2
Q	heat transfer, J or kJ
Qr	heat transfer rate, W or kW
Ra	Rayleigh number
s	specific entropy, kJ/kg
S	entropy, kJ/K
t	time, s
T	temperature, °C or K
Ts	absolute temperature of object surface, K
T_{am}	ambient Temperature, K
u	specific internal energy, kJ/kg; U internal energy, kJ
X	length for plate, m
U_T	over all heat transfer coefficient W/Km^2

Greek Letters

Φ	*temperature difference, °C or K*
Θ	*angle*
β	*volumetric coefficient of thermal expansion, 1/K*
μ	*dynamic viscosity, kg/m s*
ρ	*density, kg/m^3*
υ	*kinematic viscosity, m^2/s*
Δ	*thickness of the stagnant film of fluid on the surface, m*
ΔT	*temperature difference, K; overall temperature difference, °C or K*
ε	*surface emissivity*
Σ	*summation*
π	*number (= 3.14159)*
δ	*characteristic length ,m*
α	*absorptivity coefficient*

Subscript and superscript

av	*average*
D	*diameter*
h	*heat generation*
H	*high temperature*
hs	*heat storage*
i	*component; input*
ie	*internal energy*
liq	*liquid*
l	*liquid*
L	*low temperature*
mix	*mixture*
n	*nth value*
r	*radiation*
t	*total; thermal*
tot	*total*
0	*surroundings; ambient; environment; reference*
1	*first value; 1st state; initial*

Contents

1 Introduction

The future when energy consumption depends on renewable energy may not seem a long way away from our world. We are burning fossil fuel which threatens the very existence upon creatures on earth. From this point of view, utilizing solar energy is no longer a fragment of imagination. The amount of light that hits the surface of the earth from the sun during two hours is equal to the energy we use to power the entire world for a year. However, now a days finding a way how to harness, store and utilizes solar energy is a challenge for scientists and engineers.

The most common and popular type of a solar cooker is probably a box type of solar cooker, which is simple, easy, cheap to design and uses direct solar rays to heat, cook or pasteurize food or drink. Its design is based on the concept of a traditional modern oven where the food is placed inside of an insulated box for purposes of retaining or trapping the solar rays that have been converted to heat energy. [1]

Recently quite a number of researches and projects have been carried out to optimize the cooking efficiency and to study how to harness the enormous amount of solar energy, how to convert it to heat form and store it for a later usage when the sun is not shining is highly gaining a concern. One application of solar energy can be using it in solar cookers which are seen to have a high potential in many rural parts of the developing nations where a huge amount of the total available energy resource is spent on the energy for cooking which is primarily supplied by burning wood. These places receive a high amount of solar radiation throughout the year. According to literature source solar radiation in these places has a mean daily illumination intensity of 5-7 kWh/m^2 for over 275 days of a year. The wood for cooking in the rural of the developing world is collected by women and children who have to walk long distances every day. The literature source has also pointed out women and children of especially sparse developing regions spend more than 90 hours of wood gathering per month. Besides collecting firewood being a tedious job, indoor cooking over wood fire has shown to kill an estimated of 5 million children every year causing respiratory disorders. The source seems like solar cookers can have an invaluable contribution in changing the lives of the needy people of the developing world as they can be built with a very small amount of money and knowledge and use the free and abundant energy from the sun as their cooking fuel. It is estimated in the literature that the use of solar cookers has a potential of decreasing firewood use by 36% which is roughly equivalent to 246 million metric tons of wood each year with an average of 6.28 MJ of energy per a kilogram of wood burnt and a CO_2 equivalent emission of 90 grams per a MJ of energy, burning wood corresponds to 565 grams of CO_2 equivalent emissions per kilogram of wood burned. This in turn would provide nearly 140 million metric tons of net greenhouse gas offset per year. [2]

This thesis mainly focuses on finding out how thermal energy storage (TES) material will affect the solar cooker performance and for how long it will retain a higher temperature inside a solar cooker using solar radiation. An attempt was made to determine their physical properties in order to predict how much thermal energy it would able to store, to evaluate the performance of solar cooker heat gain and its efficiency with their thermodynamic properties taken into account. Lapland granite rocks were selected as the TES material, and polycarbonate cover glass, stone wool, plywood and their different combinations were used in the assessment project.

2 Theoretical background

In a previous study [3] tried to study certain solutions for the solar cooker specifically for a box type cooker to optimize its limitations in terms of slow cooking at a low temperature. The aim of the project was to research the possibilities to optimize the performance of a box type solar cooker by studying different approaches to find suitable reflective surface materials and good insulation and thermal energy storage materials to allow for better energy capture, heat retention and to extend cooking time into off-sunshine hours. The performance of sensible heat thermal energy storage materials (TES) paired with 5 cm thick insulating layer of stone wool was studied by heating them up and observing the air temperature changes in the solar cooker box after placing the closed insulated box against a reference object for 8 hours. The reflectivity of client-provided sample reflector materials was studied with a thermal camera. Each of the thermal energy storage materials of volume 1.8 l successfully kept the air temperature of a stone wool insulated box with volume of 24 l above 40 °C for 4 hours. Sauna rocks statistically outperformed other materials. Steels ranked highest on the reflectivity scale, with aluminium coming second; however, other properties of aluminium might make it a more suitable reflector material. Mirrors and films were found to be least appropriate candidates for reflector surface material. [3]

The results of the previous study showed that there is a need for further research. This thesis mainly studies the thermal storage materials of Lapland granite rocks. The focus is on retaining thermal energy by finding their specific heat capacity thermal conductivity of different rock types and insulation materials. The research effort involves determination of thermal properties of various rock types available in the north and northeast of Europe modelling for the experiment, demonstration of the system performance, manipulation of a mathematical model to predict the temperature variation in the system, and development of guidelines for applying the proposed storage system efficiency and its overall performance with and without TES materials.

3 Solar cooker

One of the many ways solar energy can be put to use can be using solar cookers to supply the heat for cooking which would otherwise be supplied from direct or indirect burning of carbon fuels. Cooking by the sun in a box type solar cooker is quite an old concept which has its documented applications dated as far back as 18th century. In 1767 the French-Swiss physicist, Horace de Saussure, designed the first to be fabricated hot-box solar cooker from an insulated box which has two glass panes as its cover. [1] Basically, solar cookers work by absorbing solar energy and converting it to heat that is necessary for cooking certain food types. Figure 1 shown below is an example of box type solar cooker solid works designed and constructed by Environmental Engineering department students in Helsinki Metropolia University of Applied Science.

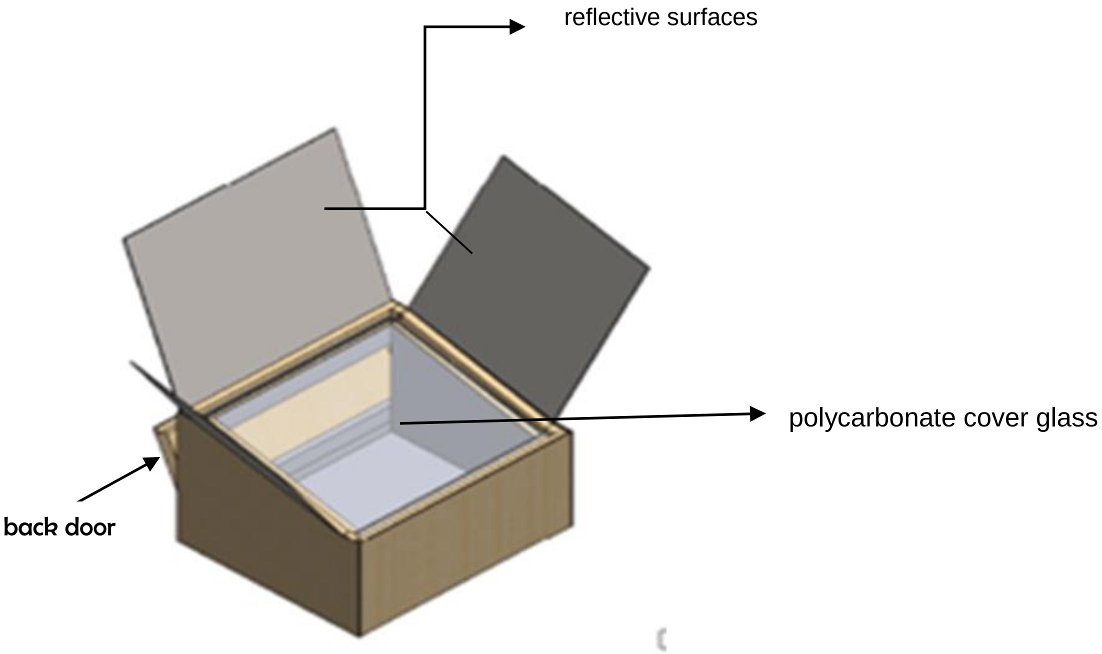

Figure 1. Top view of solar cooker box type.

A box type solar cooker shown in Figure 2 was constructed using a plywood, stone wool insulation and a Lapland granite TES material. The TES material of 5.86Kg, thickness of 6 cm and 30cm x 30cm base area also included.

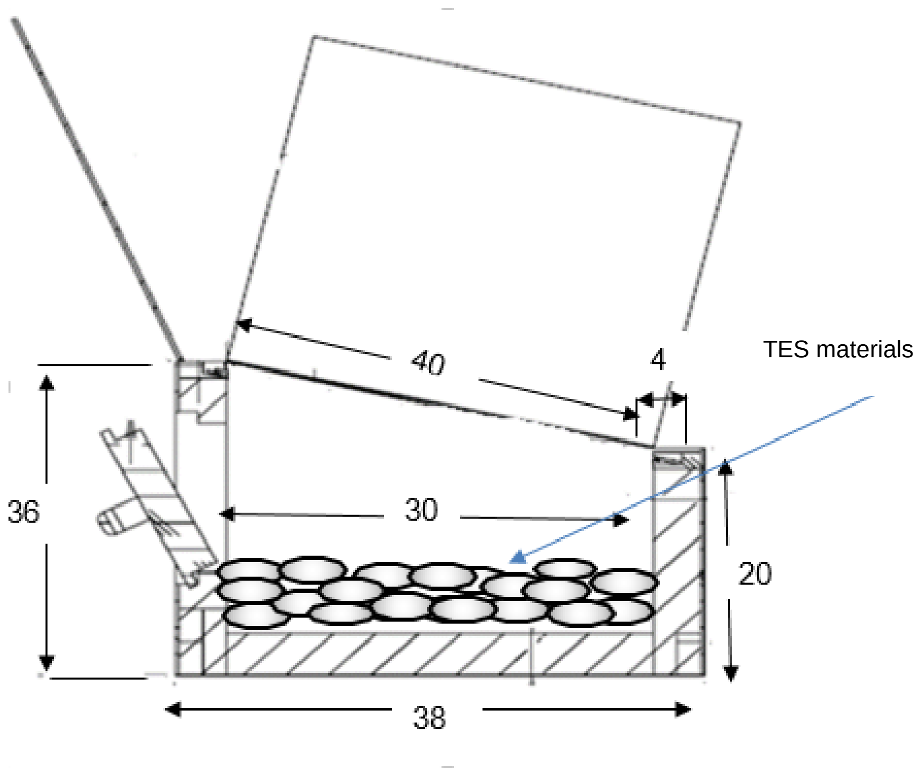

Figure 2. Sectional side view of box type solar cooker with TES materials.

4 Overview of TES materials

Five different types of TES materials collected from north and northeast of Europe were purchased to study their physical and thermal properties. They exhibit a higher compacted molecular pattern, density and heat capacity. Nevertheless, their size and colour might looked different, most of their thermal and physical properties are alike. Due to its abundance, availability in most areas and widely studied, Lapland granite was comparatively selected form other TES materials such as Archipelago or black stone, Scandinavian green, red and sauna rock.

4.1 Thermal energy storage TES

The thermal energy storage (TES) can be defined as the temporary storage of thermal energy at high or low temperature. Solar energy or the product of solar process can be stored in different forms as electrical, chemical, mechanical and thermal energy. It’s an advantageous to develop an efficient and cheaper source of energy from solar. [4]

4.2 Importance of TES

Solar energy is the most important among renewable energy sources due to its quantitative abundance .Problem of energy crisis and environmental threat as a result of continuous use of fossil fuels, scientists and researchers are putting efforts to develop technologies for an effective use of solar energy. Thermal energy storage system potentially offers a cheaper and simpler way. The concept of TES has existed for years and decades. Energy storage can minimize the rate of mismatch between energy supply and energy demand, and it plays an important role in energy conservation. Therefore, the need for the storage of solar energy can have a significant impact on energy sectors. Otherwise, solar energy has to be used as soon as it is received. But the technical use of solar energy presently poses problems primarily because of inefficient collection and storage. [4]

4.3 Size and duration of thermal storage

Characteristics of a storage system is the extended time during which energy can be kept or stored with a reasonable heat losses. The amount of energy stored per unit volume as shown in Figure 3 is volumetric energy capacity storage. A good system should have a long storage time and a small volume per unit of stored energy. [5]

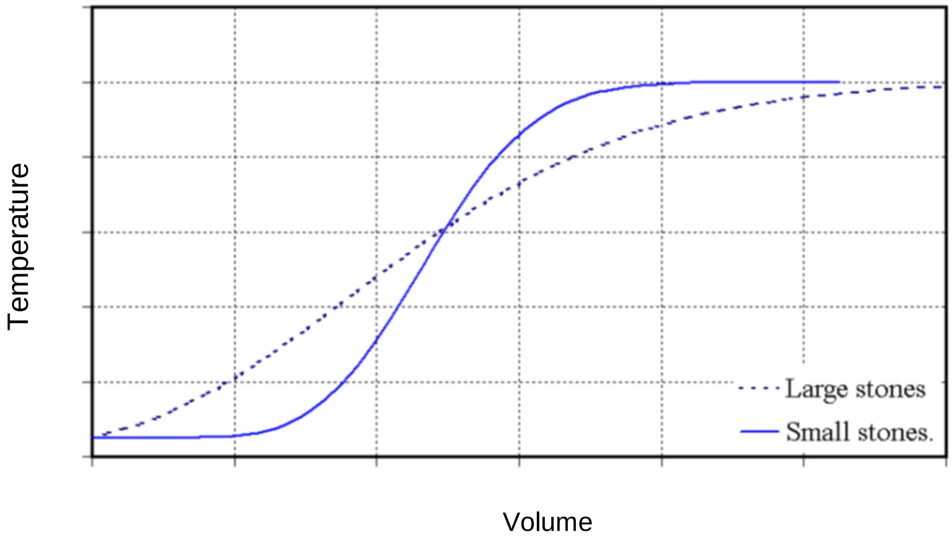

Figure 3. Effect of the size of packed-bed rock discharging temperature. [7]

5 Application mode of TES

The technology of thermal energy storage has been developed to a point where it can have a significant effect on modern life. Although the techniques to utilize high and low solar energy temperature sources for different purpose, it is still possible to retain thermal energy for shorter and longer period of time effectively since tthermal energy may last for very short time because of losses by radiation, convection and conduction.[4]

5.1 Space heating

The major nontechnical use of thermal storage was to maintain a constant temperature in dwelling, to keep it warm during the nights. Packed-bed rock TES material plays a greater role for countries where the temperature difference is higher between day and night. The stored thermal energy is transferred using air in tube as heat exchanger media for space heating integrated buildings. [4]

5.2 Extended cooking time

One of the challenges to utilize the solar energy is limited only during a higher solar radiation. Coupling TES materials with a solar cooker can also have an impact to extend cooking possibility for a short time. This is the main objective of this thesis to investigate the effectiveness of solar cooker, if TES material is used together. [5]

5.3 Power plants

In large scaled heat storage at power plant using concentrated solar reflectors to store the solar energy with molten salt as TES materials for electricity production during evening demand. The addition of thermal storage allows to produce steam for the power plants. Other materials that have a high heat of fusion at high temperatures have also been suggested for this application. [6]

6 Methods of thermal energy storage

There are three main physical ways for thermal energy storage, such as, sensible heat, phase change reactions and thermochemical reactions.

6.1 Sensible heat

Heating a liquid or a solid, without changing its phase is called sensible heat storage. The amount of energy stored depends on the temperature change of the material and can be expressed in Equation 1.

$$E=m\int_{T_1}^{T_2} C_P \, dT \tag{1}$$

where m is the mass and C_p, the specific heat at constant pressure. T_1 and T_2 represent the lower and upper temperature levels between which the storage operates. The difference ($T_2 – T_1$) is referred to as the temperature swing. [4]

6.2 Latent heat

Heating a material, causing a change in its phase (usually melting) is called latent heat storage. The amount of energy stored (E) in this case depends upon the mass (m) and latent heat of fusion (λ) of the material. This can be expressed as following equation:

$$E=m\lambda \tag{2}$$

The storage operates isothermally at the melting point of the material. If isothermal operation at the phase change temperature is difficult, the system operates over a range of temperatures T_1 to T_2 that includes the melting point. The sensible heat contributions have to be considered and the amount of energy stored can be calculated by: [4]

$$E= m\ [\{\int_{T_1}^{T^*} C_{ps}\, dT\ \} + \lambda + \int_{T^*}^{T_2} C_{pl} dT\ ]\} \tag{3}$$

Where C_{ps} and C_{pl} represents the specific heats of the solid and liquid phases and T^* is the melting point.

6.3 Chemical energy

Using heat to produce a certain physicochemical reaction and then storing the products. Absorbing and adsorbing are two examples for the bond reaction. The heat is released when the reverse reaction is made to occur. In this case also, the storage operates essentially isothermally during the reactions. However, the temperature at which heat flows from the heat supply is usually different, because of the required storage material and vice versa. [4].Figure 4 shows various techniques for a higher temperature TES material types.

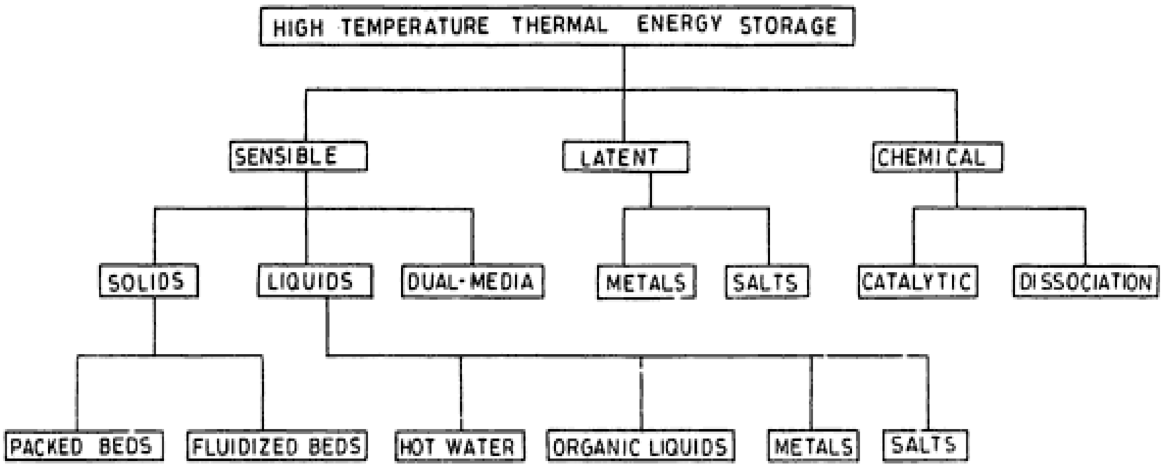

Fig 4. Overview of various techniques for high temperature TES. [5]

7 Consideration for selection TES materials

Of the above methods, sensible and latent heat storage systems are in use, chemical energy storage systems are being proposed for use in the future for medium and high temperature applications. The specific application for which a thermal storage system is to be used determines the method to be adopted. Some of the considerations, which determine the selection of the method of storage and its design, are as follows: [4]

- The temperature range, over which the storage has to operate.
- The capacity of the storage system
- Heat losses from the storage have to be kept to a minimum.
- The rate of charging and discharging.

8 Basic principles of sensible TES

In the case of sensible heat storage systems for solar cooker, energy is stored or extracted by heating or cooling a liquid or a solid, which does not change its phase during this process. A variety of substances have been used in such systems. These include liquids such as water, heat transfer oils and certain inorganic molten salts, and solid such as rocks, pebbles and refractory. In the case of solid, the material is invariably in porous form and heat is stored or extracted by the flow of a gas or a liquid through the pores or voids. [4]

Sensible heat storage systems are simpler in design than latent heat systems. However, they suffer from the disadvantage of being bigger in size. For this reason, an important criterion in selecting a material for sensible heat storage is its (ρC_p) value. A second disadvantage associated with sensible heat systems is that they cannot store or deliver energy at a constant temperature. Performance of a thermal heat storage is characterized by storage capacity, heat input and output rates while charging and discharging and storage efficiency. The storage capacity of a sensible heat storage with a solid or liquid storage medium as follows by: [4]

$$Qs = mc\Delta T = V\rho c\Delta T \tag{4}$$

where m is mass, V is volume, c is specific heat, ρ is density and $\Delta T = T_{max} - T_{min}$ is maximum temperature difference between maximum and minimum temperatures of the medium. This expression can be used to calculate the mass and volume of storage material required to store a given quantity of energy. For a packed bed used for energy storage, the porosity of the bed must be taken into considered. When the heat capacity of the energy-transferring medium in the storage is neglected, the volume of the packed-bed storage the equation is stated: [4]

$$V = Qs / \rho c(1 - \varepsilon)\Delta T \tag{5}$$

Where ε is the porosity of the packed bed. The storage energy density per unit mass and the storage energy density per unit volume are defined as follows: [3]

$$q = Qs/m = c(T_{max} - T_{min}) \qquad (6)$$

$$qv = Qs/V = \rho\, c(T_{max} - T_{min}) \qquad (7)$$

9 Comparison of TES models

Theoretical evaluation of different types of TES models are listed below. Several input variables are considered to define and predict the performance of the TES material and the experimental results of a box type solar cooker.

9.1 Exergy

The available energy in a packed-bed rock is called exergy. It is a straight forward prediction of the amount of energy stored or available in the packed rock beds is given by: [3]

$$EX = Q - \frac{T_{am}}{T} Q \qquad (8)$$

Where Q the amount heat gained the temperature in kelvin unit of the packed bed rock and T_{am} is the ambient temperature.
For a varying temperature of finite size the exergy changes is given by:

$$\Delta EX = \Delta H - T_{am}\, \Delta S - \Delta(PV) \qquad (9)$$

Where H is the enthalpy, S entropy V, volume and P pressure but under atmospheric pressure where $P=P_{am.}$ According to 1st and 2nd laws of thermodynamics Equation 9 reduced as follows:

$$\Delta EX = (H_2 - H_1) - T_{am}(S_2 - S_1) - (P - P_{am})(V_2 - V_1) \qquad (10)$$

$$\Delta EX = m\, C_p\, [(T_2 - T_1) - T_{am}\ ln \frac{T2}{T1}] \qquad (11)$$

In fact thermal energy storage systems must store useful work, not just energy. An analysis based on the second Law of thermodynamics for a full charge-discharge cycle includes losses of energy from entropy production caused by heat transfer between the fluid and solid; heat transfer between the air exiting the bed and space gap. This analysis determines optimum bed performance and design parameters. The total thermodynamic availability in a packed bed may be calculated from the expression given below: [5]

$$\psi = \int_o^L \rho_c \, C_s (1- \varepsilon) \, A_{cs} [(Ts-T_0)-T_0 \, ln \frac{T_s}{T_o}] \, dx \qquad (12)$$

where ψ is the thermodynamically available stored thermal energy To is the initial bed temperature before charging , *Ts* is the rock temperature ρ_S is the rock density ,*Cs* the specific heat capacity of the rocks, ε is the void fraction between the rocks and *Acs* the cross sectional area of the bed of length L. [5]

9.2 Efficiency of Thermal Energy Storage device

The first-law efficiency of thermal energy storage systems can be defined as the ratio of the energy extracted from the storage to the energy stored into it.

$$\eta = \frac{mC(T - T_0)}{mC(T_\infty - T_0)} \qquad (13)$$

Where mC is the total heat capacity of the storage medium and T and T_0 are the maximum and minimum temperatures of the storage during discharging respectively, and T_∞, is the maximum temperature at the end of the charging period. Heat losses to environment between the end of discharging and the beginning of the charging periods, as well as during these processes are neglected. [4]

10 Packed-bed rock fill as solid storage media

The difficulties and limitations relative to liquids can be avoided by using solid materials for storing thermal energy as sensible heat. But larger amounts of solids are needed than using water, due to the fact that solids, in general, have a lower storing capacity than water. Theoretically, water has three times the heat capacity of rock on a volume than water to store the same amount of the sensible heat .Packed-bed heat storage is an air based thermal storage with filled rock of different sizes and shapes packed loosely in a highly insulated container. Rock properties vary directly from rock type. Rock temperature, heat capacity, and density, thermal diffusivity were found from experimental results and are shown in Table 1-2 appendix 2. When rock are filled in solar cooker box to form packed bed , the air between the gap of each rock act as a heat transfer media and play a greater role in heat transfer is known as void since heat transfer between gas and beds of rock significantly exist.[7]

11 Evaluation of TES material physical properties and quantities

Generally, physical properties of a material can be observed without changing their identity of the substance .They are expressed in as colour, density, hardness, pressure and temperature. In a thermodynamic system a closed, open or isolated substance poses certain quantities of matter under a well-defined system and boundaries and substances. Examples are temperature, specific heat capacity enthalpy and entropy. [9]

11.1 Solar radiation

The solar irradiance (I in W/m^2) is the power density incident on an object due to illumination from the sun. While the solar radiation incident on the Earth's atmosphere is relatively constant, the radiation at the Earth's surface varies widely due to the following:

- atmospheric effects, including absorption and scattering
- local variations in the atmosphere, such as water vapor, clouds, and pollution
- latitude of the location and
- the season of the year and the time of day.

The above effects have several impacts on the solar radiation received at the Earth's surface. These changes include variations in the overall power received, the spectral content of the light and the angle from which light is incident on a surface. In addition, a key change is that the variability of the solar radiation at a particular location increases dramatically. The variability is due to both local effects such as clouds and seasonal variations, as well as other effects such as the length of the day at a particular latitude. Desert regions tend to have lower variations due to local atmospheric phenomena such as clouds. Equatorial regions have low variability between seasons. The amount of energy reaching the surface of the Earth every hour is greater than the amount of energy used by the Earth's population over an entire year. [8]

11.2 Temperature

Temperature is a physical quantity used to measure hotness or coldness of a substance.. Heat is a form of energy that is convertible to other form of energy. [9]

11.3 Density

Rock density has been measured from the mass m_S and volume V_S.

$$\rho = \frac{m_s}{V_s} \tag{14}$$

11.4 Specific heat capacity

Heat capacity is a measure of the ability of the material to absorb or release thermal energy .Materials suitable for heat storage should have a larger heat capacity and be convenient to add or withdraw heat from them. The specific heat capacity of a substance, C is the amount of energy needed to raise the temperature of 1 g of a substance by 1^oC. [9]

$$Q = mC\Delta T \tag{15}$$

The second law of thermodynamics can be used to determine how much thermal energy is absorbed by heavier and denser pure solids. [9]

11.5 Thermal conductivity

Thermal conductivity (*K*) is the intrinsic property of a material which relates its ability to conduct heat. It is defined as the quantity of heat *Q* transmitted through a unit thickness (dx) in a direction normal to a surface of unit area *A* due to a unit temperature gradient d*T* under steady state conditions and when the heat transfer is dependent only on the temperature gradient.Measuring the thermal conductivity of the rock is more difficult than measuring specific heat capacity. [10]

$$Q = KA\ \frac{dT}{dx} \tag{16}$$

11.6 Thermal diffusivity

Thermal diffusivity (with the unit m^2/s) is a material-specific property for characterizing unsteady heat conduction. This value describes how quickly a material reacts to a change in temperature. It is given by by the following equation: [10]

$$K_r = \frac{K}{\rho C_p} \tag{17}$$

Where K_r thermal diffusivity, ρ desnity and C_p heat capacity of TES materials.

11.7 Porosity of the rocks

The porosity of the material ε is the space gap in a material and is a fraction of the volume of voids over the total volume or void fraction, is the ratio of the void volume V_f to the total volume V_0 is given by: [7]

$$\varepsilon = \frac{V_f}{V_0} \tag{18}$$

The void or space gap between the samples which are crushed in a packed-rock bed by filling a container with rocks and pouring water into the container until it fills the gap between the rocks The void is as a value between 0 to 1. [7]

11.8 Characteristic length

To determine characteristic length (Size of the rocks), the surface area of an irregularly shaped object is difficult to measure. However, it can be assumed that the rock fragments are spherical with a diameter D given, where δ is the characteristic length of the rock fragment is as the following: [5]

$$\delta = \pi \frac{D}{2} \tag{19}$$

11.9 Thermal absorbability of solar irradiance and discharge

The solar radiation which passes through the polycarbonate glass cover top of the solar cooker is absorbed by a packed-bed rocks. The efficiency of the rock to store or charge directly depends on the specific heat capacity, the size in a diameter of the rocks and the heat transfer from the rock to the air by convection and radiation inside the box and between the rock fragment space gaps. [11]

11.9.1 Thermal charge

The energy gained by the mass of a packed- bed rock is given by:

$$Q_1 = m_r C_r \frac{dT}{dt} = \alpha_r I_r A_{r,Top} - h_r A_r (T_r - T_0) - QL_{,Tot} \tag{20}$$

where m_r is the mass of the rocks in the box, C_r is the specific heat capacity of the rocks; α_r is the absorptivity coefficient of the rocks. Absorptivity is the amount of radiation absorbed by a surface compared to that absorbed by a black body of solid object values lie between 0 and 1. I_r is the solar radiation or heat flux of value 1000W/m^2 conventionally assumed when the solar irradiation is perpendicular to the reflective collector material, $A_{r,Top}$ is the solar collection top area of the packed rock bed, T_r is the rock temperature, T_0 the surrounding ambient temperature of the solar cooker box, h_r is the convection heat transfer from rock to the air inside the box, A_r is the area of all the rock fragments and $Q_{L,Tot}$ the total heat loss through the wall of the box. [11]

$$QL,_{Tot} = U_T A_T (T_0 - T_r) \tag{21}$$

where U_T is the overall total heat resistance coefficient of all six sides of the solar cooker box and A_t I s the sum of all area of the sides of the solar cooker box.

$$U_{T=} \frac{1}{\frac{1}{h_i}+\frac{1}{R_T}+\frac{1}{h_i}} \tag{22}$$

where R_T is the sum of heat resistance value of each insulation material of all sides of box d given by:

$$R_T = \sum_i^n \frac{d_i}{k_i} \tag{23}$$

where di is the thickness of the insulation material and k_i is the thermal conductivity of constant.

$$h_r = \frac{\kappa Nu}{\delta} \tag{24}$$

where k is the thermal conductivity of the packed bed rock Nu is the Nusselt number, and δ is the characteristic length of the all rocks mention in equation (13) above. *Nu* can be determined using the following equation:

$$Nu \quad = 2 + \frac{0.589\, Ra^{\frac{1}{4}}}{[1+(\frac{0.469}{Pr})^{\frac{9}{16}} \;]^{4/9}} \tag{25}$$

where P_r is the prandle number which is about 0.7 for dry air at 0-200ºC and the Rayleigh number, Ra is given by the following equation:

$$Ra \;=\; \frac{g\beta_r}{\upsilon\kappa_r}(T_r - T_0)\delta^3 \tag{26}$$

where g is the acceleration due to gravity β_r is the thermal expansion coefficient of the rocks, υ is the kinematic viscosity of the air and κ_r the thermal diffusivity of rocks. [11]

11.9.2 Thermal discharge

When there is no available radiation, the packed-bed rocks start to lose thermal energy by convection to the air inside the insulated cooker box and the thermal loss by the rock is given by the following equation: [11]

$$Q_2 = m_r C_r \frac{dT}{dt} = -h_r A_r (T_r - T_0) - Q_{L,Tot} \qquad (27)$$

12 Experiments and results

A number of small scale experiments were carried out inside and outside Metropolia's environmental engineering lab to predict the physical quantities and properties of different types of TES materials. Data of solar radiation and ambient temperature from Vantaa metrology institute were used. The lab has a room temperature average of 20-21 °C. All temperature readings of the air temperature inside the cooking boxes were collected using thermocouples attached to a lab quest data collector. The solar cooker temperature performance test took overall 20 hours, of which 4 hours with solar radiation and 16 hours without radiation.

12.1 Physical properties and quantities of TES materials

The determined physical property values mass, density and specific heat capacity of each TES materials are presented below in Table 1. One of the most often used techniques to determine a specific heat capacity of a substance is method of mixtures. A beaker, called calorimeter of the known specific heat capacity Sc and mass mc is partially filled with a mass m_w of water at a temperature T_1 and then mounted in a suitable manner so that it isothermally insulated from the outside world. A mass M of the substance of an unknown specific heat capacity c is heated to a higher temperature T_b (usually in boiling water) and then quickly transferred to the calorimeter. The temperature of the calorimeter and the water contained quickly rises to a value T_2. It then slowly begins to fall as heat is lost to the room. If all the masses are measured in grams, the temperatures in degrees Celsius and the specific heat capacities in calories per gram per degree Celsius, the rock has thus given Mc*(T_b - T_2) calories of heat to the calorimeter and the contained water. If no losses occur this must be equal to the heat gained by them and calculated the following equation: [12]

$$Mc\ (Tb - T2) = (mc\ Sc + mw)*(T2 - T1) \tag{28}$$

Table 1.Physical properties of TES materials

Types of TES materials	mass(Kg)	Volume (ml)	Density (Kg/m^3)	Heat Capacity(J/gK)
Red rock	0.211	125	1690	0.939
Scandinavian Green river rock	0.0865	25	3460	1.115
Lapland Granite	0.2615	100	2092	0.543
Black Rock	0.1244	50	2490	0.854
Sauna Rock	0.2057	60	3430	0.837

12.2 Temperature performance solar cooker without TES materials

Solar cooker with a volume of 0.0246m^3, thickness of 4 cm of plywood and mineral wool together as insulation material and the top part of the solar cooker covered by a polycarbonate glass were used for experiments. The thermal storage, a Lapland granite rock bed of 5.89 kg with an area of 30 cm x 30 cm and thickness of 6 cm was placed at the bottom and painted with black color. Experiment was made to assess the characteristics of the packed bed storage to evaluate the change in temperature by using Vantaa Metrology Institute's solar incident radiation recorded data together with the ambient or room temperature. Figure 4 shows the amount of solar radiation data values for Vantaa area for 24 hours.

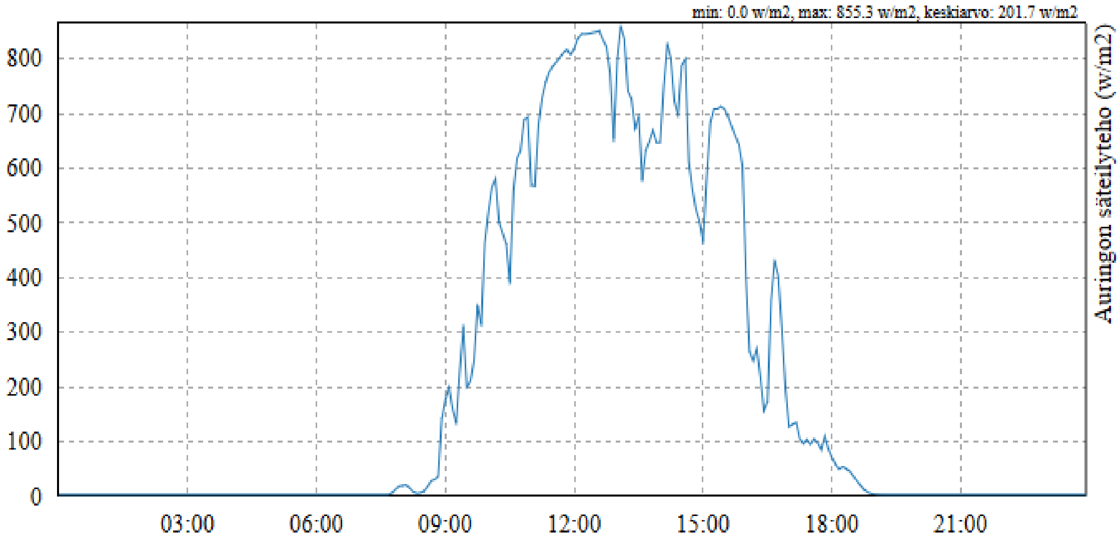

Figure 4. The amount of solar radiation values for Vantaa area. [13]

The temperature performance of the solar cooker was first tested using solar radiation for 4 hours from 13:00 to 17:00 and then at a room temperature without solar radiation for 16 hours from 17:00 to 9:00. When there was no solar radiation the interior air temperature dropped immediately and took 7 hours and 40 minutes to reach an equilibrium with the room temperature as shown in Figure 5.

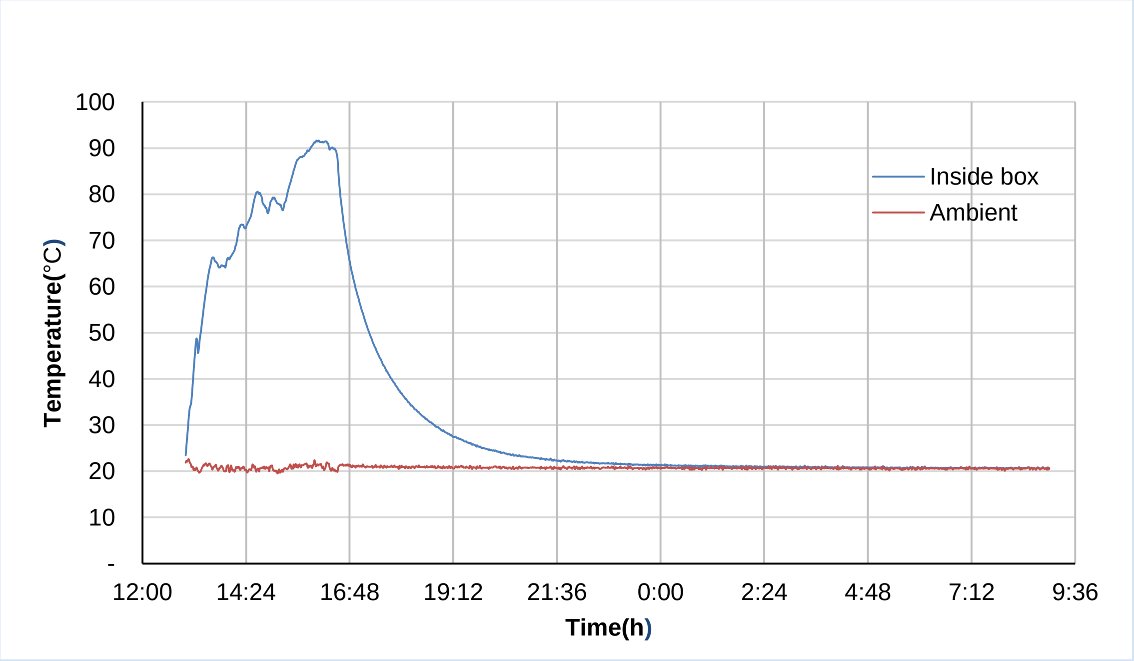

Figure 5. Interior air temperature of a solar cooker without TES materials.

12.3 Temperature performance solar cooker with TES materials

The amount of solar radiation received during the experiment is shown in Figure 6. Under similar circumstances mentioned to those above the temperature performance of the solar cooker was tested using solar radiation for 4 hours from 13:00 to 17:00 and then placed at a room temperature without solar radiation it took 16 hours from 17:00 to 9:00. Figure 7 shows the temperature of the solar cooker correspondingly took 16 hours to be equilibrium to the room temperature as well.

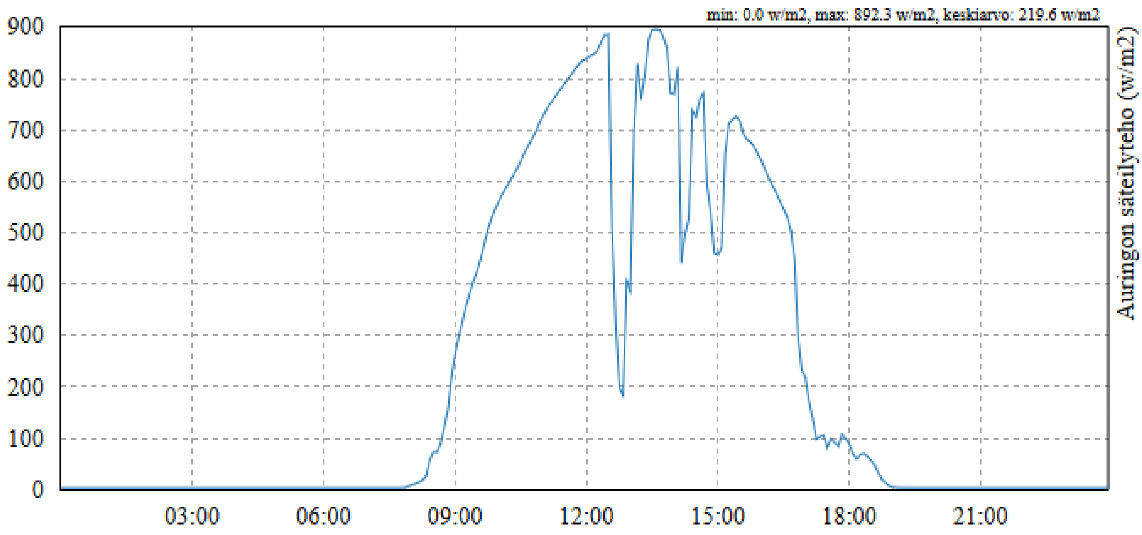

Figure 6. The amount of solar radiation values for Vantaa area. [13]

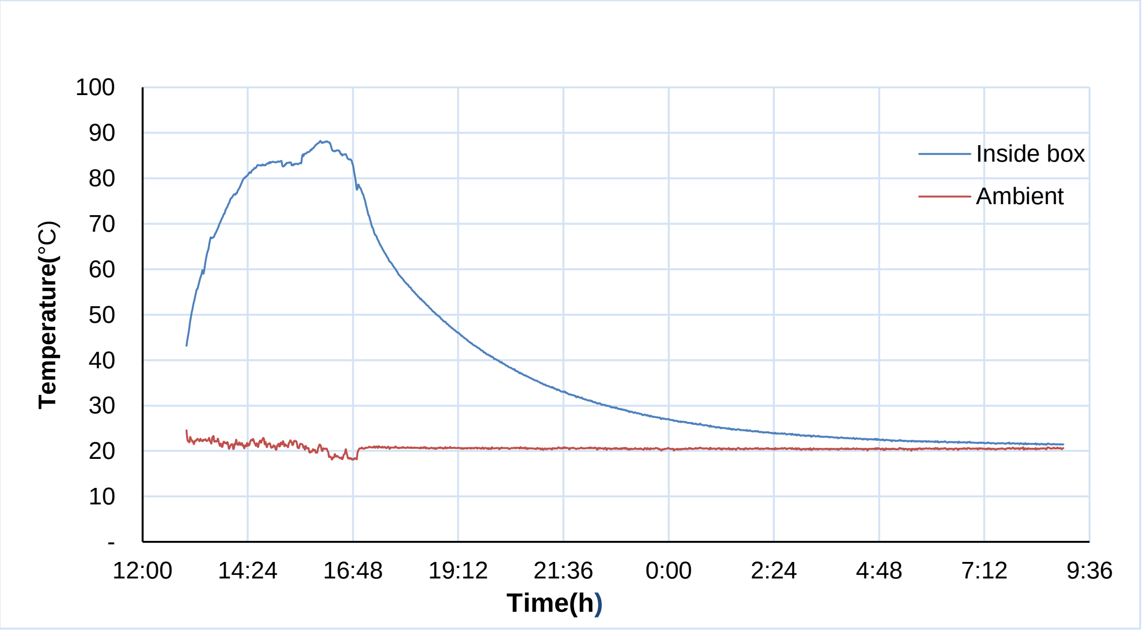

Figure 7. Interior air temperature of a solar cooker with TES materials

Figure 8 demonstrates a comparison of the interior air temperature of both type solar cooker. A rapid increase pattern was achieved with and without TES materials in similar manner during solar radiation. Before the solar cooker was placed into a room without solar radiation, the increment of the temperature during radiation was around 1-2 °C per second. The results shows that after 17:00 when there was no solar radiation, the interior air temperature dropped while the ambient or room temperature remained constant.

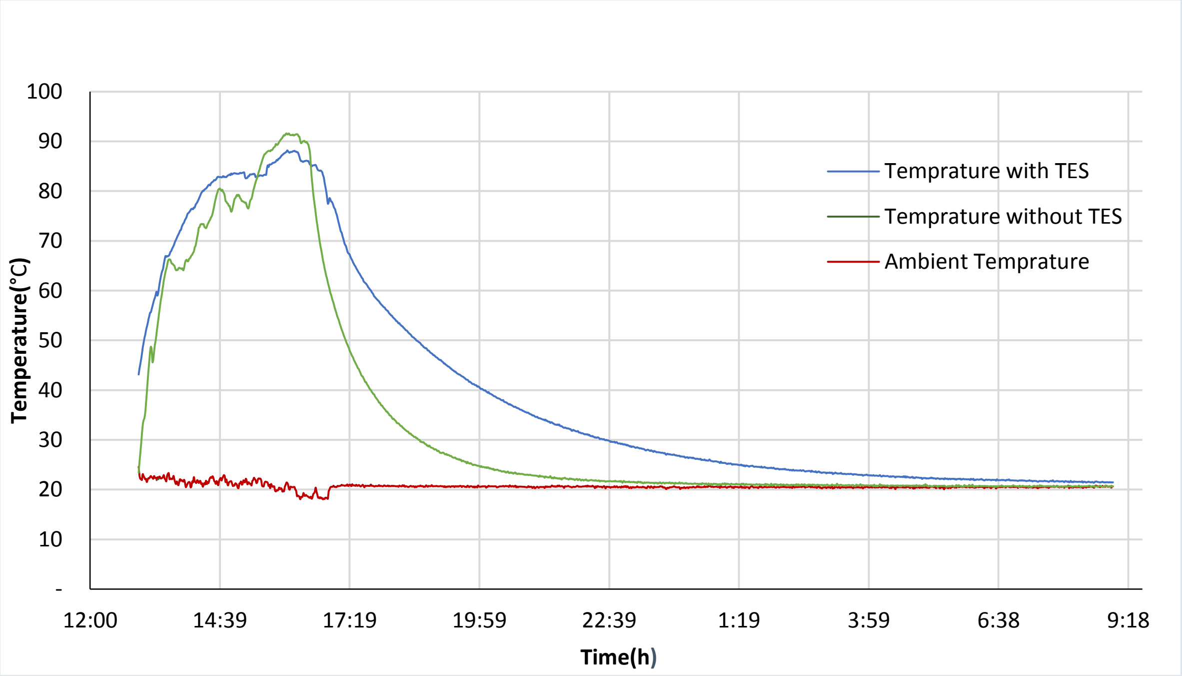

Figure 8. Comparison of solar cooker air temperature with and without TES materials

Due to the sensible heat property of the granite, the temperature difference was viewed 10-13°C after 3 hours in all conditions. The performance of the solar cooker with a storage system for a packed-bed rocks. Thermal storage system of the box together with packed bed rocks, thermal gain or charging, is given volume for a 0.0054m3 rock. The amount of the solar radiation due to the direct gain is given by the following equation:

$$Q_r= m_rC_r\,\Delta T= [V_{bed}(1- \varepsilon)\,\rho_r]C_rT \tag{29}$$

where ΔT is the change temperature increment within the specific time Cr the specific heat capacity of the rock, Mr the mass of the rock and V_{bed} bulk volume of the bed rock packed. The void constant is assumed to be 0.6.From the estimated and correctional constants the amount of energy gained by the packed bed rock between 13:00 and 17:00

is estimated to be 110KJ using Equation 14, and the amount of radiation received over the specified period of time was 798KJ. The efficiency η of the rock fragments as packed bed to convert the radiation energy to store is can be calculated using the following equation: [9]

$$\eta = \frac{Q_r}{I} \tag{30}$$

where the Q_r is the amount of solar radiation stored and I is the amount of radiation received. Using Equation 30, the efficiency of the solar cooker together with TES material was estimated to be 14%.

Table 2. Summarized experimental and calculated results of a solar cooker with and without TES material.

	Solar cooker without TES material	Solar cooker with TES material
Maximum Temperature (ºC)	90.9	88.1
Average solar flux (W/m^2)	526.9	615.8
Heat gained(stored)(W)	__	7.67
Heat loss (W)	-158.7	-158.7
Efficiency (%)	8.9	14.0

13 Summary

Solar energy can be stored temporarily by heating a packed bed rock storage in which air is as based thermal storage media in an insulated system. Solar radiation that hits the rock fragments is the main source of energy for the solar cooker. On the basis of previous studies and experimental findings, it was decided to evaluate the main input variables for Lapland granite only. The results of a previous project showed the thermal performance of a solar cooker with a different thermal storage materials. Sauna rocks TES material were studied to assess their temperature change by heating them up for 3 hours at a temperature of about 150°C in oven as a source of thermal energy. Then the rock were transferred to an insulated solar cooker box and the temperature was recorded for 8 hours. The results indicated that the tested TES materials kept the temperature of the insulated box air above 40°C for at least 4 hours at an average ambient temperature of 18°C. However, this thesis concludes that using TES material can optimize the temperature of a solar cooker. The most compelling evidence that supports the conclusion was gained when Lapland granite was directly heated up using solar radiation in an insulated solar cooker for 4 hours at an average ambient temperature of 20 °C and placed into a room to avoid solar radiation. The temperature was recorded for 16 hours. Under those circumstances when TES materials were used, the solar cooker temperature was above 40 °C for 3 hours and 45 minutes while the temperature of the solar cooker without TES material was above 40°C for only 45 minutes at an average room temperature of 20°C. The amount of solar energy stored or gained in the rock bed was estimated to be 110KJ.The average of solar radiation received over a specified period of time during 13:00 to 17:00 was estimated to be 798KJ. The efficiency of this storage system was found to be about 14%. Despite the source of the thermal energy used, the experiment duration time and the prototype solar cooker from the earlier study coupled with the limitation of variables in other case similar to this one ,combining the TES materials with solar cooker can predominantly optimize the extended cooking capability slightly longer.

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Appendix 1. Measurement of granite's heat capacity

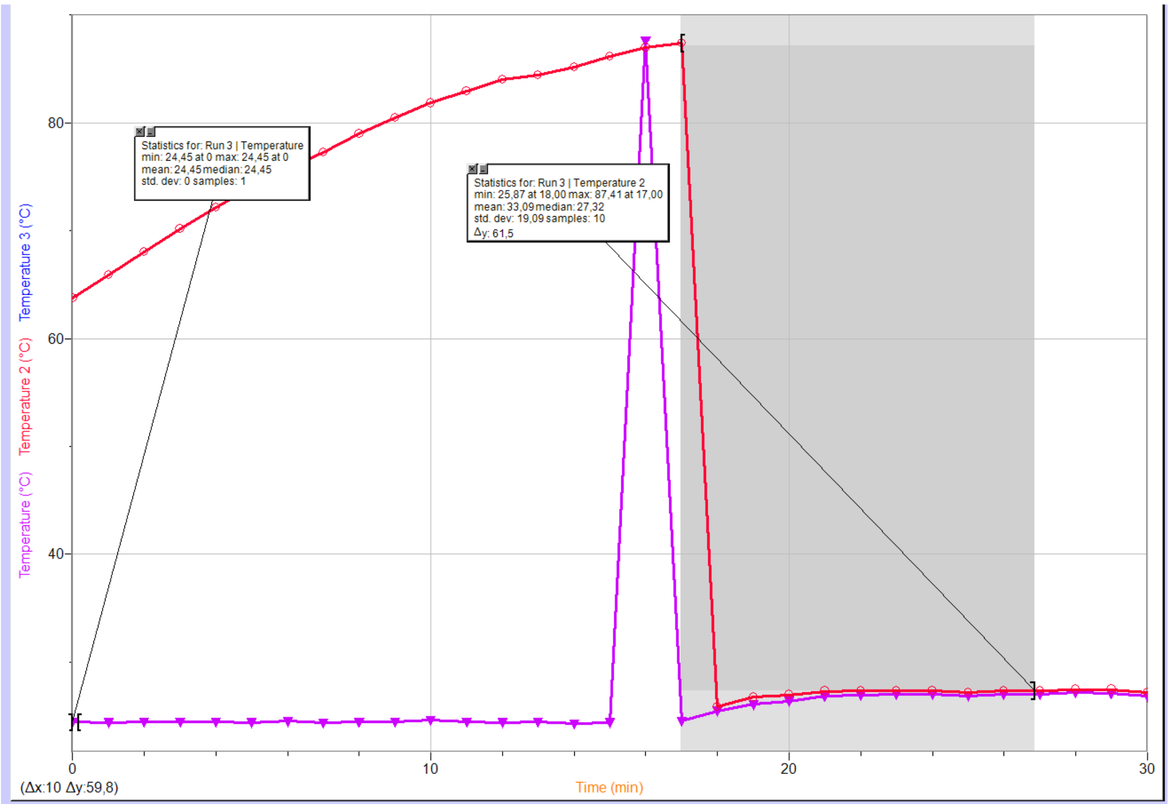
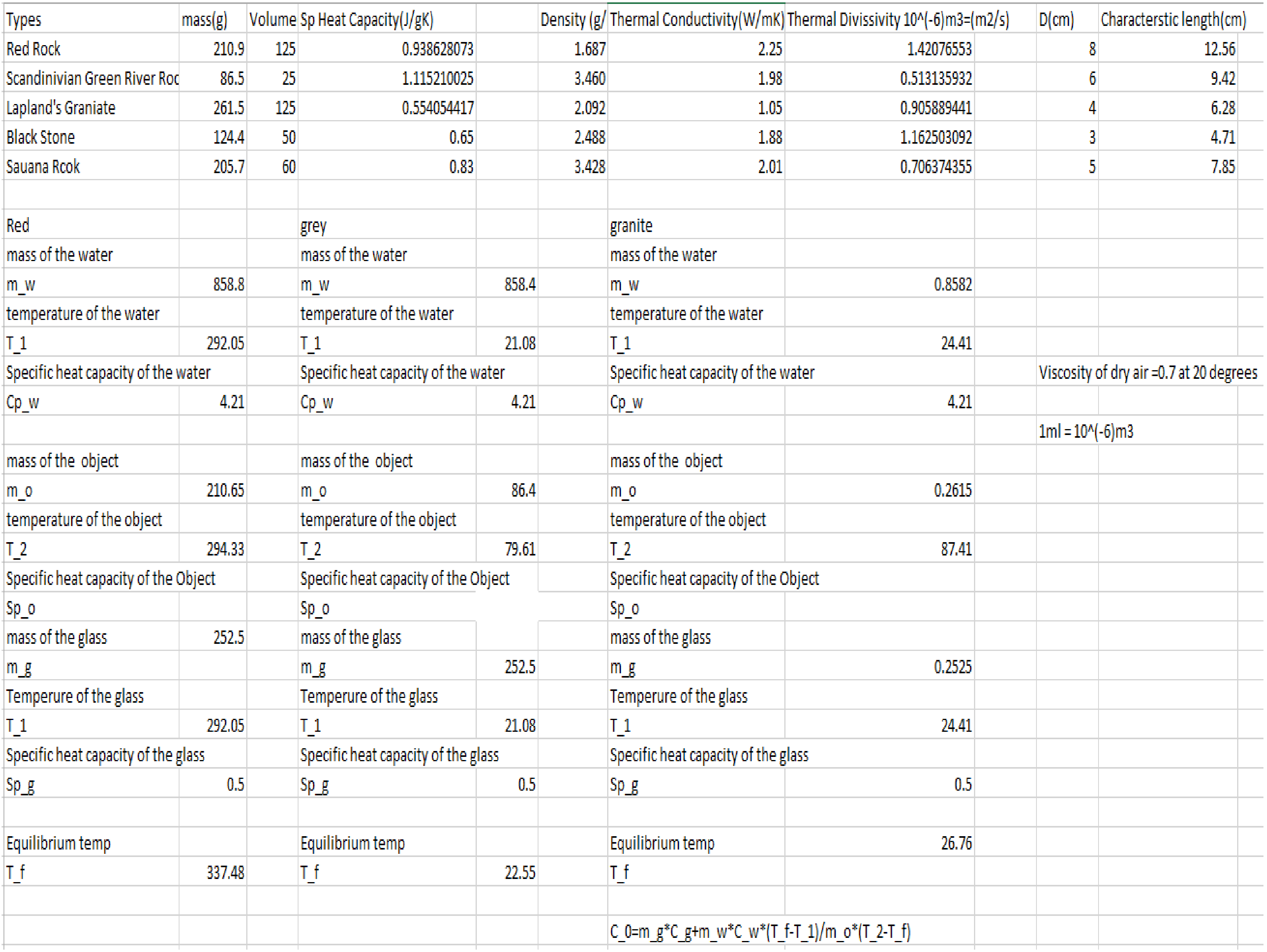


Figure 1-1. Specific heat capacity experiment for Lapland granite

Table1-1. List of thermal conductivity constants

Insulation used material	Thermal conductivity constant(W/mk)
Ply wood	0.03
Stone wool	0.03
polycarbonate glass cover	0.19

Table 1-2. Physical properties and quantities of TES material calculations



Types	mass(g)	Volume	Sp Heat Capacity(J/gK)		Density (g/	Thermal Conductivity(W/mK)	Thermal Divissivity 10^(-6)m3=(m2/s)		D(cm)	Characterstic length(cm)
Red Rock	210.9	125	0.938628073		1.687	2.25	1.42076553		8	12.56
Scandinivian Green River Roc	86.5	25	1.115210025		3.460	1.98	0.513135932		6	9.42
Lapland's Graniate	261.5	125	0.554054417		2.092	1.05	0.905889441		4	6.28
Black Stone	124.4	50	0.65		2.488	1.88	1.162503092		3	4.71
Sauana Rcok	205.7	60	0.83		3.428	2.01	0.706374355		5	7.85
Red			grey			granite				
mass of the water			mass of the water			mass of the water				
m_w	858.8		m_w	858.4		m_w	0.8582			
temperature of the water			temperature of the water			temperature of the water				
T_1	292.05		T_1	21.08		T_1	24.41			
Specific heat capacity of the water			Specific heat capacity of the water			Specific heat capacity of the water			Viscosity of dry air =0.7 at 20 degrees	
Cp_w	4.21		Cp_w	4.21		Cp_w	4.21			
									1ml = 10^(-6)m3	
mass of the object			mass of the object			mass of the object				
m_o	210.65		m_o	86.4		m_o	0.2615			
temperature of the object			temperature of the object			temperature of the object				
T_2	294.33		T_2	79.61		T_2	87.41			
Specific heat capacity of the Object			Specific heat capacity of the Object			Specific heat capacity of the Object				
Sp_o			Sp_o			Sp_o				
mass of the glass	252.5		mass of the glass			mass of the glass				
m_g			m_g	252.5		m_g	0.2525			
Temperure of the glass			Temperure of the glass			Temperure of the glass				
T_1	292.05		T_1	21.08		T_1	24.41			
Specific heat capacity of the glass			Specific heat capacity of the glass			Specific heat capacity of the glass				
Sp_g	0.5		Sp_g	0.5		Sp_g	0.5			
Equilibrium temp			Equilibrium temp			Equilibrium temp	26.76			
T_f	337.48		T_f	22.55		T_f				
						C_0=m_g*C_g+m_w*C_w*(T_f-T_1)/m_o*(T_2-T_f)				

Appendix 2. Radiation and ambient temperature

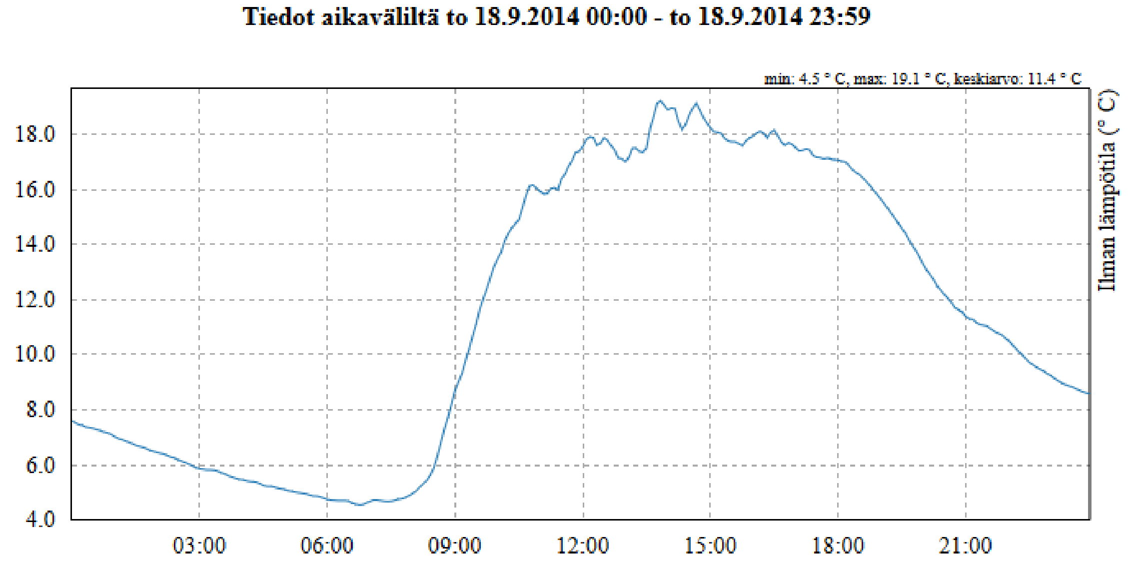


Figure 2-1. Ambient air temperature of a solar cooker with TES materials. [13]

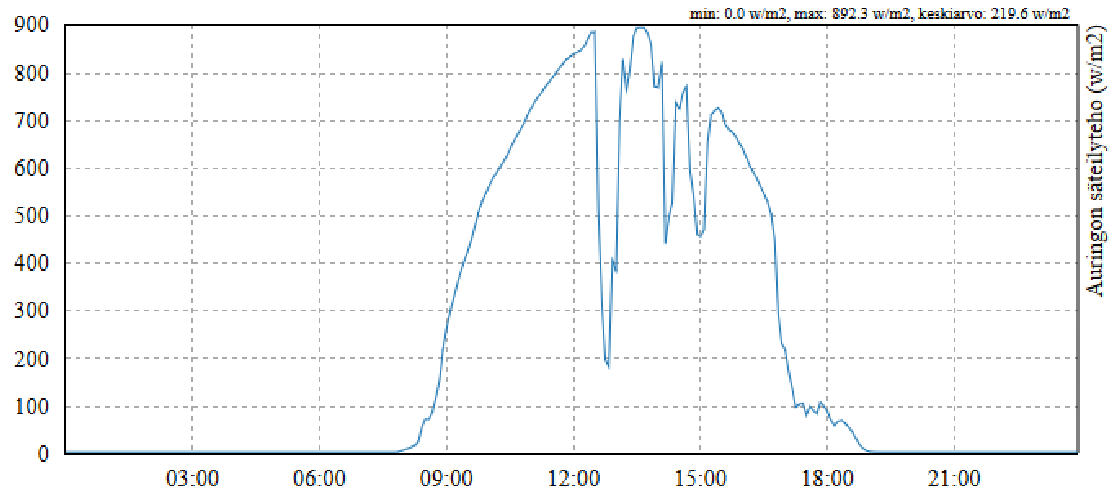


Figure 2-2. Solar radiation of a solar cooker with TES materials. [13]

Table 2-1. Selected solar flux received and ambient temperature data for TES material.

Time of Day	Solar Radiation (W/m2)	Ambient Temperature(C)
12:00	836.5	17.5
12:10	844.0	17.9
12:30	882.4	17.8
12:50	179.6	17.1
13:00	381.1	16.9
13:10	821.9	17.4
13:35	892.3	18.1
14:00	766.0	18.8
14:10	441.4	18.9
14:40	767.6	19.1
15:00	452.9	18.2
15:25	723.0	17.7
15:40	677.1	17.5
16:00	636.1	17.9
17:00	214.9	17.5
18:00	85.7	17.0
19:00	0	15.6
20:00	0	13.2
21:00	0	11.3
22:00	0	10.5
23:00	0	9.2
0:00	0	7.6
1:00	0	7.0
2:00	0	6.4
3:00	0	5.8
4:00	0	5.4
5:00	0	5.0
6:00	0	4.7
7:00	0	4.6
8:00	0	4.9

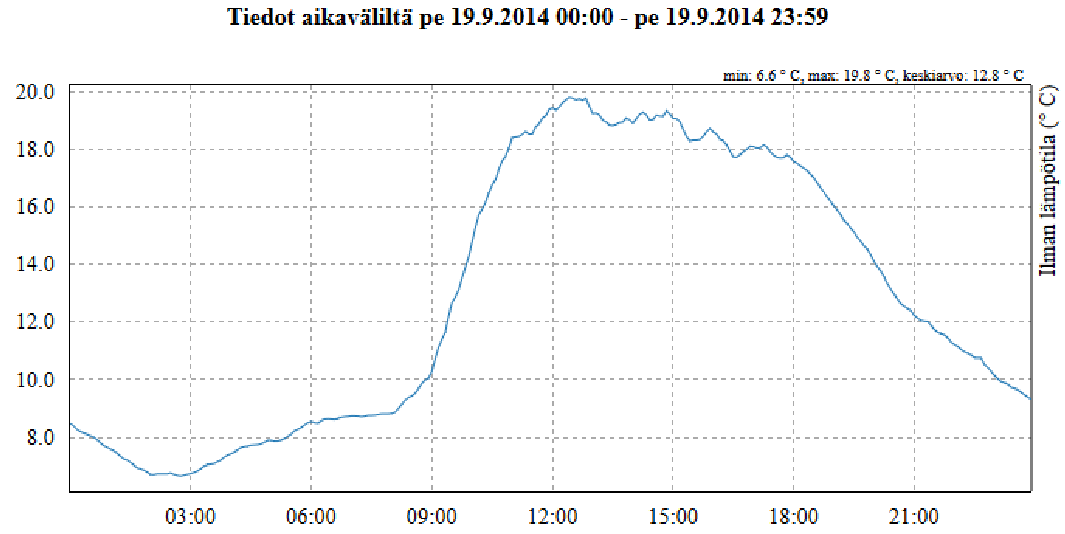


Figure 2-3. Ambient air temperature a solar cooker without TES materials.[13]

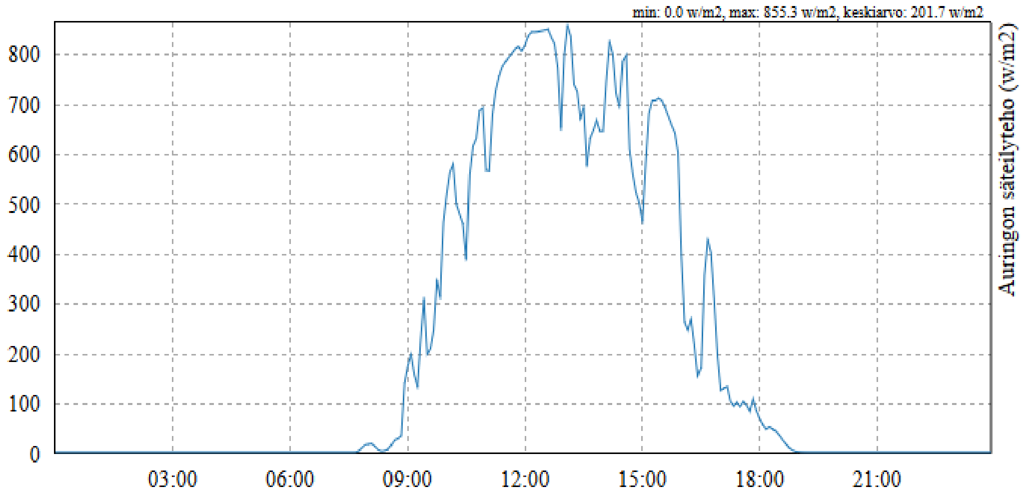
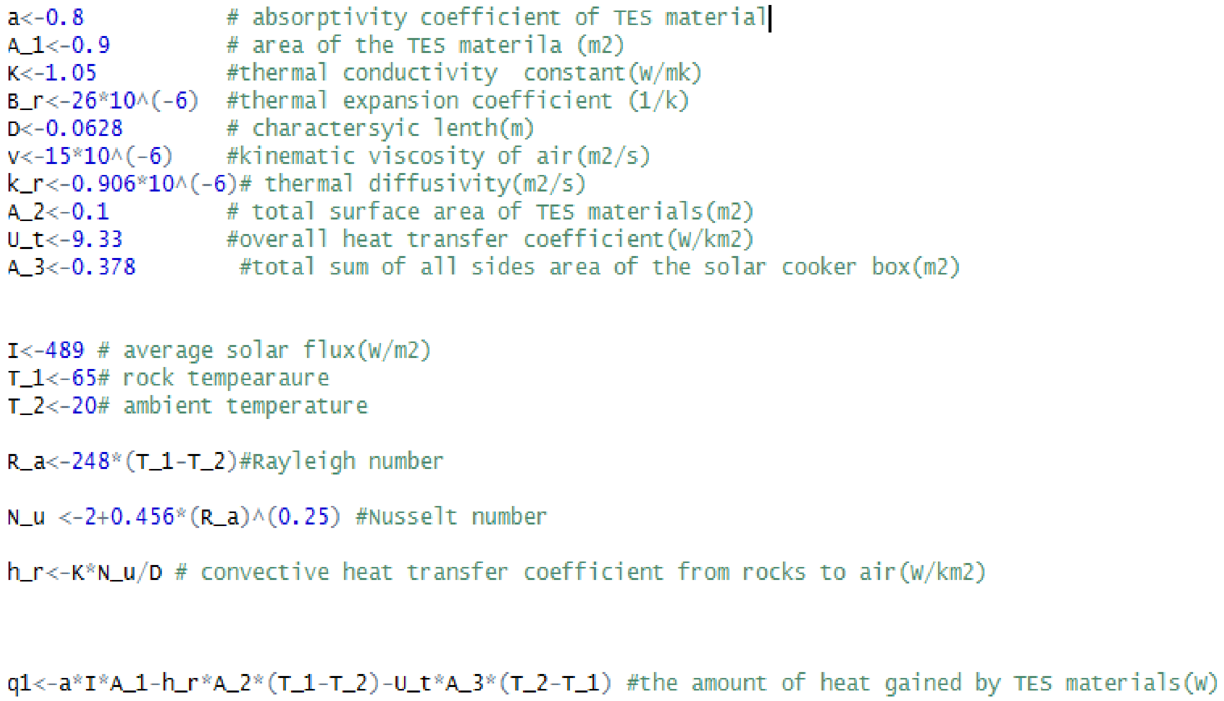


Figure 2-4. Solar radiation of a solar cooker without TES materials.[13]

Table 2-2. Selected solar flux received and ambient temperature data for solar cooker without TES material.

Time	Solar Radiation (W/m2)	Ambient Temperature(C)
12:00	815.9	19.4
12:25	844.5	19.8
13:00	796.0	19.2
13:05	855.3	19.2
13:35	576.7	18.8
14:00	644.0	18.9
14:10	822.7	19.2
15:00	463.3	19.0
15:25	710.0	18.2
16:00	396.6	18.6
16:25	153.3	17.9
16:35	355.3	17.7
16:40	426.2	17.8
17:00	123.8	18
18:00	68.0	17.5
19:00	0	16
20:00	0	14.1
21:00	0	12.2
22:00	0	11.2
23:00	0	10.1
00:00	0	8.4
1:00	0	7.5
2:00	0	6.7
3:00	0	6.7
4:00	0	7.4
5:00	0	7.8
6:00	0	8.5
7:00	0	8.7
8:00	0	8.8

Table 2-3. TES material heat gain calculation.



```
a<-0.8           # absorptivity coefficient of TES material
A_1<-0.9         # area of the TES materila (m2)
K<-1.05          #thermal conductivity  constant(W/mk)
B_r<-26*10^(-6)  #thermal expansion coefficient (1/k)
D<-0.0628        # charactersyic lenth(m)
v<-15*10^(-6)    #kinematic viscosity of air(m2/s)
k_r<-0.906*10^(-6)# thermal diffusivity(m2/s)
A_2<-0.1         # total surface area of TES materials(m2)
U_t<-9.33        #overall heat transfer coefficient(W/km2)
A_3<-0.378        #total sum of all sides area of the solar cooker box(m2)


I<-489 # average solar flux(W/m2)
T_1<-65# rock tempearaure
T_2<-20# ambient temperature

R_a<-248*(T_1-T_2)#Rayleigh number

N_u <-2+0.456*(R_a)^(0.25) #Nusselt number

h_r<-K*N_u/D # convective heat transfer coefficient from rocks to air(W/km2)



q1<-a*I*A_1-h_r*A_2*(T_1-T_2)-U_t*A_3*(T_2-T_1) #the amount of heat gained by TES materials(W)
```