Optimization of Tekniikka elämää palvelemaan (TEP) ry's box-type solar cooker

Insulation improvement

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The purpose of this thesis was to evaluate the cooking performance of an existing, field tested box-type solar cooker by studying computer plotted rates of temperature change in the cooking chamber and to suggest improvement ideas. The solar cooker was originally designed by Maria Telkes, a Hungarian-American scientist and inventor who worked on solar technologies, and its design was modified by Kari Silfverberg, an architect doing volunteer work for a Finnish non-governmental association called Technology For Life, Finland (Tekniikka elämää palvelemaan or TEP in short), which distributes free solar cookers to countries in the developing world.

Thermal simulations in Solidworks software, researches on different types of solar cookers and the results of actual performance tests on kari Silvferberg's box-type solar cooker and its modified version named Metropolia 1 made in Metropolia's Environmental Engineering Laboratory were used to devise design modifications for the different parts of the solar cooker that can improve the cooking performance. An improved version of the conventional box-type solar cooker incorporating the design modifications was made and experimentally investigated for its insulation. The results obtained suggest that the improved version has a better insulation than TEP ry's box-type solar cooker.

The experimental and thermal simulation results showed that, the insulation of TEP ry's box-type solar cooker can be improved by adding an additional insulation layer of polyurethane to its existing stone wool insulation and by using double-paned glazing in place of the existing single pane glazing. Thermal simulations in SolidWorks software and computer plots of the temperature versus time for the inside of a solar cooker that is heated to 100°C and left at room temperature for 5 hours were made for the TEP and Metropolia version-1 solar cookers and compared. It was observed from these plots and thermal simulations that the rate of temperature change for Metropolia 1 was lesser, which suggests that the design of Metropolia 1 can be taken as one improvement option to that of the TEP solar cooker.

Keywords	TEP ry., CFD, box-type solar cooker, SolidWorks CAD,

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Contents

1 Introduction

Energy from solar radiation is the largest source of carbon-neutral energy. As much as 4.3 × 1020 joules of energy strikes the earth in one hour which is greater than the 4.1 × 1020 joules of energy that is consumed on earth in one year (U.S. department of energy, 2005). At the moment, approximately 14% of total world energy demand is covered by energy from renewable sources such as solar energy. It is observed that exploitation of solar energy is very minimal, but that solar energy has a potential for higher coverage of the world's energy demand in the future (Cuce, Cuce, Wood and Riffat 2014).

Among the varied applications of Sun's energy solar cooking is one, solar cookers are seen to be highly prospective in many remote areas of the developing world where solar radiation has a mean daily radiance intensity of 5-7 kwh/m^2 for over 275 days of a year. A major share of the total available energy resource in these places is used up for cooking which is primarily supplied from wood fuel (Cuce and Cuce 2013).

Fuel wood in the rural areas of the developing world is collected by women and children who have to walk long distances every day. Abate(2014) stated that, women and children of especially sparse developing regions spend more than 90 hours of wood gathering per month. Besides, the tedious job of collecting firewood, indoor cooking over wood fire as pointed out by literature (Abate 2014), is killing an estimated amount of 5 million children every year from respiratory disorders. It appears that solar cookers can have an invaluable contribution to the needy people of the developing world in assigning time for more productive activities such as going to school and for the betterment of their health. Solar cookers 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.

According to Abate (2014) using solar cookers has a potential of minimizing firewood use by 36%, this is roughly equivalent to 246 million metric tons of wood each year. It is assumed that an average of 6.28 MJ of energy is gained from a kilogram of wood burnt and that the CO_2 equivalent emission of wood fuel is 90 g per an MJ of energy, which corresponds to 565 grams CO_2 equivalent emissions per kilogram of wood burned. This is nearly 140 million metric tons of net greenhouse gas offset per year (Abate 2014).

Cooking by the sun in a box-type solar cooker is quite an old concept, which has its recognized applications as old as 18th century. In 1767, Horace de Saussure, the French-Swiss physicist, designed the first to be fabricated hot-box solar cooker from an insulated box which has two glass panes as its cover (Saxsena, Varun, Pandey and Srivastav 2011). Design modifications and new designs of box-type solar cooker have been seen ever since Horace de Saussure and there still seem to exist a design space for improving cooking performance; hence this thesis project was conducted.

Modifications to improve the cooking performance of solar cookers have been carried out by many; for example, Harmim, Boukar and Amar (2008) studied a finned cooking vessel to increase the efficiency of solar cookers and to minimize cooking time but among the different solar cookers in existence, the box-type solar cooker has attracted many modifiers such as the commissioner and author of this thesis project due to its straightforwardness and ease of construction.

The box-type solar cooker that was studied and which later gets improvement ideas in this thesis project was provided by a Finnish non-governmental association called Technology for Life, Finland (Tekniikka elämää palvelemaan ry. or TEP in short).

Technology for Life, Finland is a Finnish non-governmental organization that is composed of people working in the field of technology or people who has interest in the effects of technology to humans and the surrounding. The organization is established with the aims of: promoting the use of technology to improve living conditions, justice and peace; and enhancing the moral wakefulness of the people who work in technology (Tekniikka Elämää Palvelemaan, 2006).

As one of its aims, TEP ry. does technology projects in some developing nations. For example, in its technology project, Appropriate Technology Project, TEP ry. has established a green Namibia Development centre in Namibia where locals get education on do-it-yourself-from-local-materials type of solar cookers. (Tekniikka Elämää Palvelemaan, 2006)

2 Box-type solar cooker

Basically, solar cookers work by absorbing solar energy and converting it to heat that is necessary for cooking food. The heat from the absorbed solar energy needs to be trapped inside a closed compartment and insulated to prevent it from escaping

This thesis project resulted in a solution to the common problems associated with box type solar cookers: slow cooking times and inability to cook food after the sun sets, which is the usual time to prepare dinner for most people in the sunny developing regions of the world where TEP ry donates box-type solar cookers. The slowness in cooking might be caused by several factors, the major one being poor insulation and poor reflector design, and improvement ideas are discussed later in the sections below. The problem of inability to cook after dusk can be solved by incorporating heat storage materials inside box type solar cookers as has been done by a fellow student, Solomon Abate (Abate 2014), who has also worked his thesis project on box-type solar cookers.

2.1 Working principle

As the name entails and Figure 1 depicts, box-type solar cookers are used to cook or heat up food using the sunlight as a source of energy. In simple terms, as electrical stoves get powered by electricity, solar ovens get powered by the sun. Sunlight, either directly or reflected from reflectors enters the box through the glass or plastic cover. This sunlight is absorbed and converted to heat energy by the cook pot and black coloured interior, which makes the temperature of the inside of the solar cooker to rise. The rise in temperature will continue until the heat lost by the cooker is equal to the heat gained from sunlight. Heat gain inside a solar box is achieved as a result of the conversion of sunlight absorbed by the black coloured interior and the cook pot into a radiant energy with a wavelength that cannot radiate back outside the cooking area through the glass or plastic cover. Entrapped by the insulation of the box, the radiant energy is absorbed by the black interior and cooking pot that is conducted to the food hence cooking happens (Alfs 2015).

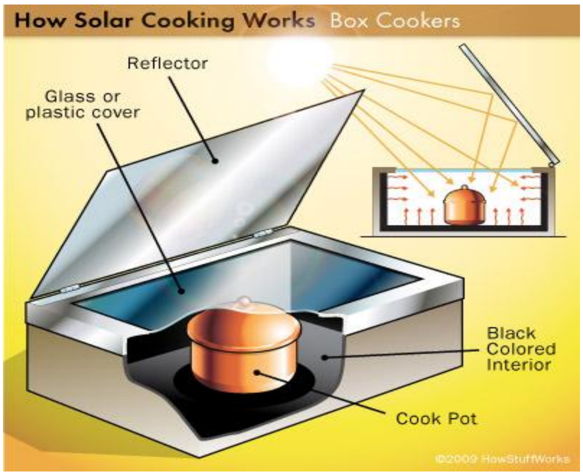


Figure 1. Box-type solar cooker (HowStuffWorks, 2009)

2.2 Theory

A solar oven or box-type solar cooker is an energy converter; it converts solar energy that is in the form of visible and near-infrared light into thermal energy or heat.

Heat transfer

Heat transfer study is made to either estimate the rate of flow of energy as heat through the boundary of a system both under steady and transient conditions or to determine the temperature field under steady and transient conditions, which also will provide the information about the slope and time rate of change of temperature at a range of locations and time. i.e. T (x, y, z, τ) and dT/dx, dT/dy, dT/dz, dT/dτ etc. These two are interconnected, one being dependent on the other. Nevertheless explicit solutions may be generally required for one or the other (Kothandaraman 2006).

Basic laws governing heat transfer and their application

First law of thermodynamics or the energy conservation principle: This law states the rule for the relationship between the heat flow, energy stored and energy generated in a given system.

For a closed system the energy conservation principle states the following:

- Change in the internal energy of a system = the net heat flow across the system boundary + heat generated inside the system

- The change in internal energy in a given volume is equal to the product of volume density and specific heat ρcV and dT where the group ρcV is called the heat capacity of the system (Kothandaraman 2006).

The second law of thermodynamics establishes the direction of energy transport in the form of heat. This law theorizes that energy as heat through a system boundary flows in the direction of the lower temperature or along the negative temperature gradient (Kothandaraman 2006).

Newton's law of motion is applied to determine fluid flow parameters (Kothandaraman 2006)

The law of conservation of mass is necessary to determine flow parameters (Kothandaraman 2006)

Rate equations differ according to the mode of heat transfer and important to mathematically represent heat transfers (Kothandaraman 2006).

Modes of Heat Transfer

Energy in the form of heat is transferred from one point to another by conduction, convection or radiation modes of heat transfer.

Conduction

An increase in temperature in a solid makes its building molecules experience an increase in vibrational kinetic energy and as every molecule is bonded in some way to neighbouring molecules, usually by electrical force fields, this energy can be passed through the solid. The transfer of heat can thus be seen as thermal energy transfer due to the presence of a temperature difference (Theodore 2011).

Heat power is dependent upon the heat transfer area (A), temperature difference (T1 – T2), thermal conductivity of the material (k), and the thickness of the separating wall (L) and is mathematically modelled according to Fourier's law that lays the governing equations for the rate of heat flow by conduction(Tohka 2010). For one-dimensional steady state heat conduction, Fourier's law states as follows:

$$\dot{Q} = -\frac{kAdT}{dx} = kA\left(-\frac{dT}{dx}\right) = -kA(T_B - T_A)/L \quad (1)$$

where,

$\dot{Q}$ = heat flow rate (w/m$^{2)}$

k = thermal conductivity (w/mk)

T = temperature (k)

A = area (m^2)

L = length (m)

Convection

In this mode of heat transfer energy is transported as heat due to a flowing fluid over an unchanging solid. There are two types of convection in existence namely natural convection where movement of a fluid occurs as a result of a density difference that is caused by a temperature difference and forced convection where the flow of a fluid happens as a result of an induction of motion by for example, a blower, a fan or a pump (Tohka 2010)

Newton's law of cooling is used to mathematically model the convection heat transfer and heat power by convection as follows:

$$\phi = \alpha_c A(T_1 - T_2) \quad (2)$$

where:

ϕ = heat power (w) A = area (m^2)

α_c= convective heat coefficient (w/m^2 k)

T = Absolute temperature Kelvin (k)

Radiation

Thermal radiation is an electromagnetic radiation given out by a certain physical body due to its temperature and with a loss of its internal energy. All solids, liquids and some gases that are heated give off thermal radiation (Tohka 2010).

Mathematically, heat emitted by radiation is modelled using Stefan-Boltzmann's law

$$q = \sigma T^4 A \quad (3)$$

where:

q = heat transfer per unit time (w)

σ = 5.6703 * 10^{-8} ($w/m^2 k^4$) the-Stefan-Boltzmann constant

T = Absolute temperature Kelvin (k)

A = area of the emitting body (m^2)

2.3 TEP ry's box-type solar cooker

TEP ry's box-type solar cooker that is shown in Figure 2 is the conventional box type solar cooker where the basic frame is made of plywood in a shape of a truncated rectangle followed by a 50mm thick insulation of stone wool that is laminated with thin aluminium metal sheets for reflecting solar radiation and re-radiating heat for cooking into the box. Beneath the top cover of the box, there is a window-like structure or a glazing to allow sun radiation during cooking. It is a 2 mm sheet of polycarbonate material inside a wooden frame that has leather belt hinges for opening and closing. The absorber plate where cooking pots are placed is 58 cm x 58 cm rectangular sheet of matte-black-painted aluminium which has a high solar radiation absorbance. Cooking in the box is done using pots of stainless steel coated in matte black. Cooking pots are placed above the absorber plate and receive the heat for cooking from the absorber plate through conduction and radiation heat transfers. Additional heat for cooking is received from the aluminium walls of the cooking box that reflect solar radiation.

Figure 2. TEP ry's box-type solar cooker

The solar cooker has been field tested under the east African sun in Ethiopia and a temperature of up to 150 ^{o}C was achieved at around noon on a bright sunny day in May.

Kari Silfverberg's designing experience in building box-type solar cooker has been shared with two elementary schools in Ethiopia, and box-type solar cookers have been built that are now being used as teaching materials.

2.3.2 Design

Figure 3 shows a sectional CAD schematic of TEP's box-type solar cooker with its major components labelled. All dimensions are given in millimetres.

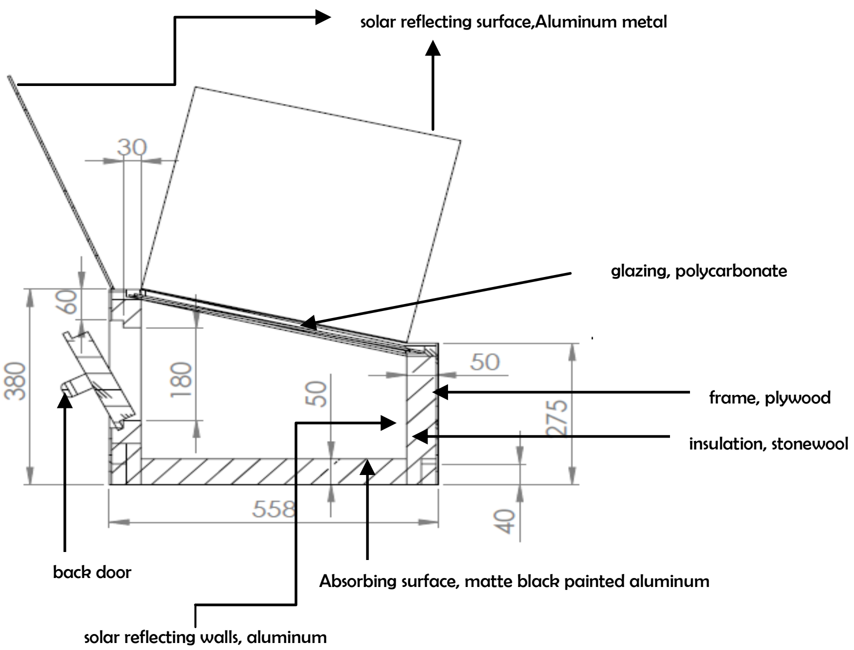


Figure 3. Sectional schematics of TEP ry's box-type solar cooker

This thesis will focussed mainly on the glazing and insulation parts of the sectional CAD above as this two sections of box-type solar cooker are mainly important when it comes to improving insulation.

2.3.3 Insulation and Glazing

The heat retaining capacity of a box-type solar cooker largely depends on two of its components that are indicated in Figure 3: namely insulation and glazing. Good insulation traps the heat from solar radiation for a longer period.

Glazing is a solar-radiation-absorbing, transparent top cover of the box-type solar cooker and an insulation preventing convection heat transfer to the ambient air can be single or double paned, which affects the insulation capacity of the box. Insulation increases with increasing the number of panes used. In TFL's box solar cooker, the walls and the absorber surface are insulated with 50 mm thick mineral wool that has a low heat conductance coefficient k= 0.03 W/mK, which can be improved by choosing an insulation material with lower heat conductance.

Glazing for the box solar cooker is made of polycarbonate material. This material was chosen for its good solar radiation transparency and low thermal conduction and convection coefficients.

2.3.4 Thermodynamic analysis of TEP ry's box-type solar cooker

In order to optimize the heat retaining or insulating capacity of TFL's box-type solar cooker, which in part was the purpose of this thesis, the rate of temperature change of the cooking chamber was seen to be the part that could be influenced. The smaller this rate the better the cooking performance.

Although losing heat from a hotter heat source for example, a box-type solar cooker to an ambient at a lower temperature is an unavoidable observable fact, its rate of heat loss can be decelerated by insulating it or making improvements in its insulation design. A low rate of change of temperature in the cooking chamber of a box-type solar cooker can be easily achieved by improving its insulation. This can be achieved either by choosing an insulation material with very low heat conduction or by increasing the number of panes used to construct the glazing or by combining both. Other areas of development that have been researched and believed to have a positive impact on the cooking performance can be a change in the design or shape of the cooking chamber, a change in the design of cooking pots and a change in the design of the absorber plate.

2.4 Metropolia 1 box-type solar cooker

A smaller version of TEP's box-type solar cooker, Metropolia 1 as is seen in Figure 4, was built basically out of scrap fridge doors collected from Työpaikka ja Toimisto Ky's junkyard, a waste recycling facility in Herttoniemi. The fridge doors are white painted light metal with an insulation layer of 40 mm thick polyurethane, an insulation material with a low heat conductance coefficient of k = 0.03 – 0.02 W/m.k. The basic frame is further insulated with a layer of 10 mm thick stone wool, which is then laminated with polyester silver foil for reflecting heat and incident solar radiation inside the box. The 30 cm x 30 cm absorber surface laminated with a polyester silver foil provides the heat for cooking by conduction and radiation heat transfers.

Figure 4. Experimental rig of the Metropolia 1 box-type solar cooker

2.4.1 Design

The overall design of the Metropolia 1 box-type solar cooker is shown in the sectional schematic CAD drawing in Figure 5. Basic components and reasons for choosing them are explained below the figure.

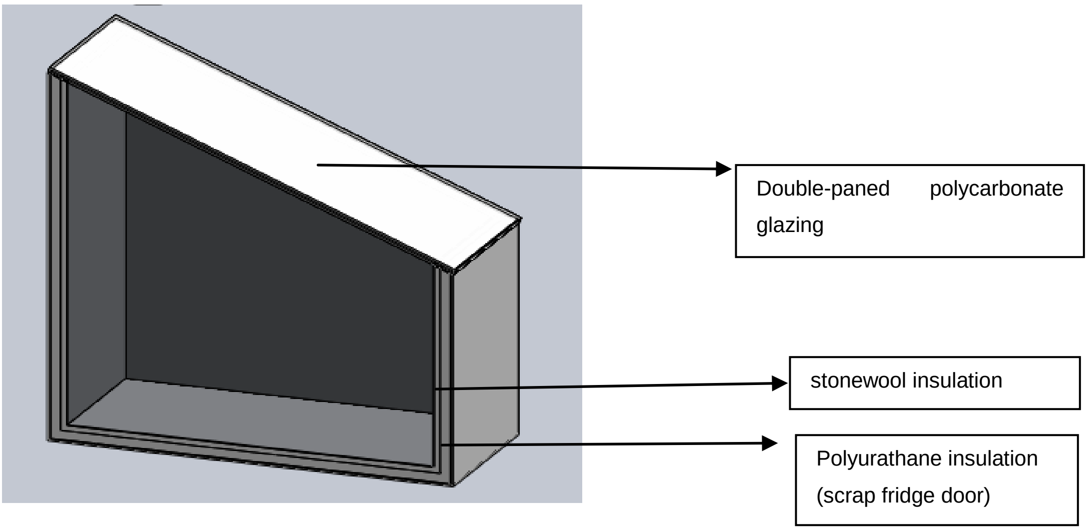


Figure 5. Sectional schematics of Metropolia 1 box-type solar cooker

Double paned polycarbonate glazing was used as a transparent top cover in Metropolia 1 box-type solar cooker and its insulation has an extra insulation layer of polyurethane when compared to TEP ry's box-type solar cooker that has stonewool insulation only. This type of design can reduce heat loses due to conduction.

Multi layered system of insulation as an envelope for a building is a viable option when it comes to thermal optimization under unsteady conditions. Multi-layered wall systems that are built as a set of dissimilar and separate layers grant high thermal resistance. (Simões, Simões and Tadeu 2012).

The reason behind choosing a smaller size for the cooking box is that with reduction in size high temperature inside the box can be achieved in a shorter period of time than when using a larger box.

2.4.2 Insulation and Glazing

The insulation of Metropolia 1 box-type solar cooker is a mixture of polyurethane and stone wool insulation layers. The logic behind such a structure is that the thicker the insulation layer is the better the heat retention is. Besides, combining insulations that have very low heat conductance coefficients together can greatly improve the heat retention capacity of the solar cooker (Cuce et al 2014).

A double paned glazing in place of the single pane glazing that was used in TEP ry's box-type solar cooker was used in Metropolia 1 box-type solar cooker. Double pane glazing was chosen as it can reduce the loss of heat to the ambient by convection as it has a dead air gap that is known to be a good insulator of heat. The glazing did also get a reduction in size that came as a result of the reduced size of the cooking chamber.

2.4.3 Thermodynamic analysis of cooking performance

The box-type solar cooker was experimentally tested to find its heat retention. Besides, the two box-type cookers were designed and a thermal simulation study was done in SolidWorks software. It was observed that the insulation of Metropolia 1 box-type solar cooker has improved compared to TEP's box-type solar cooker.

Experimentally it was found out that the Metropolia 1 box-type solar cooker was 20 ^{o}C hotter than the TEP ry's box-type solar cooker. This improvement could also be seen from thermal simulation results that were carried out on the solar cookers using SolidWorks simulation software.

The result of experiments and thermal simulation results of TEP's and Metropolia 1 solar cookers indicate that the heat retention of TEP's solar cooker can be improved by modifying the following aspects of the cooker;

- Shape of the solar cooker
  Kumar, Chavda and Mistry (2010) pointed out a solar cooker cum dryer designed in a truncated pyramid shape has been tested, and it was found out that it has a better performance than the conventional box type cooker as is the case with Metropolia 1 and TEP ry box-type solar cookers, as solar insolation falls both on its side and absorber plates compared to the rectangular chamber which gets insolation only on its absorber plate.

- Glazing

The glazing of TEP’s box-type solar cooker can be improved by changing the single-pane glazing into a double-pane glazing where the gap of air between the panes acts as insulation.This design can maximize the insulation of heat to the ambient as there is an added layer of air insulation which is known to have a low thermal conductance *k*=0.03 W/m.K

- Heat storage material

Another area for improvement to TEP’s box-type solar cooker is its absorber surface. It is suggested that a heat storage material be included underneath the absorber surface to store heat and to make it possible to cook food during sunset hours (Abate 2014).

- Insulation material

Instead of using the stone wool insulation that is used in TEP’s box-type solar cooker it is suggested that it be replaced with silica aerogel insulation. (Cuce et al 2014), mentioned as can be seen from the thermal conductivity table in Figure 6 that aerogel insulations are good thermal insulators that almost cancel out two of the three known heat transfer mechanisms of convection, radiation and conduction.

Insulation product	Chemical composition	λ (W/m K)
Mineral wool	Inorganic oxides	0.034–0.045
Glass wool	Silicon dioxide	0.031–0.043
Foam glass	Silicon dioxide	0.038–0.050
Expanded polystyrene (EPS)	Polymer foam	0.029–0.055
Extruded polystyrene (XPS)	Polymer foam	0.029–0.048
Phenolic resin foam	Polymer foam	0.021–0.025
Polyurethane foam	Polymer foam	0.020–0.029
Silica aerogels	SiO_2 based aerogel	0.012–0.020
Organic aerogels	Aerogels derived from organic compounds	0.012–0.020
Vacuum insulation panels (VIP)	Silica core sealed and evacuated in laminate foil	0.003–0.011
Vacuum glazing (VG)	Double glazing unit with evacuated space and pillars	0.003–0.008

Figure 6. Overview of thermal insulation materials sorted by their thermal conductivity range (Cuce et al 2014)

3 Experiment

This section presents how the experiment to find out the improvement in insulation was carried out. The first section of this chapter discusses the setup of the experiment and the last section discusses the results of the experiment.

3.1 Experimental setup

All experiments were carried out inside Metropolia's environmental engineering laboratory. The laboratory had constantly regulated room temperature of 20-22 in degree Celsius. The wind speed was assumed to be close to 3m/s. All temperature readings of the air temperature inside the box-type solar cookers were collected using stainless steel thermocouples shown in Figure 7 that were attached to a labquest data collector.

Figure 7. Stainless steel thermocouple probe used to measure the air temperature inside TEP ry and Metropolia 1 box-type solar cookers

The thermocouples used in this experiment can identify a temperature in the range of -40 to 135 °C with an accuracy in the range of ±0.2°C to ±0.5°C and the maximum temperature that they can tolerate without damage is 150 °C (Vernier Software and Technology 2015). Specification and the working principle of the thermocouple used for the experiments can be seen in Appendix 3.

The heat insulating performances of TEP's and Metropolia1's solar boxes were tested using Suomalainen Vuolukivi stones in a shape of an 8mm diameter disk that are shown in Figure 8. The stones were heated to about 150 0c inside an oven for 3 hours at a temperature of nearly 150 °C. These stones were then placed inside the TEP and Metropolia 1 box-type solar cookers and temperature versus time data was collected using thermocouples that read data about the air temperature inside the cooking chamber.

Figure 8. Experimental setup, Metropolia 1 box-type solar cooker insulation being tested

3.2 Results

As can be seen from the temperature versus time plot in Figure 9, the rate of temperature change in the Metropolia 1 box-type solar cooker, the slope of the blue curve, is a positive value compared to the slope of the green curve in Figure 10 which is a negative value which seems to indicate there was an improvement in insulation.

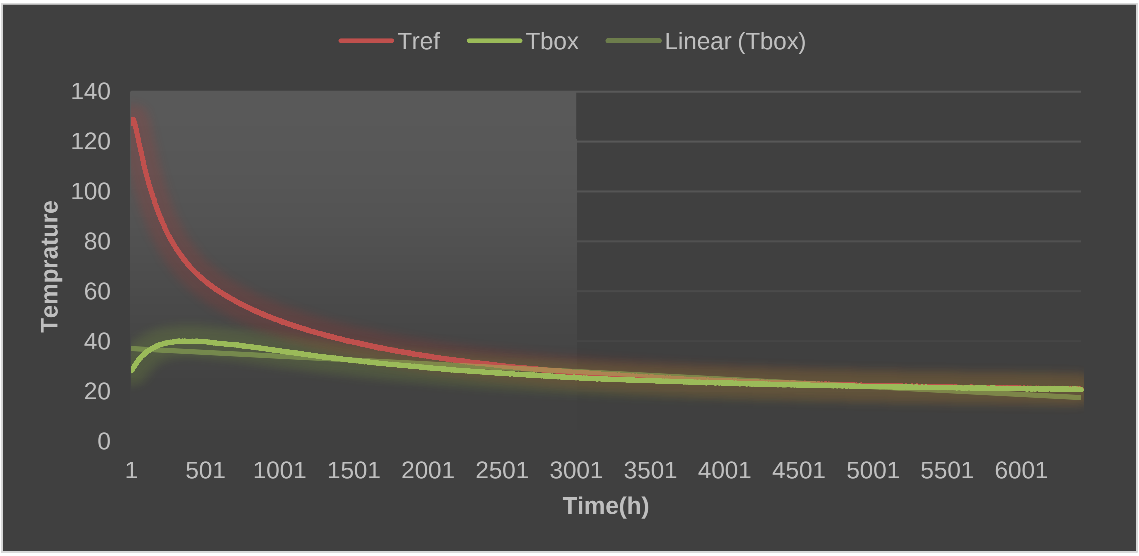


Figure 9: Time versus temperature plot for TEP's box-type solar cooker

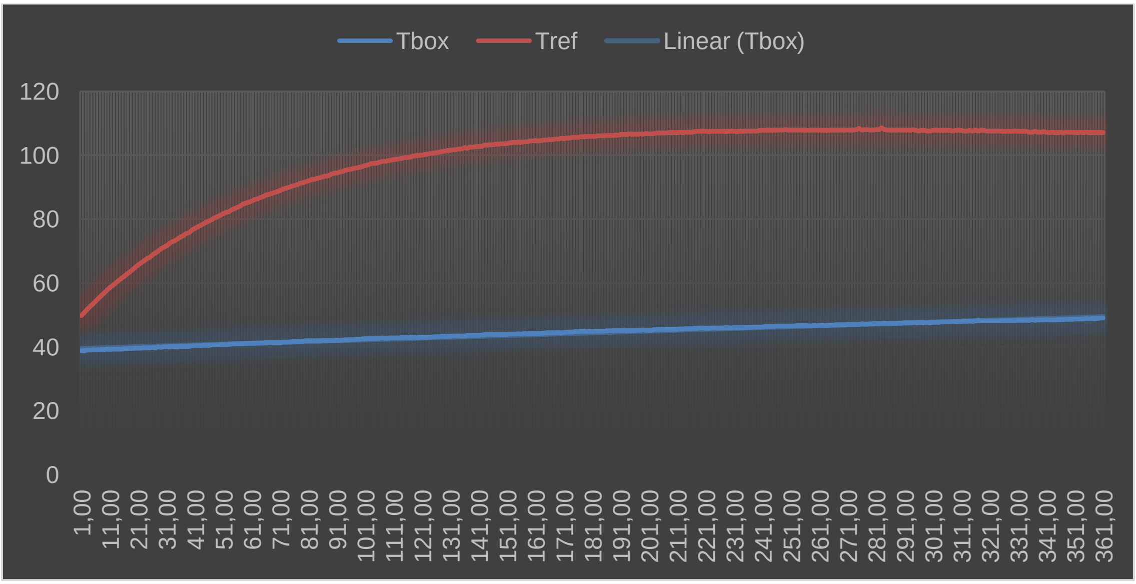
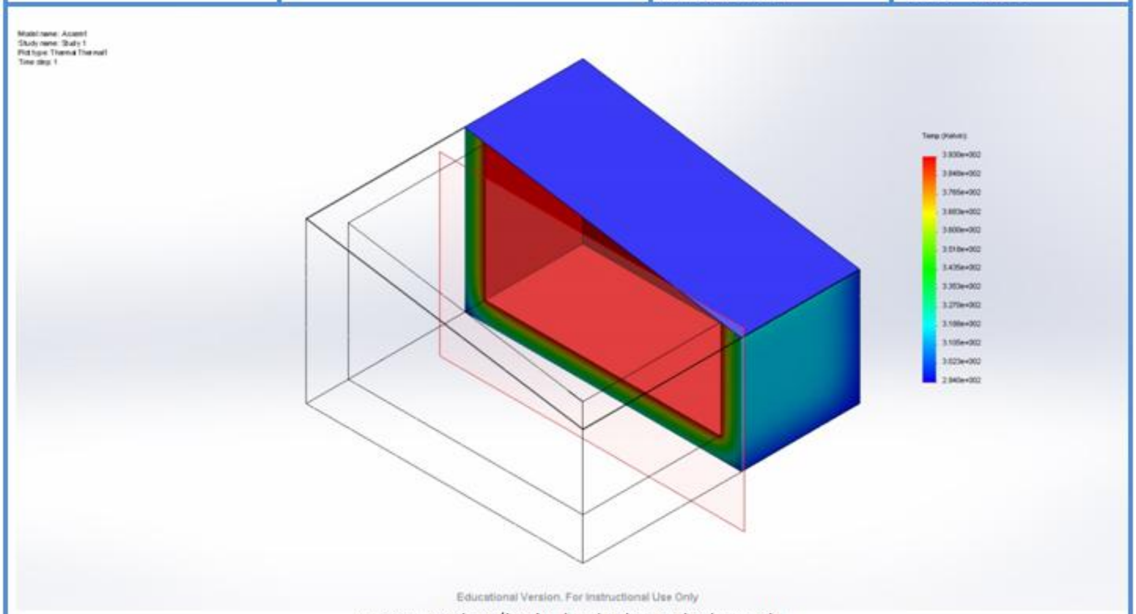


Figure 10. Time versus temperature plot for Metropolia 1 box-type solar cooker

The improvement in insulation of TEp ry's box-type cooker can further be seen on the thermal simulation images shown in Figure 11 and Figure 12,

Name	Type	Min	Max
Thermal1	TEMP: Temperature	294 Kelvin Node: 152963	393 Kelvin Node: 129983



Assem1-Study 1(kari's box)-Thermal-Thermal1

Figure 11. Thermal simulation results for TEP ry box-type solar cooker

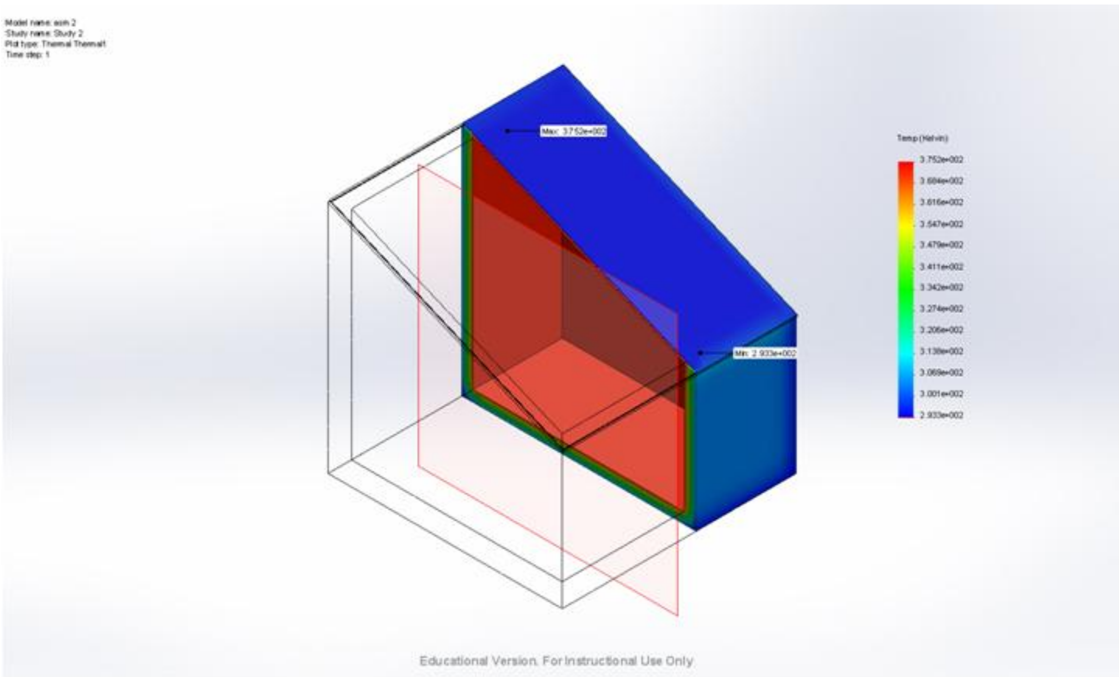


Figure 12. Thermal simulation results for Metropolia 1 box-type solar cooker

To further see the improvement in insulation, let's refer to the close-up thermal images of TEP ry and Metropolia 1 box-type solar cookers generated by SolidWorks Simulation in Figure 12 and Figure 13.

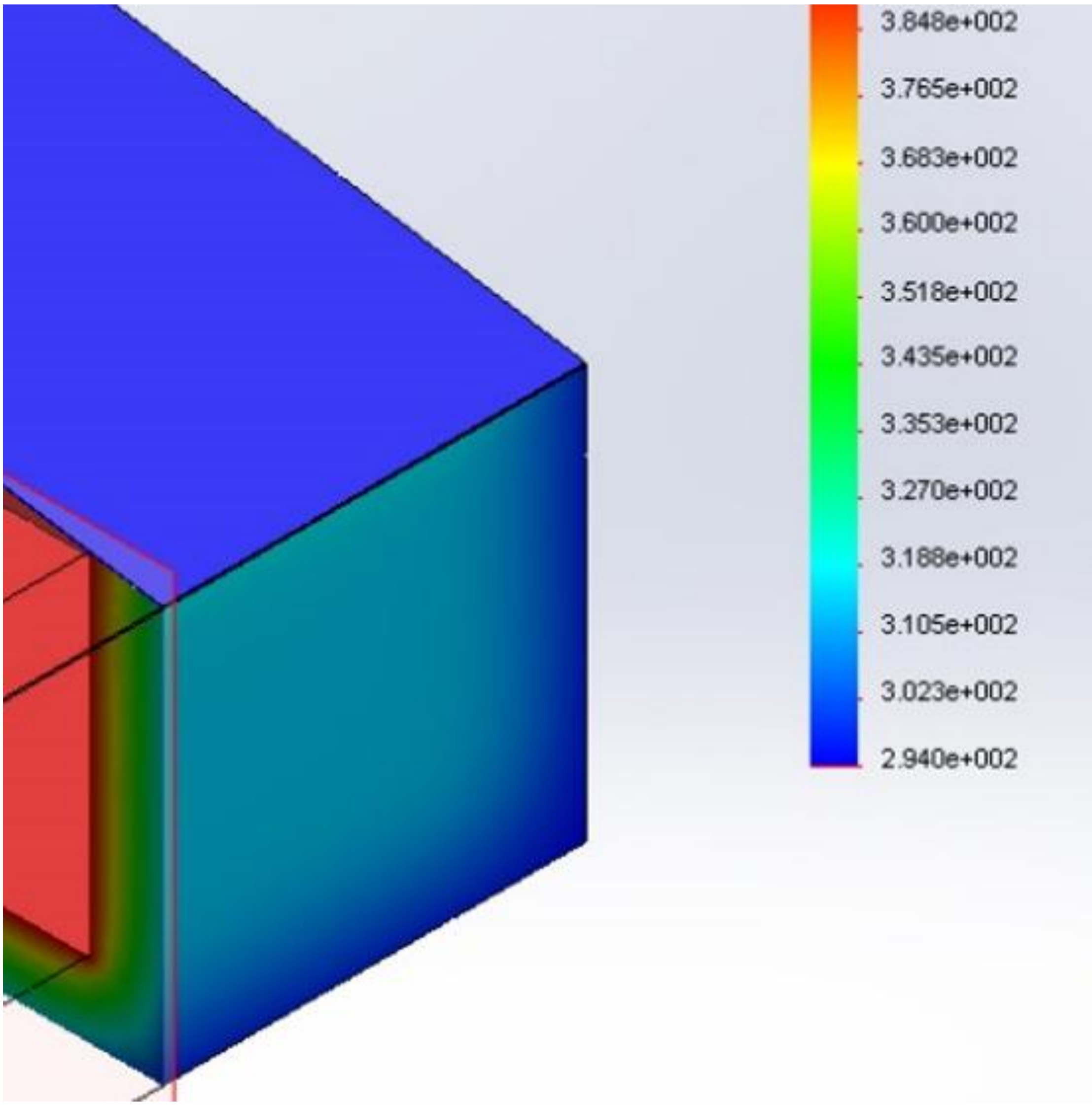


Figure 13. Close-up image of the side of TEP ry's box-type solar cooker

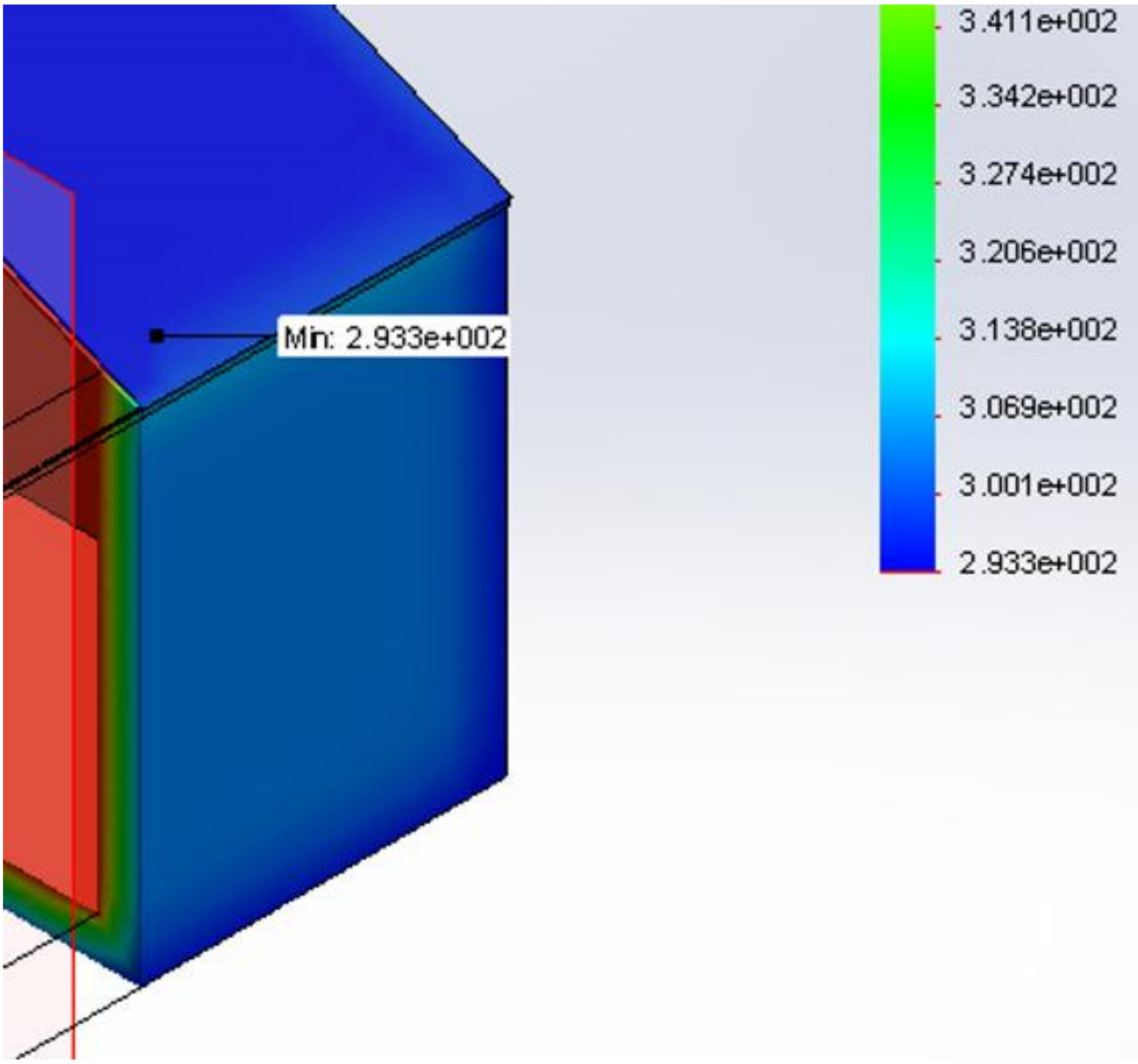


Figure 14. Close-up image of the side of Metropolia 1 box-type solar cooker

Comparing the close-up images for the sides of TEP ry and Metropolia 1 box-type solar cookers on Figure 12 and Figure 13, it can be observed that the outer most layer of the side of TEP ry box-type solar cooker was at a temperature in the range of 3.105e+002 - 3.188e+002 Kelvin, while it was in the range of 3.001e+002 – 3.069e+002 Kelvin for Metropolia 1 box-type solar cooker.

As every factor that affects the performance of a solar cooker was kept the same except for the design in insulation in the two box-type solar cookers, the above readings for the temperature of the sides of the two box-type solar cookers can tell us that heat from the inside of TEP ry's box-type solar cooker to the outside travels faster than it does in Metropolia 1 box-type solar cooker. This, in turn, tells us heat blockage to the surrounding in Metropolia 1 box-type solar cooker is better than heat blockage to the surrounding in TEP ry box-type solar cooker.

3.3 Discussion

This thesis work aimed at improving the heat insulation of a conventional box-type solar cooker. A conventional box type solar-cooker owned by TEP ry was studied and used as a base material to come up with improvement ideas. This section will discuss the meaning of the results obtained, how the results relate to the suggested design improvements and how the results support the design modifications.

Theoretical comparison

In principle, by making a heat transfer study it is possible to estimate the rate of flow of energy as heat through the boundary of a system for example a box-type solar cooker, both under steady and transient conditions. It is also possible that, by making a heat transfer study, one can determine the temperature field of a system under steady and transient conditions, which also will provide the information about the slope and time rate of change of temperature at a range of locations and time. i.e. $T(x, y, z, \tau)$ and dT/dx, dT/dy, dT/dz, $dT/d\tau$ etc. (Kothandaraman 2006)

Heat transfer equations and fundamental laws governing heat transfers that Mathematically characterize the different heat transfers involved in TEP ry's and Metropolia 1 box-type solar cookers were used to theoretically compare the two box-type solar cookers.

Referring to Temperature versus time plots on Figure 9 for TEP ry box-type solar cooker and Figure 10 for Metropolia 1 box-type solar cooker, time rate of change of temperature or slope for TEP ry's box-type solar cooker was a positive value or there was a temperature build up for some time, until the internal box temperature reaches to a temperature of 40 °C and became negative after this indicating a gradual loss of heat to the surrounding until internal box temperature has the same temperature as its surrounding, in this case room temperature or 20 °C over a period of three hours. On the other hand, looking at the time rate of change of temperature on Figure 10 for Metropolia 1 box-type solar cooker a positive slope or a gradual temperature build up was seen until the internal box temperature reaches 60 °C over a period of three hours; this is a very good indication of an improvement in insulation.

Computational verification in SolidWorks Simulation

Computational Fluid Dynamics (CFD) is a state-of-the-art method that applies mathematical equations and computer algorithms to simulate fluid flow and heat and mass transfer in a defined system. Multi-scale and multi-phase phenomena in complex material processing systems can be captured using CFD modelling and simulation tools (Laurentiu, Herve and Nagy 2012).

According to Solidworks steady state thermal simulation carried out on the TEP ry and Metropolia 1 box-type solar cookers, it was seen that while TEP ry's box-type solar cooker outer most layer was at a temperature in the range of 3.105e+002 - 3.188e+002 Kelvin, it was in the range of 3.001e+002 – 3.069e+002 Kelvin for Metropolia 1 box-type solar cooker, this is an indication that the inside of Metropolia 1 box-type solar cooker was about 20 kelvin hotter than TEP ry's box-type solar cooker and insulation improvement design was a success.

Further explanations can be viewed in Appendix 2 which shows the simulation results for the box-type solar cookers in this thesis work.

4 Conclusions and future work

The aim of the project was met to some degree. The plan of achieving better insulation than TEP ry's box-type solar cooker can be said to have been success. The lack of skill in building a product and in using some important software made conducting this thesis project difficult.

According to the results obtained a conventional box-type solar cooker that has a stonewool insulation and single pane glazing performed less efficiently or cooks slower than a box-type solar cooker that has stonewool and polyurethane insulation with a double glazing. Polyurethane insulation mixed with stonewool can maximize the efficiency of box-type solar cookers or is an efficient insulation design; furthermore double-pane glazing can insulate box-type solar cookers better than single pane glazing.

It has taken the author of this thesis more than two months to be able to use the simulation functionality of SolidWorks software. It was necessary to use something to support the experimental results as the experiment largely requires the inclusion of sunlight which was not usually available in this part of the hemisphere; besides, simulation makes it possible to avoid human errors that occur due to lack of skill in building the box-type solar cookers.

This thesis work can be used as a reference material for students who has interest in improving the efficiency of solar cookers, and they might hopefully end up with the most efficient solar cookers in existence mixing this work with the varied and complex vast resources regarding solar cookers.

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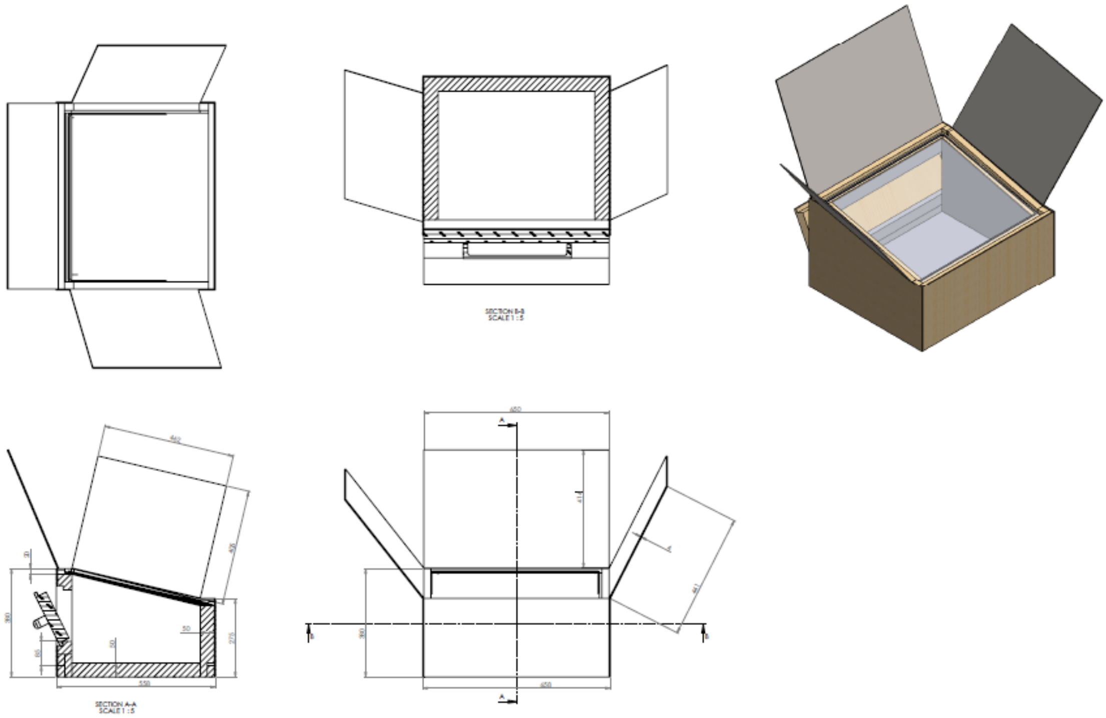
Appendices

Appendix 1. TEP ry's box-type solar cooker SolidWorks CAD generated assembly design



Appendix 2. SolidWorks Simulation generated thermal simulation steps and results

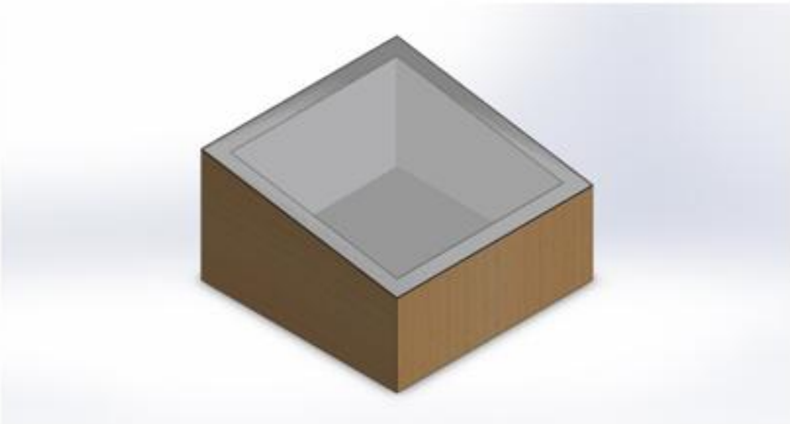
Simulation of Assem1

Date: 10 April 2015

Designer: Solidworks

Study name: Study 1

Analysis type: Thermal(Steady state)



Description

This is thermal simulation and analysis results report generated by SolidWorks Simulation for TEP ry's and its improved version Metroplia 1 box-solar cookers.

Thermal analyses can be executed to find temperature distribution, temperature gradient and heat flowing in a design or model, as well as the heat exchanged between a model and its environment. In this analysis I wanted to find out how the TEP ry's and Metroplia 1 box solar cookers behave when they are subjected to a heat input that led the internal box temperature to a 100 degree celicius and an ambient temperature of 21 degree celicius. Using a color coding that represents the different temperature zones of the models under study I was able to compare the heat retentions of the models.

The models for the box-type cookers were created by SolidWorks CAD and simulated in SolidWorks Simulation which uses SolidWorks CAD software for creating and editing model geometry.

Assumptions

Steady state analysis based on the assumption enough time has passed for heat flow to stabilize.

Model Information

Study Properties

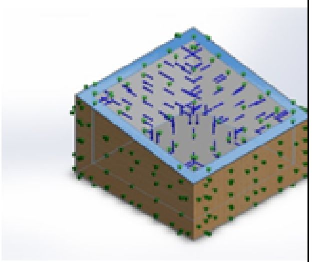
Study name	Study 1
Analysis type	Thermal(Steady state)
Mesh type	Solid Mesh
Solver type	FFEPlus
Solution type	Steady state

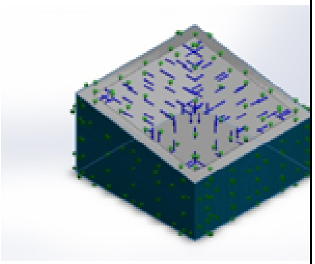
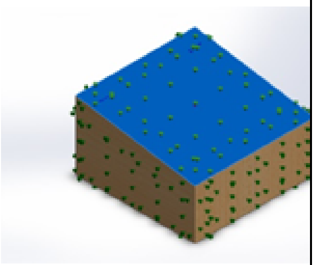
Contact resistance defined?	No
Result folder	SolidWorks document (E:\thermal simulation)

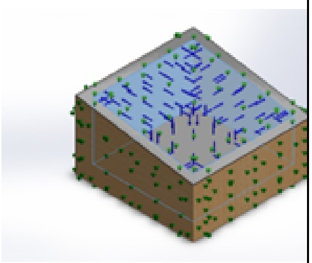
Units

Unit system:	SI (MKS)
Length/Displacement	mm
Temperature	Kelvin
Angular velocity	Rad/sec
Pressure/Stress	N/m^2

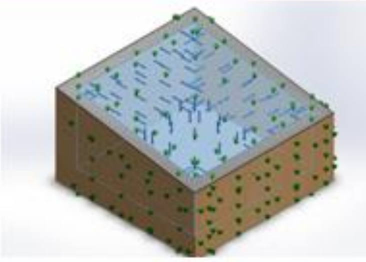
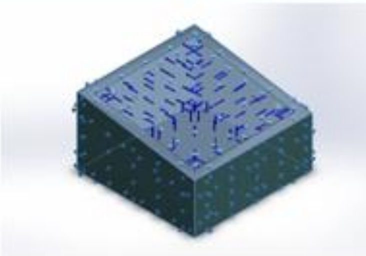
Material Properties

Model Reference	Properties	Components
	**Name:** Rubber **Model type:** Linear Elastic Isotropic **Default failure criterion:** Unknown **Thermal conductivity:** 0.14 W/(m.K) **Mass density:** 1000 kg/m^3	**SolidBody 1(Cut-Extrude2)(insulation-1)** **while selecting material for kari's box insulation, stone wool couldn't be found, some insulation with a similar property was used instead**
Curve Data:N/A		

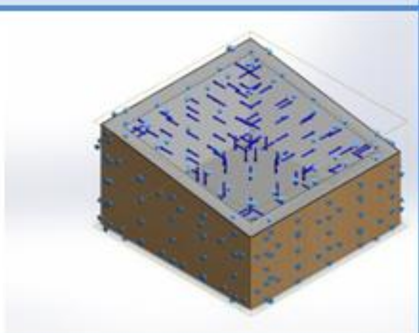
	Name: Balsa Model type: Linear Elastic Isotropic Default failure criterion: Unknown Thermal conductivity: 0.05 W/(m.K) Mass density: 159.99 kg/m^3	SolidBody 1(Boss-Extrude3)(plywood-1)
Curve Data:N/A		
	Name: PC High Viscosity Model type: Linear Elastic Isotropic Default failure criterion: Unknown Thermal conductivity: 0.189 W/(m.K) Specific heat: 1535 J/(kg.K) Mass density: 1190 kg/m^3	SolidBody 1(Boss-Extrude1)(polycarbonate-3)
Curve Data:N/A		

	Name: Pure Silver Model type: Linear Elastic Isotropic Default failure criterion: Unknown Thermal conductivity: 420 W/(m.K) Specific heat: 230 J/(kg.K) Mass density: 11000 kg/m^3	SolidBody 1(Cut-Extrude2)(silver lamination-1)
Curve Data:N/A		

Thermal Loads

Load name	Load Image	Load Details
Tempera-ture-1		Entities: 5 face(s) Temperature: 393 Kelvin
Convec-tion-1		Entities: 6 face(s) Convection Coefficient: 10 (W/m^2)/K Time variation: Off Temperature variation: Off Bulk Ambient Temperature: 294 Kelvin Time variation: Off

Contact Information

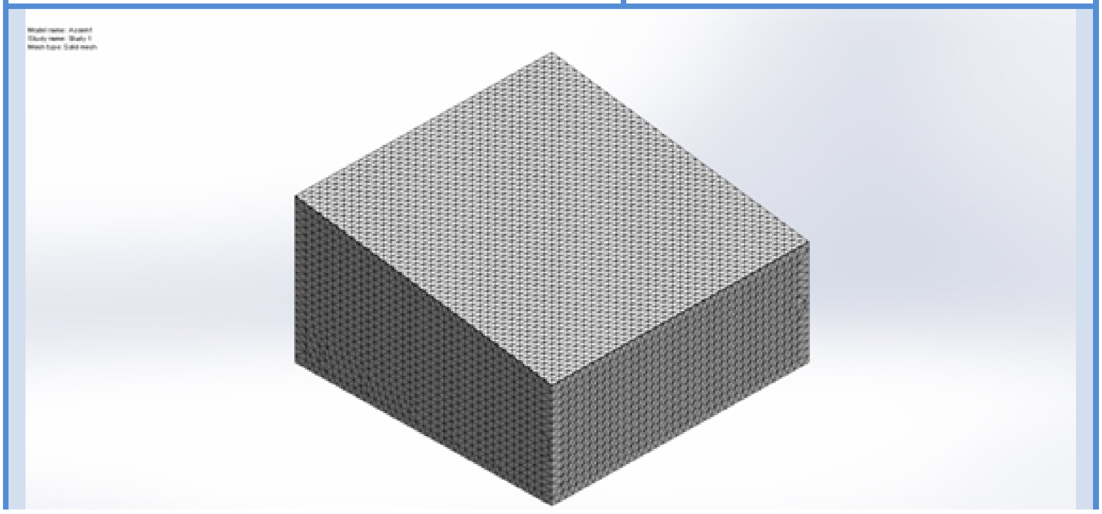
Contact	Contact Image	Contact Properties
Global Contact		**Type:** **Bonded** **Components:** **1 component(s)** **Options:** **Compatible mesh**

Mesh Information

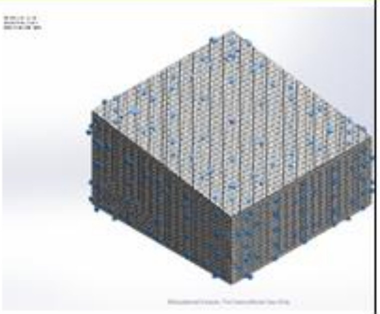
Mesh type	Solid Mesh
Mesher Used:	Standard mesh
Automatic Transition:	Off
Include Mesh Auto Loops:	Off
Jacobian points	4 Points
Element Size	18 mm
Tolerance	0.9 mm
Mesh Quality	High
Remesh failed parts with incompatible mesh	Off

Mesh Information - Details

Total Nodes	177925
Total Elements	115856
Maximum Aspect Ratio	27.691
% of elements with Aspect Ratio < 3	54
% of elements with Aspect Ratio > 10	24.5
% of distorted elements(Jacobian)	0.000863
Time to complete mesh(hh;mm;ss):	00:00:11
Computer name:	C351-05



Mesh Control Information:

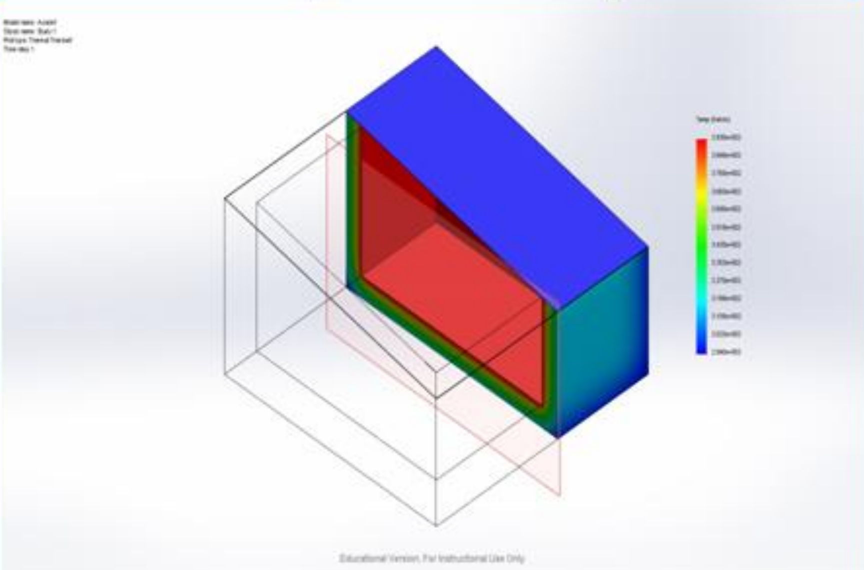
Mesh Control Name	Mesh Control Image	Mesh Control Details
Control-1		**Entities:** 1 Solid Body (s) **Units:** mm **Size:** 27.6845 **Ratio:** 1.2

Sensor Details

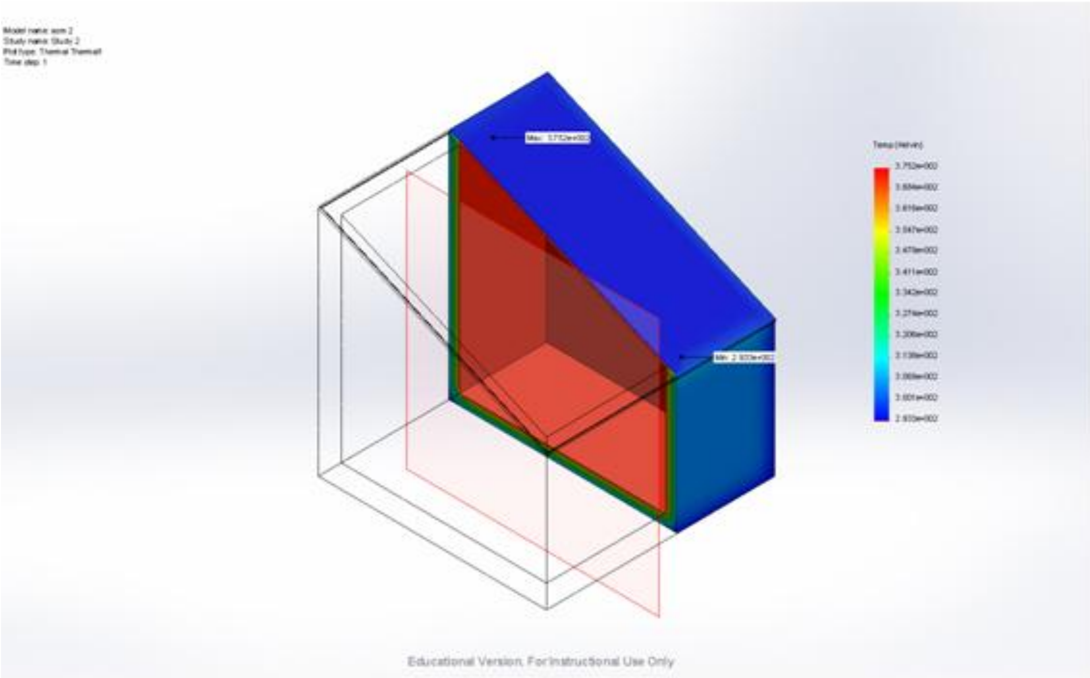
No Data

Study Results

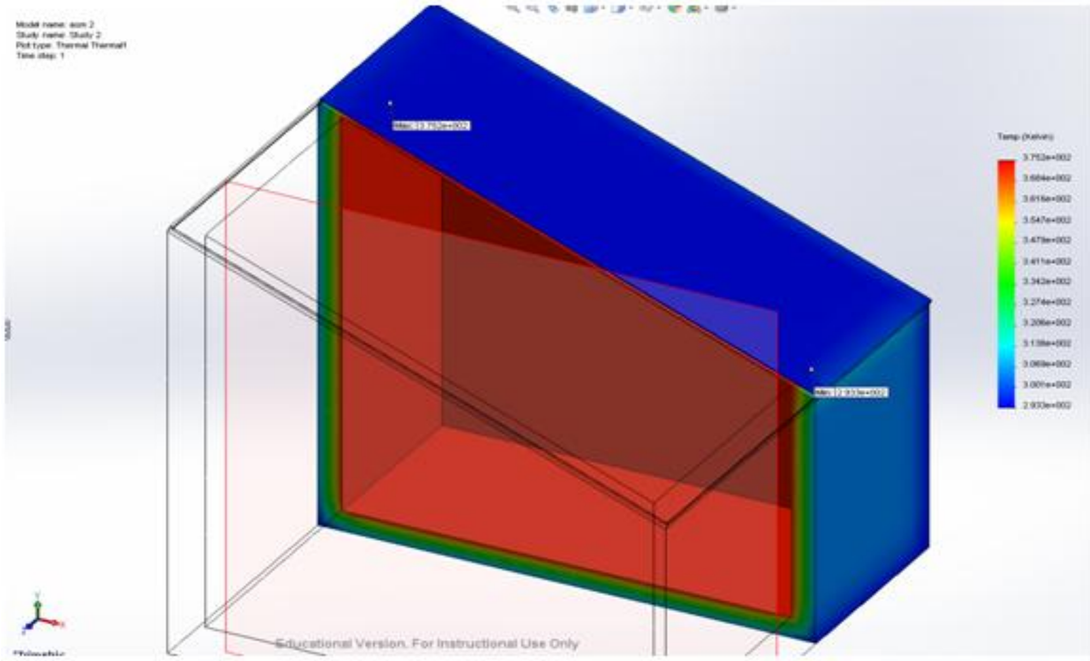
Name	Type	Min	Max
Thermal1	TEMP: Temperature	294 Kelvin Node: 152963	393 Kelvin Node: 129983



Assem1-Study 1(kari's box)-Thermal-Thermal1

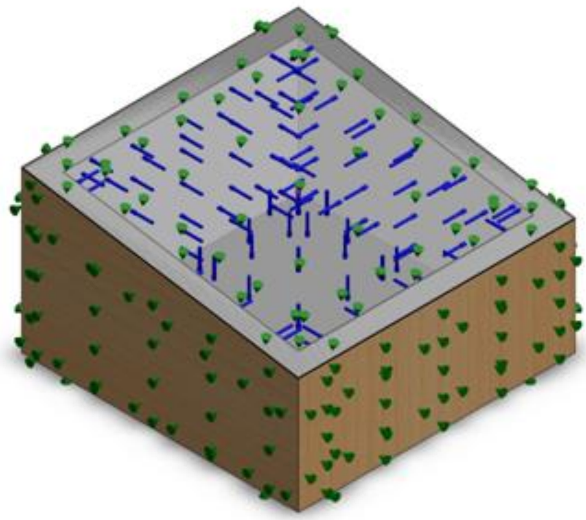


Metropolia 1 box cooker temperature distributions represented as colors

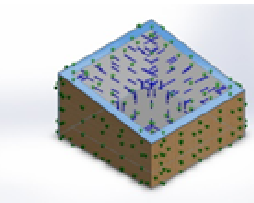
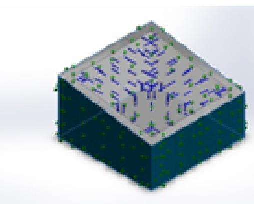


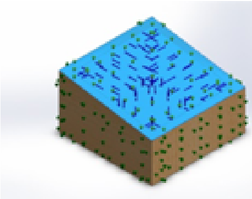
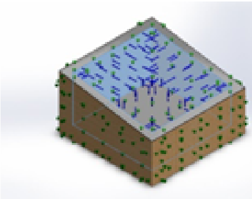
Kari's box temperature distributions represented as colors.

Model name: Assem1:Kari's box

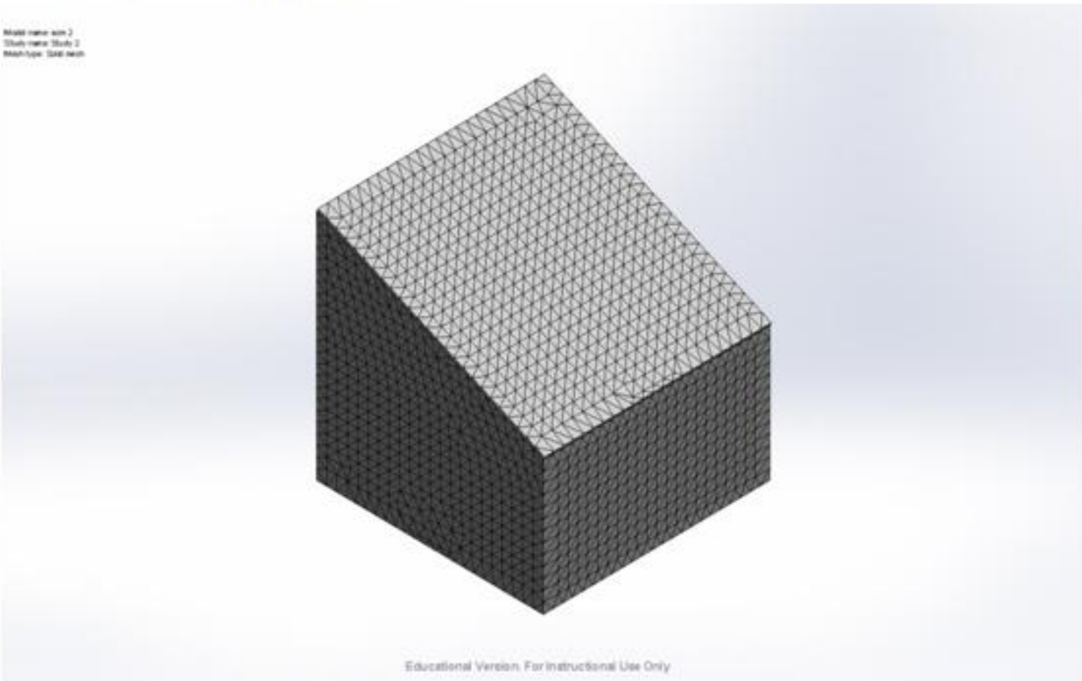


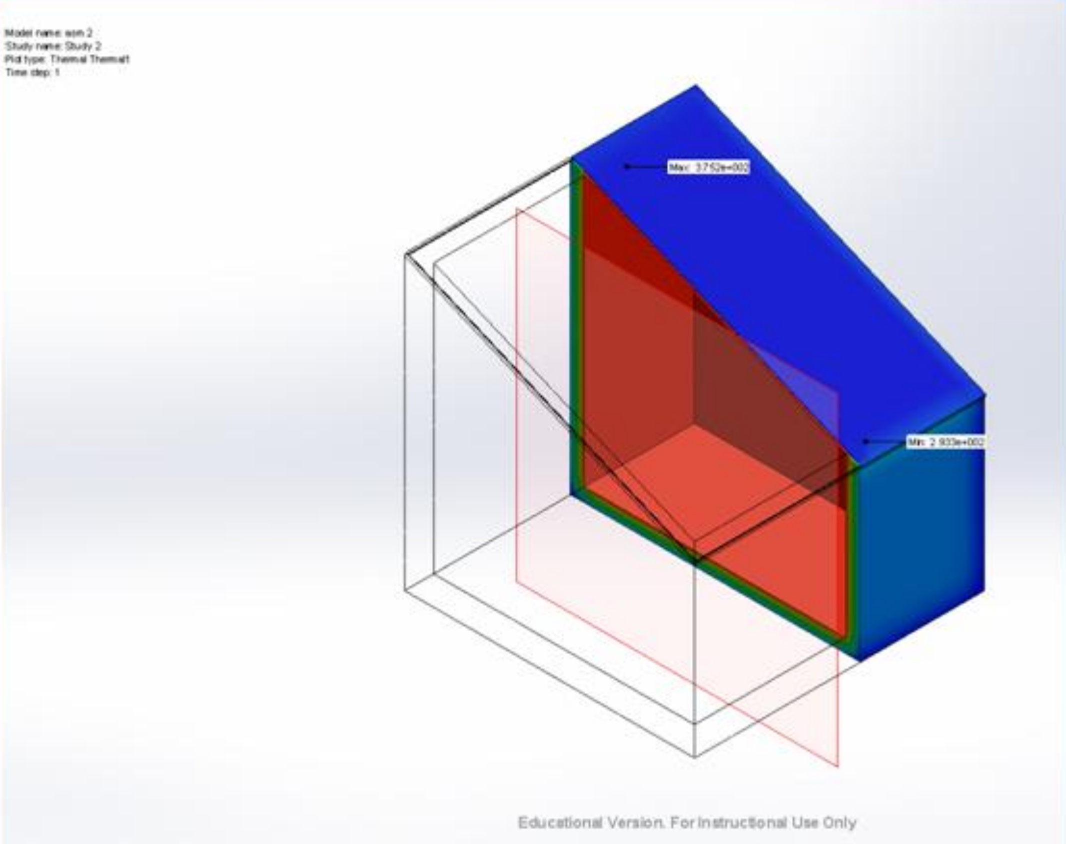
Current Configuration: Default

Solid Bodies			
Document Name and Reference	**Treated As**	**Volumetric Properties**	**Document Path/Date Modified**
Cut-Extrude2 	Solid Body	**Mass:51.884 kg** **Volume:0.051884 m^3** **Density:1000 kg/m^3** **Weight:508.463 N**	**E:\thermal simulation\insulation.SLDPRT** Apr 10 12:59:58 2015
Boss-Extrude3 	Solid Body	**Mass:0.411838 kg** **Volume:0.00257415 m^3** **Density:159.99 kg/m^3** **Weight:4.03602 N**	**E:\thermal simulation\plywood.SLDPRT** Apr 10 12:59:58 2015

Boss-Extrude1 	Solid Body	**Mass:1.04349 kg** **Volume:0.000876884 m^3** **Density:1190 kg/m^3** **Weight:10.2262 N**	**E:\thermal simulation\polycarbonate.SLDPRT** Apr 10 12:54:58 2015
Cut-Extrude2 	Solid Body	**Mass:10.275 kg** **Volume:0.00093409 m^3** **Density:11000 kg/m^3** **Weight:100.695 N**	**E:\thermal simulation\silver lamination.SLDPRT** Apr 10 12:59:58 2015

Meshing for Metropolia 1 box-type solar cooker





asm 2-Study 2-metropolia 1 thermal simulation

Appendix 3: thermocouple used for the experiment

Stainless Steel Temperature Probe

(Order Code TMP-BTA)

The Stainless Steel Temperature Probe is a rugged, general-purpose laboratory temperature sensor. It is designed to be used as you would use a thermometer for experiments in chemistry, physics, biology, Earth science, and environmental science. **Note**: Do not completely submerge the sensor. The handle is not waterproof. Typical uses include the following:

- heat of fusion experiments
- monitoring endothermic and exothermic reactions
- weather studies
- specific heat experiments
- insulation studies

Collecting Data with the Stainless Steel Temperature Probe

This sensor can be used with the following interfaces to collect data.

- Vernier LabQuest® 2 or original LabQuest® as a standalone device or with a computer
- Vernier LabQuest® Mini with a computer
- Vernier LabPro® with a computer or TI graphing calculator
- Vernier Go!® Link
- Vernier EasyLink®
- Vernier SensorDAQ®
- CBL 2™
- TI-Nspire™ Lab Cradle

Here is the general procedure to follow when using the Stainless Steel Temperature Probe:

1. Connect the Stainless Steel Temperature Probe to the interface.
2. Start the data-collection software.
3. The software will identify the Stainless Steel Temperature Probe and load a default data-collection setup. You are now ready to collect data.

Data-Collection Software

This sensor can be used with an interface and the following data-collection software.

- **Logger *Pro*** This computer program is used with LabQuest 2, LabQuest, LabQuest Mini, LabPro, or Go!Link.
- **Logger Lite** This computer program is used with LabQuest 2, LabQuest, LabQuest Mini, LabPro, or Go!Link.
- **LabQuest App** This program is used when LabQuest 2 or LabQuest is used as a standalone device.
- **EasyData App** This calculator application for the TI-83 Plus and TI-84 Plus can be used with CBL 2™, LabPro, and Vernier EasyLink. We recommend version 2.0 or newer, which can be downloaded from the Vernier web site, www.vernier.com/easy/easydata.html, and then transferred to the calculator. See the Vernier web site, www.vernier.com/calc/software/index.html for more information on the App and Program Transfer Guidebook.
- **DataMate program** Use DataMate with LabPro or CBL 2™ and TI-73, TI-83, TI-84, TI-86, TI-89, and Voyage 200 calculators. See the LabPro and CBL 2™ Guidebooks for instructions on transferring DataMate to the calculator.
- **DataQuest™ Software for TI-Nspire™** This calculator application for the TI-Nspire can be used with the EasyLink or TI-Nspire Lab Cradle.
- **LabVIEW™** National Instruments LabVIEW™ software is a graphical programming language sold by National Instruments. It is used with SensorDAQ and can be used with a number of other Vernier interfaces. See www.vernier.com/labview for more information.

NOTE: Vernier products are designed for educational use. Our products are not designed nor recommended for any industrial, medical, or commercial process such as life support, patient diagnosis, control of a manufacturing process, or industrial testing of any kind.

Specifications

Temperature range:		–40 to 135°C (–40 to 275°F)
Maximum temperature that the sensor can tolerate without damage:		150°C
13-bit resolution (SensorDAQ):		
	0.09°C	(–40 to 0°C)
	0.02°C	(0 to 40°C)
	0.05°C	(40 to 100°C)
	0.13°C	(100 to 135°C)
12-bit resolution (LabPro, LabQuest 2, LabQuest, LabQuest Mini, TI-Nspire™ Lab Cradle):		
	0.17°C	(–40 to 0°C)
	0.03°C	(0 to 40°C)
	0.1°C	(40 to 100°C)
	0.25°C	(100 to 135°C)
10-bit resolution (CBL 2™):		
	0.68°C	(–40 to 0°C)
	0.12°C	(0 to 40°C)
	0.4°C	(40 to 100°C)
	1.0°C	(100 to 135°C)
Temperature sensor:		20 kΩ NTC Thermistor
Accuracy:		±0.2°C at 0°C, ±0.5°C at 100°C
Response time (time for 90% change in reading):		10 seconds (in water, with stirring)
		400 seconds (in still air)
		90 seconds (in moving air)

Probe dimensions:	Probe length (handle plus body): 15.5 cm Stainless steel body: length 10.5 cm, diameter 4.0 mm Probe handle: length 5.0 cm, diameter 1.25 cm

This sensor is equipped with circuitry that supports auto-ID. When used LabQuest 2, LabQuest, LabQuest Mini, LabPro, Go! Link, TI-Nspire™ Lab Cradle, SensorDAQ, EasyLink, or CBL 2™, the data-collection software identifies the sensor and uses pre-defined parameters to configure an experiment appropriate to the recognized sensor.

How the Stainless Steel Temperature Probe Works

This probe uses the 20 kΩ NTC Thermistor. The thermistor is a variable resistor whose resistance decreases nonlinearly with increasing temperature. The best-fit approximation to this nonlinear characteristic is the Steinhart-Hart equation. At 25° C, the resistance is approximately 4.3% per °C. The interface measures the resistance value, R, at a particular temperature, and converts the resistance using the Steinhart-Hart equation:

$$T = [K_0 + K_1(\ln 1000R) + K_2(\ln 1000R)^3]^{-1} - 273.15$$

where T is temperature (°C), R is the measured resistance in kΩ, $K_0 = 1.02119 \times 10^{-3}$, $K_1 = 2.22468 \times 10^{-4}$, and $K_2 = 1.33342 \times 10^{-7}$. Our programs perform this conversion and provide readings in °C (or other units, if you load a different calibration).

Chemical Tolerance

The Stainless Steel Temperature Probe body is constructed from grade 316 stainless steel.[1] This high-grade stainless steel provides a high level of corrosion resistance for use in the science classroom. Here are some general guidelines for usage:

- The probe handle is constructed of molded plasticized Santoprene®. While this material is very chemical resistant, we recommend that you avoid submerging the probe beyond the stainless steel portion.
- Always wash the probe thoroughly after use.

Maximum acid exposure time	
1 M HCl	20 min
2 M HCl	10 min
3 M HCl	5 min
1 M H_2SO_4	48 hours
2 M H_2SO_4	20 min
3 M H_2SO_4	10 min
1 M HNO_3	48 hours
2 M HNO_3	48 hours
3 M HNO_3	48 hours
1 M CH_3COOH	48 hours
2 M CH_3COOH	48 hours
3 M CH_3COOH	48 hours
1 M H_3PO_4	48 hours
2 M H_3PO_4	48 hours
3 M H_3PO_4	48 hours

[1] Grade 316 stainless steel has a composition of 0.08% carbon, 2.0% manganese, 0.75% silicon, 0.04% phosphorus, 0.03% sulfur, 16-18% chromium, 10-14% nickel, 2-3% molybdenum, and 0.1% nitrogen.

- The probe can be left continuously in water at temperatures within the range of –40° to 150°C. Continuous usage in saltwater will cause only minor discoloration of the probe, with no negative effect on performance.
- You can leave the probe continuously in most organic compounds, such as methanol, ethanol, 1-propanol, 2-propanol, 1-butanol, n-hexane, lauric acid, paradichlorobenzene, phenyl salicylate, and benzoic acid. The probe should not be left in n-pentane for more than 1 hour.
- The probe can be left in strong basic solutions, such as NaOH, for up to 48 hours, with only minor discoloration. We do not recommend usage in basic solutions that are greater than 3 M in concentration.
- The chart provides the maximum length of time we recommend for probe exposure to some common acids. Probes left in an acid longer than these times may bubble and/or discolor, but will still be functional. We do not recommend probes be left to soak in any acid longer than 48 hours.

Optional Calibration Procedure

In most cases, the Stainless Steel Temperature Probe will not need to be calibrated. It is calibrated extremely well before it ships. However, if the need arises to calibrate the sensor, and you are using Logger *Pro* 3.3 or newer, the sensor can be custom-calibrated. See www.vernier.com/til/1310 for more information. **Note**: this can only be done on computers, and cannot be done from DataMate, EasyData (calculators), DataQuest, or the LabQuest App.

Warranty

Vernier warrants this product to be free from defects in materials and workmanship for a period of five years from the date of shipment to the customer. This warranty does not cover damage to the product caused by abuse or improper use. Broken clips do not compromise the performance of the sensor. For proper storage, see www.vernier.com/til/2377/

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