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Thermal analysis of a directly heated solar heat storage

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Submission date: October 2014
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Masters Thesis

Thermal analysis of a directly heated solar heat storage

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A thesis submitted in fulfilment of the requirements for the degree of Master of Science

October 2014

NORWEGIAN UNIVERSITY OF SCIENCE AND TECHNOLOGY

Abstract

Faculty of Engineering Science and Technology
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A solar heat storage was designed and simulated. The Scheffler reflector is used to concentrate sun rays that are used to charge a thermal storage.

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Abbreviations

TES	**T**hermal **E**nergy **S**torage
LHS	**L**atent **H**eat **S**torage
SHS	**S**ensible **H**eat **S**torage
PCM	**P**hase **C**hange **M**aterial
NAFEMS	**N**ational **A**gency for **F**inite **E**lement **M**ethods and **S**tandards

Symbols

a	distance	m
P	power	W (Js^{-1})
T	Temperature	°C
t	Time	(s)
h	Sensible Volumetric Enthalpy	(J/m3)
H	Total Volumetric Enthalpy	(J/m3)
k	Thermal Conductivity	(W/mK)
ω	angular frequency	$rads^{-1}$

Chapter 1

Introduction

1.1 Background

NTNU has previously been involved in the NOFU project. The project consist of five African universities and NTNU with the task to develop a heat storage for vapour based solar concentrators. THe university still do contribute to the global solar community through several projects. The main area of focus is to use solar power to produce food and hot water. The projects has ranged to focus on pure technical to pure social aspects of solar cooking.

This thesis belongs to the technical ones and has the purpose of developing a heat storage by numerical simulation. The idea is to use a directly heated solar storage with fins as heat conductors and solar salt as heat storage.

In this report it is investigated if a finned latent heat storage can be used in combination with a Scheffler reflector system. The heat storage is to use solar salts as storage medium.

1.2 Motivation

The data from the World Health Organization Household air pollution and health report can be summarized:

- Today, about 3 billion people cook over open fires and simple stoves with biomass.
- Over 4 million people die prematurely from illness because of the household air pollution caused by cooking over biomass.
- Over 50 percent of premature child deaths of children under 5 are caused by inhalation of soot caused by cooking over biomass.
- 3.8 million annual deaths are due to noncummunicable preventable diseases caused by household air pollution.

It is evident that a low or non polluting alternative to cooking over biomass will save lives. Another way solar cookers save people is by empowering them by making them less dependant on biomass. The collection of fuel in most cases takes time and effort that could rather could be spent on getting an education or generating income.

Other reasons for developing solar ovens are often accounted to environmental problems, imminent energy shortage and the high cost of energy and new powerplants.

The existing solar ovens have shown both good dissemination and bad. The Scheffler reflector system is one of them. Different societies has different needs. This means that most likely a universal solar cooker still needs a lot of development, if that is what one wish. In the meantime addressing individual needs seem to be the trend among solar cooker developers. So is the case for this thesis as well.

1.3 Limitations of study

The aim of this study is to investigate how feasible a finned solar salt heat storage used in combination with a Scheffler reflector is for cooking purposes. The method is by computer simulation of the heat storage. Assumptions for the heat input to the heat storage and for the wanted output by the consumer is based on literature and stated in the appropriate part of the thesis. The Scheffler refector is briefly introduced, and the emphasis is put on the results of the simulation of the heat storage.

1.4 Report outline

- Chapter 1: Introduction to the thesis topic
- Chapter 2: Theory and introduction to the Scheffler reflector system
- Chapter 3: Description of the simulation cases
- Chapter 4: Discussion and results
- Chapter 5: Conclusion
- Chapter 6: Recommendations on further work

Chapter 2

Theory

2.1 Solar cookers

Solar cookers are generally divided into two types; direct type cookers and indirect type cookers. The direct type commercially most successful subgroups are box type and concentrating type. The indirect cookers come in versions with a flat plate collector, with evacuated tube collector, with parabolic concentrators, or spherical reflectors.

Some solar cookes use direct heat, some heat water which again heat something else like a PCM. The job for the solar equipment is also wide in use. Among them are pasteurization cleaning of medical equipment using steam production for bread baking or frying.

Despite the long effort of developing solar cookers, improvements and tailoring for individual needs is still relevant. Some goals still driving the development include:

- Increase dissemination.
- Making it easier to use.
- To be able to cook several hours after peak sun hours.

Solar cookers can be especially effective in countries along the equator since they receive significant amounts of solar radiation for a better part of the day peaking right around the midday periods. Therefore, solar radiation can be easily used to cook a midday lunch in a reasonable time.

Cooking makes up a major part of the global energy consumption. In the developing world a lot of the energy consumption is non-commercial. In rural areas non-commercial fuel is firewood, agricultural waste and dung. In the urban areas kerosene and liquid petroleum gas makes up some of the non-commercial fuels.

The box type solar oven has its limitations. These cookers cannot be used during partly cloudy days or in late evening hours. If the storage of solar energy can be implemented the solar oven will increase its useability. A solar cooker able to cook during partly cloudy or when the sun is gone will increase the utility and reliability of it.

Box cookers rarely have storage capability, yet there are some. A solar cooker without energy storage is incapable of storing the heat energy for later use, deeming it unusable on partly cloudy days or long after peak sun hours. It is then that people who already use solar cookers return to the old way by using non-commercial fuels such as firewood.

When this happens, we are back to square one. A solar cooker should be able to cope with non-optimal solar conditions. The challenges then raised to increase dissemination are:

- Reduce/eliminate the need of firewood
- Free up time for user to do other things
- Improve air quality and by that reduce respiratory impact of cooking
- Food preparation usually does not happen during peak sun hours

Heat storage is of huge interest because it enables all these things. By storing heat in a phase change material one is less dependent on perfect sun conditions, since it can stay warm for such a long time.

The general way in which we can improve a solar heat storage is to look at the thermodynamics. Improvement of the performance of a solar cooker is done by improving the heat transfer design. Mechanisms like radiation, conduction and convection is manipulated to engineer the heat transfer consciously.

Important qualities of a heat storage:

User-friendliness	Be able to cook with the heat output.
Convenience	Maintain a high heat storage capability and still have a low re-charge time.
Cost	Be able to develop and distribute on a large scale.
Safety	Make it safe to use in the presence of children.

The goal would be a solar cooker which can perform as a conventional direct solar cooker, only during non-optimal conditions. In addition, a solar cooker reaching high performance would need to be developed and used in a sustainable way.

2.1.1 Solar Radiation

The sun has a surface temperature of about 6000 K. The solar radiation reaching the surface of the earth can cover the human energy need ten thousand times over. The energy penetrating the atmosphere is subject to diffusion and absorption. This will depend on the angle of radiation when the sun rays hit the atmosphere. This means that we will not receive the same amount of solar radiation all over the surface of the earth, there are latitudinal, seasonal and daily variations.

The weather impact how much solar radiation hits a spot on the surface of the earth. On cloudy days you will not experience as much sun. Solar radiation ranges from 0 to 1500 $\frac{W}{m^2}$. Under less favorable conditions the solar radiation can be less than a quarter of maximum levels.

2.1.2 Scheffler reflector system

Fixed focus concentrators developed by Wolfgang Scheffler have proved to be a milestone in the solar oven community.

Whereas most solar cookers requires the chef to stand outside in the sun, the Scheffler reflector system enables the cooking to happen inside. This set some constrains to the orientation and design of the kitchen building.

The Scheffler reflector system is not only used for cooking. It can be used for steam generation and many other applications.

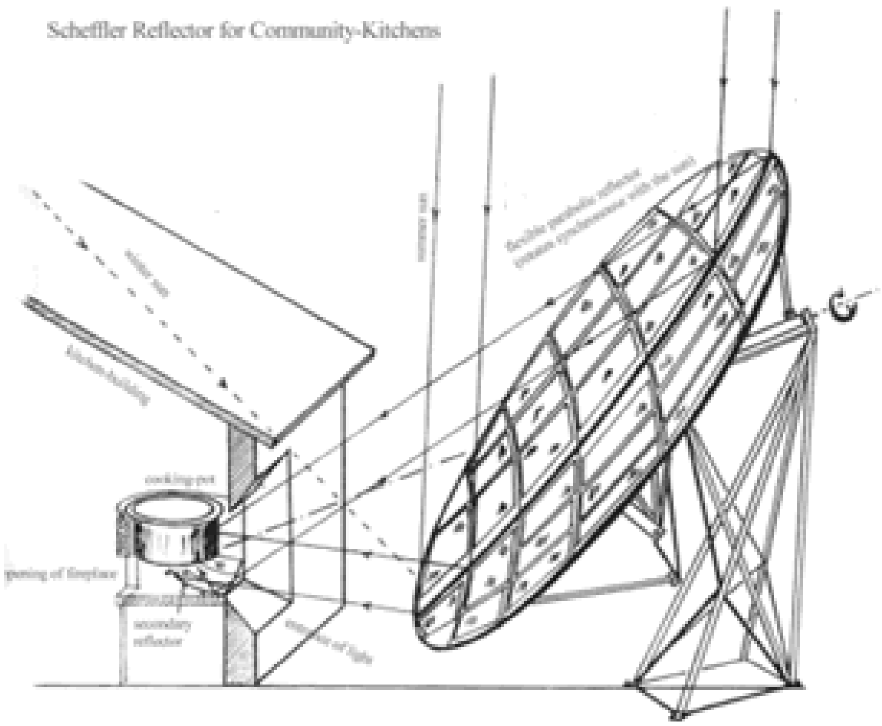


Figure 2.1: jimmymcgilligan

The job of a reflector is stopping the sun, focusing the radiation and pointing it to the wanted area. The Scheffler concentrator is not an ordinary parabola, it is made from the lateral part of a paraboloid. [Munir] This makes it easier to adjust and more flexible with regards to geometric constraints. The ability of bending and flexing is another special feature of the Scheffler reflectors.

There are 16 m^2 concentrators commercially available. Up to 60 m^2 reflector have been built for public institutions. The 16 m^2 concentrators provide 5kW of thermal heat at focus on a normal day. For family use the 2 m^2 and 2.7 m^2 are appropriate. A 2.7 m^2 reflector can typically bring 1.2 liter of water to boiling point within 10 minutes. The bigger reflectors are all used to produce steam, either for cooking of for industrial processes.

Scheffler reflectors were specially developed with the aim to assist regions which has less energy at therri disposal, but have abundant sunlight.

About half of the power of the sunlight which is collected by the reflector becomes finally available in the cooking vessel.

The Scheffler concentrator has unrealised potential application in domestic and industrial configurations. [Munir]

Industrial processes using heat at a mean temperature level include: sterilizing, extraction, pasteurizing, drying, solar cooling and air conditioning, hydrolizing, distillation and evaporation, washing and cleaning, and polymerization. [Munir]. The temperature range of these processes lie between 60 and 280 degC. [Kalogirou, 2003]

A normal setup would be a outdoor reflector and an indoor cooker. The storage is inside the wall of the builing or just inside the wall. The cooker needs to be in a height convenient for cooking, which will decide the position of the reflector. The reflector needs to be adjustable and easy to use.

Wolfgang Scheffler has at some point estimated that the installed area of Scheffler reflectors is about 8000 m^2. This means there are some designs out there we can learn from.

Several ways of using the Scheffler concentrator for cooking purposes has been investigated by others before:

- Multistage evaporators
- Heating air and bed rock

- Heating water
- Direct heat

2.1.3 Success stories

Production of agave sirup in Mexico.

Gregor Schapers wrote in 2009 about agave syrup production in Mexico. Solar cooking is a new type of cooking in Mexico. They first tried with the SK-14 solar cooker. It meant they had to cook outside, which proved impractical, so they went back to using gas stoves. After the Scheffler reflectors were installed they could move solar cooking inside. The only difficulties they experienced were adjusting the reflector. The Scheffler reflector made agave syrup has a superior quality to the biogas cooked because of the more gentle heating.

Swiss GloboSol

Globosol has cooked food for festival attendees for more than 10 years using solar cooking. The pancakes are made on a tin based heat storage using a Scheffler reflector. During intermittent sun conditions the melting of tin as a PCM makes up for the loss of heat input to a certain degree. Days with rain all the time requires other means of cooking. The cooking facility has been used 20 times each year serving up to 250 pancakes each day. Setting up the Scheffler dishes requires training. [Goetz solar kitchen]

Solar community bakery in Argentinian Altiplano.

The Scheffler reflector developed for the Argentinian bakery was made to protect the sparse vegetation. The reflector has an area of 8 m2. The 200 liters oven reach temperatures up to 350 degC with the power imput of 3 kW. The oven has a sensible heat storage in a pebble bed and a zic-zac receiver. An immense amount of fuel is saved. " [1]

Solar steam sterilizers for rural hospitals in India.

A 10 m2 Scheffler reflector is used together with an iron block to produce steam out of water. The reason for using solar power is the high cost of conventional fuel and the unreliability of the electricity grid. Most rural hospitals in India are supplied by diesel generators. Steam production is the main energy consumer. The focal point has heat resistant glass to reduce convection losses. The absorber area is closed off by an insulated lid during night. 67 liters of steam can be produced 3 to 4 times a day. [2]

Development of a solar crematorium. In India most people are cremated on an open woodpile. Trials for a solar powered crematorium were performed by Wolfgang Scheffler during the winter 2004-2005. After experimenting with different Scheffler reflector configurations they were able to reach 900 degC inside the cremation chamber. This design can save 200 to 300 kg of wood used for each cremation. [3]

Nan cooking in Afghanistan.
The NGO Afghan Renewable Energy Center has made the Afghan village of Bedsmochk into a solar energy model. This model can be spread over the neighbouring municipalities and beyond. Among the things that has been done is the introduction of the Scheffler reflector. The aim of this is to alleviate women from the hard work collecting firewood, and to keep them form inhaling poisonous gases when cow dung is burned. The Scheffler reflector is on par compared to the traditional Tandur oven when it comes to nan production. The social structure in the villages will not allow for them to share a reflector, and the reflector is to costly for single households. It was concluded that this is only suitable for institutional cooking. [6]

Marmelade production in Argentina. CEDESOL Ingenieria has made a Scheffler reflector based marmelade production facility in Argentina. The area of the reflector is 4,5 m2 and it is equipped with a clockwork tracking mechanism. A lift has been installed to raise the cooking pot 160 centimeters above ground level. During periods with lack of sun a conventional gas cooker is used. The experience achieved producing marmelade has been expanded to tropical fruits, turning them into jam, marmelades and stewed fruits. The break even of the Scheffler reflector investment will be reached within 6,5 years. [5]

In all the above mentioned projects we have seen the impact of the Scheffler reflector. Many projects have socioeconomic effects by improving production processes and making them decentralized, other have positive effect on respiratory health by eliminating nasty exhaust from burning firewood.

2.2 Heat transfer

Heat transfer is the movement of energy due to a temperature difference. It is possible to enhance the qualities we are looking for by altering the heat transfer. Always keeping the governing laws in mind is a good way to make sure the end product will work as it is supposed to. Solar ovens are subject to the same heat transfer laws which govern all heat transfer.

2.2.1 Conduction

Conduction may be viewed as a transfer of energy from the more energetic to the less energetic part of a substance due to interactions between particles. It can be explained by considering a gas without bulk motion. The gas has energy related to random translational motion, internal rotational and vibrational motions of the molecules. [8]

2.2.2 Convection

Convection comprise to mechanisms of heat transfer. One is related to random molecular motion, the other to bulk motion of the fluid. When a large number of molecules moves together, with a temperature gradient present, contributes to heat transfer. [8] Natural convection is transfer of energy in fluids, usually after mixing one fluid with unequal temperature distribution.

2.2.3 Radiation

Radiation does not require require the presence of a medium. Bodies at non-zero temperature emits energy, radiation. Bodies emit and receive thermal radiation. Some of the energy is absorbed in the body and part of it is reflected. [8]

2.2.4 Focal area

The focal area of direct heat solar ovens has been subject to a lot of research. The focal area is necessarily an exposed highly conductive part of the solar oven. The heat storage rate then is highly dependent on wind speed. The reflected rays from the reflector form an image of a fintie size. The receiver size should not be much bigger than this image size.

To avoid unnecessary losses one should provide insulation to most of the storage and leave a small area for receiving solar rays.

Absorbent cover is a good option to avoid thermal losses from the receiver. It will reduce convective and radiation heat losses with minimal attenuation of the incident solar radiation.

2.3 Energy storage systems

Energy can be stored by sensible heat in a liquid or a solid. Or it can be stored as latent heat, as chemical energy or as products in a reversible chemical reaction. When using a PSM the storage volume can be significantly reduced.

To store heat efficiently for later use a thermal energy storage (TES) can be used. It will keep the heat during intermittent sun conditions and make it possible to cook long after sun peak hours.

A TES for solar cooking has to be reversible and rechargable. In general, TES are used for both hot and cold storage. We separate between daily and seasonal storages. The daily storage has to be charged every day to be of any use. A seasonal storage can melt a large amount of PCM during the hot season and then release it during a colder season.

The capacity of a PCM medium can be written like this [**?**]:

$$Q = \int_{T_i}^{T_m} \mathrm{m} C_p \, \mathrm{d}T + m a_m \Delta h_m + \int_{T_m}^{T_f} \mathrm{m} C_p \, \mathrm{d}T$$

$$Q = m[C_{sp}(T_m - T_i) + a_m \Delta h_m + C_{lp}(T_f - T_m)]$$

where Q is the quantity of heat stored, m is the mass of PCM, C_{sp} is the average specific heat between T_i and T_m, T_m is the melting temperature, T_i is the initial temperature, am is the fraction melted, ?hm is the heat of fusion per unit mass, C_{lp} is the average heat capacity between T_m and T_f, and T_f is the final temperature. [**?**]

The container shall be cylindrical.

2.3.1 Sensible

Sensible heat is stored energy in an object by raising its temperature. You can think of it as the temperature raise in stone, metal, earth, air, oil sand or water. It can be expressed in a simple equation like this:

$$Q = mC_p\Delta T = \rho V C_p \Delta T$$

Specific heat capacity is denoted by the small C_p.

Gases have a very low heat capacity, and are therefore inappropriate for sensible heat storage. A heat storage need to be designed such that air pockets do not form during the expansion and retraction of the solar salt.

Sensible heat is a common way to store heat. In household water tanks the water is heated and stored in the tank making use of the sensible heat capability of water. You can sense that the water is hot when touching it. It is a very simple mode of storing thermal energy. Sensible heat is also easy to engineer as the heat capacity very often is linear with respect to temperature.

When dealing with phase change sensible heat get replaced by latent heat within the phase change temperature region.

2.3.2 Latent

The heat supplied during melting is called latent heat. Latent heat is within the phase change temperature region. The object might go through a massive increase in stored energy while the temperature increases at a lower rate comparing with the sensible temperature region. The phase change can sometimes take place at constant temperature. This gives the ability to store or release a big amount of thermal energy over just a small temperature range.

The latent heat storage material needs to be carefully selected. The melting temperature, the solidification onset, the sensible heat need before melting onset, storage capacity, repeatability all has to be engineered. By choosing the correct material one can store a large amount of thermal energy in the wanted temperature range. Latent heat is volume saving and weight reducing for a specific amount of energy.

A lot of effort is put into latent energy development as it can be key to be able to store excess energy that would otherwise be wasted. A latent storage can bridge the gap between energy generation and consumption.

Compared to sensible heat latent heat is weight saving. Latent heat system is lighter and has a lower volume than sensible for a given amount of energy.

Another advantage of the latent heat storage has the capacity to store energy at a nearly constant temperature which correspond to the phase transition temperature of the phase change material.

2.3.3 Fins

As we know, most PCMs have unacceptably low thermal conductivity. This leads to slow charging and discharging rates, hence heat transfer enhancement techniques are required.

In general a fin is a geometry to enhance heat transfer. The fin extends from a solid into the adjoining fluid to enhance heat transfer. One of the main criteria for using fins is wether one side has a clearly higher heat conduction than the other. [9]

Other ways to enhance heat transfer includes bubble agitation, insertion of metal matrix into PCM, using PCM dispersed with high conductivity particles, micro-encapsulation of the PCM.

In the heat storage field of research most of the heat enhancement has been done by implementing fins. The fins are inserted into the phase change material to enhance the heat conduction. The reason for selecting fins are:

- Simplicity
- Ease of fabricatoin
- Low cost

The use of finned tubes makes sense because radiation energy has to be evenly distributed throughout the heat storage, and transferred evenly to the whole cooking surface.

In "Numerical simulation of a latent heat thermal energy storage system with enhanced heat conduction" Mussard develops a theoretical model based on enthalpy formulation and fully emplicit FDM to predict the one- and two-dimensional behaviour of a latent heat energy storage system. It was found that fins significantly increase the rate of melting of the PCM. The effect of low thermal conductivity of the PCM can be counteracted by using fins.

2.4 Phase change material

Phase change can happen in four ways. From solid to solid, from solid to fluid, from fluid to gas, from solid to gas. The most typical way in thermal energy storage is solid-fluid phase change. The fusion enthalpy is then often mentioned as melting enthalpy or melting heat. The equation shows...

Phase change materials allows for storage of latent heat. During the phase change the PCM stores a lot of heat that can be extracted later. A heat storage PCM for solar cookers needs to be designed such that:

- Storage and depletion is reversible.
- Enough storage capacity.
- The phase change happens at the desired temperature range.

- The heat input and output happens at acceptable rates.

A lot of reasearch has been done on phase change materials. Despite this, there are no applicable standard to evaluate the PCMs. A unified platform would allow for comparison and knowledge gained from one experiment to be applied to another.

Research on phase change materials was pioneered in the 1940s. It was a new wave of attention during the energy crisis in the 1970s and continued into the 1980s, especially on solar heating systems. The research is broad and productive. Both on solving specific problems and the study of the characteristics of new materials. Mentioned by many researchers is the low thermal conductivity in many PCMs. This leads to low charging and discharging rates.

Heat transfer analysis of phase change processes is complex. The solid to liquid boundaries moves depending on the speed of melting of solidification. The boundary position is not known and is part of the solution to the heat transfer problem.

As menitioned in the list above, the application of the PCM is dependent on under what temperature the phase change happens.For the heat storage designed in this thesis the PCM chosen melts between 210 to 220 degC.

For the application in solar cookers a PCM should be available at large quantities for a low cost.Further, it should not contain any poisenous, flammable or explosive components. The PCM should not be corrosive to the container it is stored in. During solidification it should not show any subcooling, as this will affect the heat output. Density changes in the PCM should be kept small to facilitate a simple heat storage geometry.

To make sure a PCM has enough storage capacity and keeping a reasonable thermal conductivity, the amount of PCM has to be limited. By choosing a PCM with high latent heat of fusion per mass one can save oneself from using a too large heat storage. A large heat storage will give higher demands for heat transfer, which in turn make heat losses a bigger issue. An efficient heat storage also require the PCM to have high specific heat, so that a large amount of sensible heat can be stored as well.

The PCM cycle evolves like this:

1. In the beginning of the heating the PCM is solid. Heat that is supplied will increase the temperature of the storage. Pure conduction.
2. The second conduction regime is entered when heat is transferred purely by conduction, but the solid to liquid interface has just begun.
3. Thirdly the thickness of the melt layer has increased a lot. This results in two separate phases of solid and liquid.
4. The convection regime starts (buoyancy). Most of the solid is melted and liquid core temperature distribution depends on geometry and not time.

2.5 Numerical method

When phase change material has been chosen, it is important to decide heat storage geometry and the thermal parameters for the container demanded for a certain amount of phase change material. One way to do this is by numerical simulation.

The COMSOL Multiphysics software make use of the Finite Element Method (FEM). It translates all the physics into numerical equations and solve them on a mesh which represent the geometry. For this to be possible, the algorithms are deployed in a solver who need a mesh, initial conditions and boundary conditions.

FEM approximate a solution over the mesh, by assigning matrices to each node in the nodal network. The element method does not attain the exact solution, but a set of functions which approximates the solution.

2.5.1 Meshing

A problem start with a geometry, in this case a heat storage. To extract results from the physics involving in the problem a mesh needs to be deployed over the geometry. The mesh is full of nodes connection the differenth paths of the mesh. The calculation is done only on the nodes and the rest of the solution is interpolated to give the full picture of what is going on. A dense mesh will detect anomalies that a coarse mesh can not detect. The mesh is so important for a good result that it is not uncommon for CFD companies to employ designated mesh engineers.

The mesh separates the volume of interest into several small volumes called elements. The calculations are solved for each node in the element mesh. The meshing process is important to get big enough resolution to solve the problem realistically. To limit simulation time it is useful to have low resolution. The results are never better than the meshing. Meshing in that sense is an art.

The mesh impacts solution accuracy. We talk about mesh independence. A mesh independent result is a result which does not change with denser mesh. The mesh needs to present the geometry accurately enough for the simulation to provide a reasonable result. A too large mesh allows for bigger errors to be introduced.

The mesh impacts the CPU time required. A good mesh is a mesh which use reasonable computing resources. A dense mesh which give really accurate results might not be computable with the available computing resources.

The mesh quality is a parameter which can be controlled. There are therefore several ways by characterizing a mesh. A mesh can be characterized by its density, adjacent cell length/volume ratios, skewness, cell type. Boundary layers often require their own parameters for meshing and mesh refinement through adaption will also enhance mesh quality.

Typical cell shapes include triangular, thetrahedron, pyramid,arbitrary polyhedron, 2D prism, prism with quadrilateral base, prism with triangular base. Either a mesh consists of only one shape, multiple shapes and some meshes are a combination of so many shapes it can only be characterized as unstructured. Unstructured meshes are useful when dealing with complex geometries.

The mesh generating process used in this thesis is the built-in in the COMSOL Multiphysics software. In addition, the geometry was also made in COMSOL Multiphysics. This eliminates problems that could appear during conversion of geometries between different softwares.

2.5.2 Boundary conditions and initial conditions

The boundary and initial conditions are values the solver needs to compute the solution. The boundary conditions controls which physics goes in and out of the domain in question. In this thesis boundary conditions was used to set ambient temperature, insulate and transfer heat in the heat storage.

The initial conditions are there to give the problem a starting point. The heat storage will have a certain temperature from the beginning of the simulation.

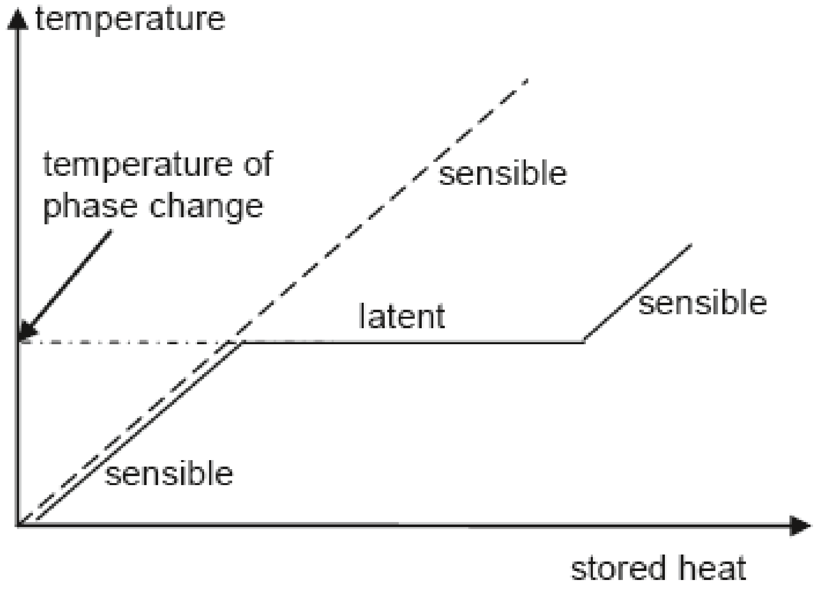


FIGURE 2.2: Donatella

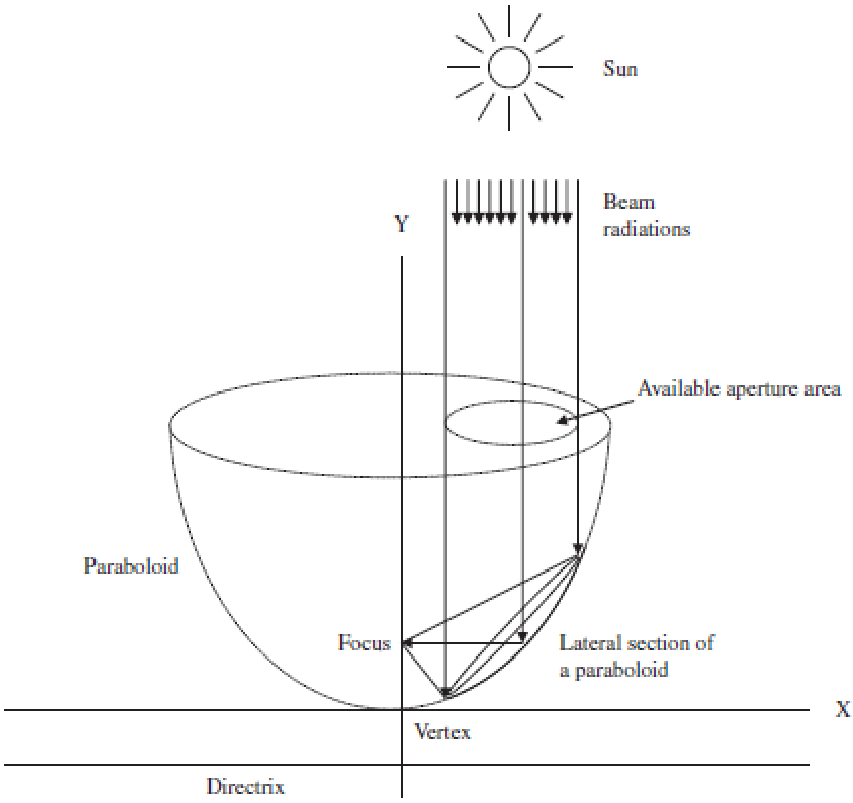


FIGURE 2.3: Awesome Image

Chapter 3

Case descriptions

	Experiment no.	Geometry	Timestep	Total time
	# 001	2D vertical cut	0.5	2500

	Experiment no.	Geometry	Timestep	Total time
	# 001	2D vertical cut	0.5	2500

	Experiment no.	Geometry	Timestep	Total time
	# 001	2D vertical cut	0.5	2500

3.1 General considerations and parameters

The selected method of investigation is by simulation. COMSOL Multiphysics will be used.

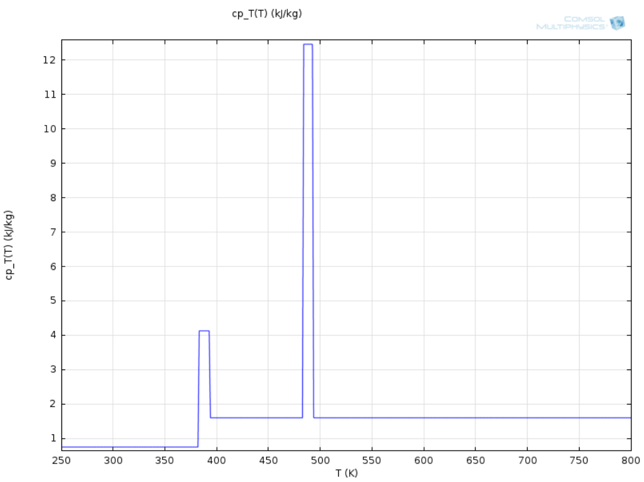
3.1.1 Assumptions

Assume that the phase transition and melting occurs in the region 110 to 120 and 210 to 220 deg C respectively. The phase transition enthalpy and enthalpy of fusion is incorporated in the modified heat capacity range. Assume initial temperature of 40 degC. Assume ambient temperature of 25 degC.

The PCM was given a varying C_p according to this table:

C_p	For temperature $[K]$
0,75	$T < 383K$
4,1	$383 \leq T \leq 388$
1,4	$388 < T < 488$
12	$488 \leq T \leq 498$
1,6	$T > 498$

The used C_p profile in comsol is plotted under:



3.2 Design conditions and criteria

A heat storage used for baking Injeras need to be 400-500 mm in diameter. For experimental and simulation purposes a smaller model is sufficient to understand the design effects. The storage is made in aluminium and the PCM is a solar salt.

The aluminum storage has dimensions:

Geometry	Size [mm]
Diameter aluminium bolt	200mm
Height aluminium bolt	200mm
Diameter cylindrical cavities	32mm
Length cylindrical cavities	150mm

Thermophysical property	Value	Unit
$NaNO3KNO3(60:40mol)$		
Thermal conductivity	0.8	W/mK
Density		
Temperature 220 degC	1800	kg/m3
Temperature 220degC	1700	kg/m3
Enthalpy of fusion	108.67	kJ/kg
Phase transition enthalpy	31.91	kJ/kg
Aluminium 6xxx-alloy		
Thermal conductivity	176	W/mK
Density	2700	kg/m3
Heat capacity	953	J/kgK

3.3 Benchmark models

Since no laboratory experiments have been performed for this thesis, the computational simulations has to be verified otherwise. This is done by comparing simulation results with results obtained in the laboratory. COMSOL offers several benchmark models to verify the strenghts and weaknesses of the software compared to experiments. The literature on the field of computational heat transfer also contain information on how software perform compared to experiment.

NAFEMS models test the capability of a finite element system, like COMSOL Multiphysics. The models provide a test which is simple to model and cheap to run.

So how does COMSOL compare to experiments?

The models presented here are

- Steady-state conduct in cylinder
- Finned heat storage

3.3.1 Boundary conditions

The plate subjective to inward heat input (solar radiation), convection and radiation heat losses. All other outside surfaces are thermally insulated.

3.4 Base case 2D

The model is a 2D horizontal representation of the heat storage. The model is identical to the aluminum bolt tested in the laboratory. The model utilize steam as working fluid.

The mesh was extra fine for the cavities and fine for the rest of the geometry. The steam is modeled as having constant temperature on the cavity surface.

Hoff plotted the temperature in the centre of each cavity. The heat propagation came out the same as Hoff, as can be seen in the following figure. The heat propagates from the vertical channels, through the metal and then to the salt. The metal use less time to reach even temperature compared to the salt. The salt along the edges melts faster than the salt in the centre of the cavity.

Time settings	Step time	0.5 s
	Total time	1000 s

3.4.1 Boundary conditions

The plate subjective to inward heat input (solar radiation), convection and radiation heat losses. All other outside surfaces are thermally insulated.

3.5 Base case 3D

3.5.1 Boundary conditions

The plate subjective to inward heat input (solar radiation), convection and radiation heat losses. All other outside surfaces are thermally insulated.

3.6 Finned heat storage

Time settings	Step time	0.5 s
	Total time	1000 s

3.6.1 Boundary conditions

The plate subjective to inward heat input (solar radiation), convection and radiation heat losses. All other outside surfaces are thermally insulated.

Chapter 4

Results and discussion

The use of steady state to validate transient conduction is not very useful.

Skriv for ditt case "It can be seen that the highly conductive copper fin helps to increase the heat penetration into the PCM which results in higher PCM temperature close to the fin."

Discussion fra Foong "From the data obtained, the model can predict the experimental results within 15 percent error."

Forenklinger som ble gjort: "For both T2 and T3, natural convection heat transfer in the melted PCM was neglected in the simulation. In addition, effect of thermal radiation within the internal wall, fin and PCM were also not considered."

4.1 Verification case

"Phase change problems, first treated as pure conduction controlled, has in recent times moved to a different level of complexity with added convection in the melt being accounted for"

4.2 Base case 2D

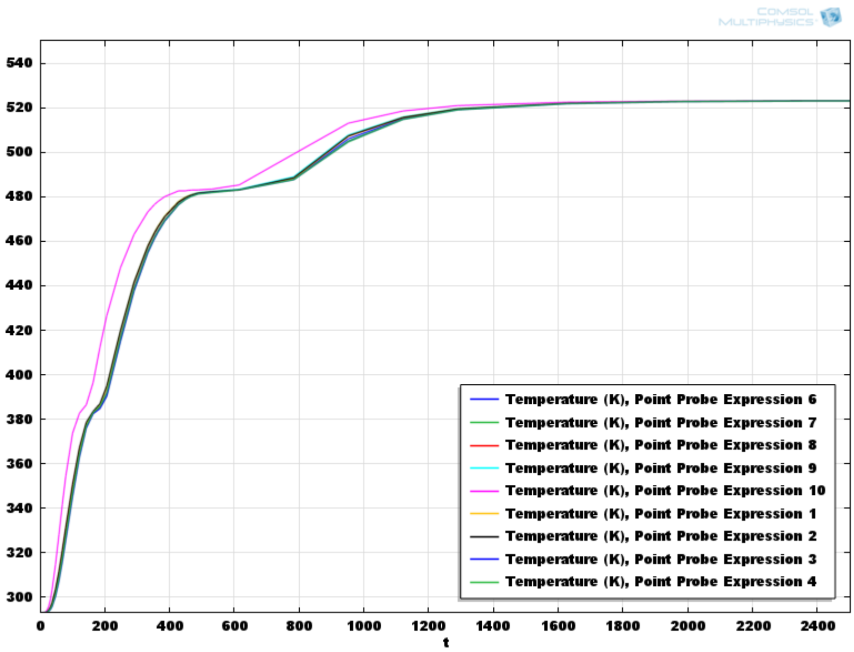


FIGURE 4.1: Heat evolution in salt chambers

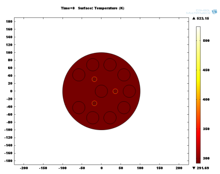


FIGURE 4.2: A figure

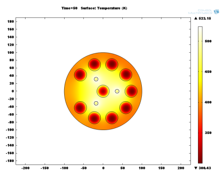


FIGURE 4.3: Another figure

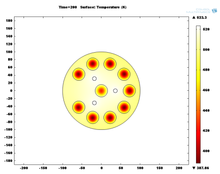


FIGURE 4.4: A figure

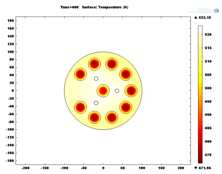


FIGURE 4.5: Another figure

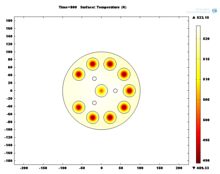


FIGURE 4.6: A figure

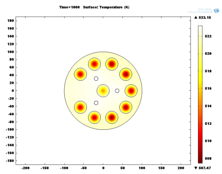


FIGURE 4.7: Another figure

4.2.1 Base case 3D

Iterate a lot. Shape factor of an eccentric circular cylinder of lenght L in a cylinder of equal lenght. [8]

Transient conduction [8] side 256.

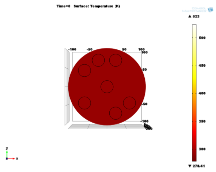


FIGURE 4.8: A figure

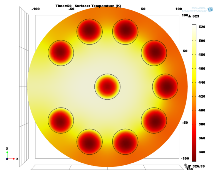


FIGURE 4.9: Another figure

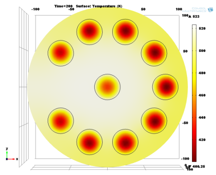


FIGURE 4.10: A figure

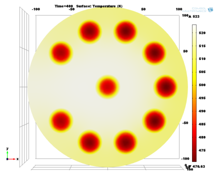


FIGURE 4.11: Another figure

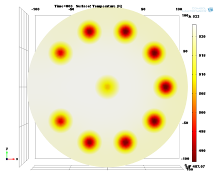


FIGURE 4.12: A figure

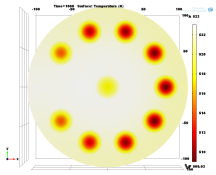


FIGURE 4.13: Another figure

4.2.1.1 Assess results

The assessment of the results will be done in chapter X about discussion.

4.2.1.2 Errors

2.3.4.2. Result accuracy (finite element simulation of heat transfer ch2)

4.3 Finned heat storage

4.3.1 Simulation setup

		Meshed
3D	Salt cavities	finer
	Working fluid	extra fine
	Aluminium	fine

		Meshed
2D	Salt cavities	extra fine
	Working fluid	fine
	Aluminium	fine

2D views

- Horizontal cut
- Vertical cut

4.4 Comsol Multiphysics

"Solutions to phase change problems include analytical, experimental and numerical using one-dimensional, two-dimensional or threedimensional models to solve energy formulated equation."

4.4.1 Finite-difference methods FDM

One dimensional problems can benefit from analytical methods. FDM makes dealing with 2- or 3D cases of transient conduction much faster and easier.

4.4.2 Meshing

4.5 Results

The thermal characteristics in the systems were analysed using isothermal contour plots and temperature time curves. Temperature gradients along the three directions of the two systems; axial, radial and angular directions were also analysed and compared.

different container materials, and different PCMs to investigate the heat transfer enhancement characteristics of PCMs.

Horbaniuc et al. [102] measured performances of fins in terms of the interface freezing stage and the time taken for complete solidification to be achieved using parabolic and exponential approximations.

Hamada et al. [75] used the effective thermal conductivity proposed by Fukai et al. [126] to assess and compare results with the control system with no heat transfer enhancement. Du har jo control system with no heat transfer enhancement.

In the case of Choi and Kim [97], the key parameters used to assess the heat transfer enhancement of the circular finned system were the ratio of overall heat transfer coefficient in the finned and the unfinned tube systems. They reported a ratio of 3.5 for a surface area ratio of 3.2 between the finned and the unfinned tube systems.

4.6 Discussion

"The model developed in this study is able to predict the experimental results quite satisfactory (less than 15illuminating system was able to melt the PCM within 2e2.5 h and reached the temperature range of 230e260 C."

"The ultimate objective of this study is to develop a small scale solar concentrating system with high temperature storage which can charge the PCM thermal storage during day time and use it in the night time for cooking purpose."

"To avoid overheating of the oil, an advanced optimization of the diameter of the pipes and/or the absorber tube should be done, to regulate the mass flow such that the critical temperature (auto-ignition point) is never reached."

Chapter 5

Conclusion

The following models are some of NAFEMS benchmark test for thermal analysis. These are necessary to validate the simulations done in this thesis. We begin with a 1D validation model, which is not directly useful to explain or models. The next NAFEMS models are 2D, which help validate the simulations done in 2D. The last one is a 3D axisymmetric model which is used to validate the 3D models presented in this thesis. By validating the models to this extent, the results are given a little more confidence. For the NAFEMS models to help further, the mesh size and convergence data has to be in the same range. Mesh validation is also done seperately to give the model further confidence.

5.0.0.1 1D conduction

A 1D benchmark simulation was performed. 1D simulation of thermal conduction result should become 297.0[K] according to NAFEMS benchmark collection. In COMSOL a temperature of 296.9671[K] is achieved.

5.0.0.2 2D plate

This NAFEMS two dimensional thermal conduction model helps validate the 2D simulations of this thesis. The model was built in COMSOL, and simulated therafter. The model is not an in-built feature of the software.

Problem description This valdation case...

It is performed... two-dimensional spatial domain 0.6 meter wide and 1 meter high The temperature is fixed at 100 degC at the lower boundary. Heat flux is set at higher and right boundaries. Convective heat transfer coefficient of $750W/m^2degc$ Initial temperature

The initial and boundary conditions of the problem are summarized as follows: A complete description of this problem is given in (reference).

The two-dimensional spatial domain is meshed by a structured grid of triangular elements. There are xxx nodes and xxx elements.

The results are shown in the figure below. The figure shows the temperature distribution at the last time step.

Validation summary

5.0.0.3 3D shell conduction

This validation is a case from the NAFEMS Benchmark for thermal analysis. It is a steady-state conduction case. The results provide a temperature distribution over a spatial domain, and a control point is included.

It is performed on a 1000 x 600 mm plate which has been bent is space to become a quarter of a cylinder.

The shell model comes already modelled in COMSOL with mesh and all initial and boundary conditions. The study and result settings are also included by default. By conducting the simulation in this version in COMSOL, the version used can be compared against other versions of COMSOL, which is an important part of the verification process.

The temperature achieved in COMSOL 4.3b is supposed to be 291.40 K which is in agreement with that from the NAFEMS benchmark. Achieved temperature in the point evaluation is 291.40494 K.

Problem description

Mesh

Results

Validation summary

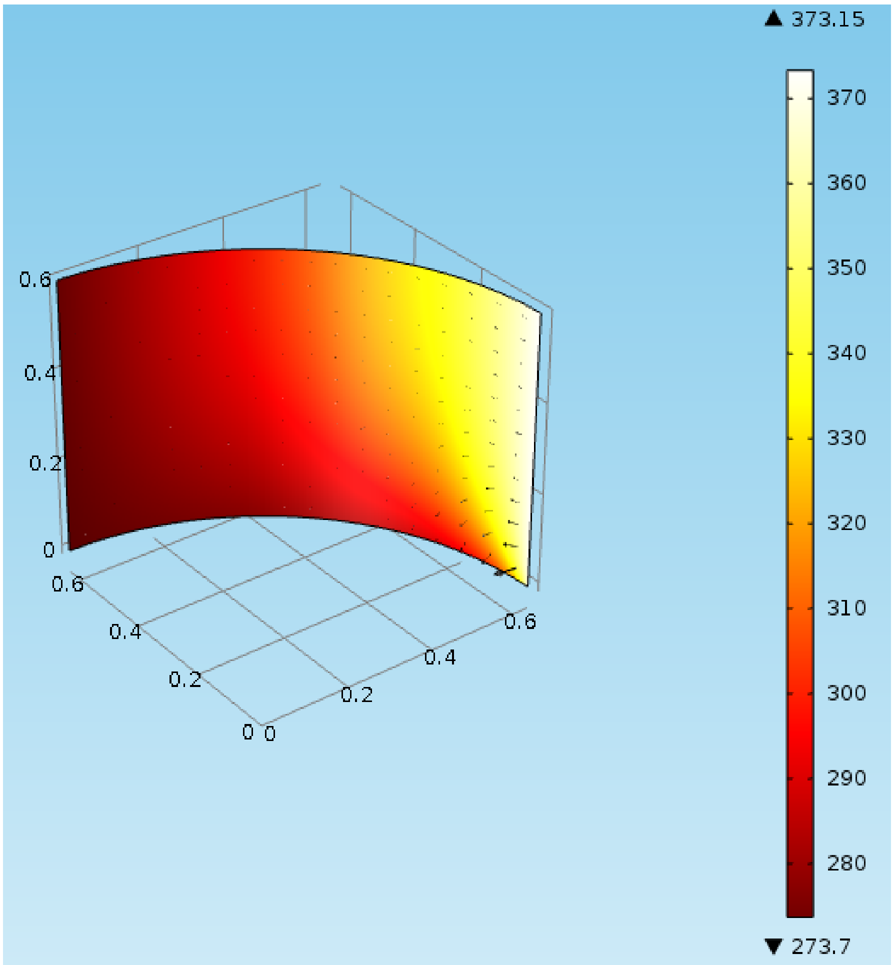


FIGURE 5.1: 3D shell validation results

5.0.0.4 Heat conduction in a cylinder

This NAFEMS model validates software for heat conduction in a cylinder. The model is axisymmetric geometry with a hole in the middle. By running a succesful simulation the NAFEMS results give good support to the spatial steady state temperature distribution in a three-dimensional geometry.

Problem description The domain is a cylinder with a radius of 0,1 meter and a hole with radius of 0,02 meter. The cylinder has a height of 1,4 meter. As before the prescribed boundary conditions are heat flux, insulation and temperature. The thermal conductivity is set to 52 $W/(mK)$.

Mesh

Results

Validation summary

5.1 Results comparison to Hoff

Results where also obtained by redoing Hoff's COMSOL simulation. Hoff provides the aluminium bolt of the laboratory experiment and all dimensions of the aluminium bolt. After these results where evaluated, a new model was modelled based on the experience.

Hoff conducted 2D simulations in COMSOL and the main results provided data of salt melting rate in the different cavities. The exact COMSOL model was remodelled and the results where analysed.

5.1.1 COMSOL 2D results

Function	Demand	Component	Importance				Achieved
			1	2	3	4	
Safety	Totally safe						Yes
Low Maintenance	Serviceable parts						Yes
Max effect							
Usage time	At least 4800 s						-
	At least 3600 s						
Recharge time	Less than 22 hours						Yes

5.2 Some sort of conclusion

"Results from the numerical methods reported appear to show that they offer a good approach to solving the phase change problem although most of the available solutions to phase change problems apply to one- or two-dimensional systems due to the complexity of the equations involved in the phase change."

The heat capacity cp used in comsol is not the same as the experimental, but it is a close approximation [foong-paper]. As can be seen from foongs paper.

"Calculations for the two-dimensional model with natural convection have not been made, as it requires experimental verification due to the complicated heat transfer in phase change materials. However, the results obtained for various parameters are useful for designing a thermal energy storage system." "Numerical simulation of a latent heat thermal energy storage system with enhanced heat conduction"

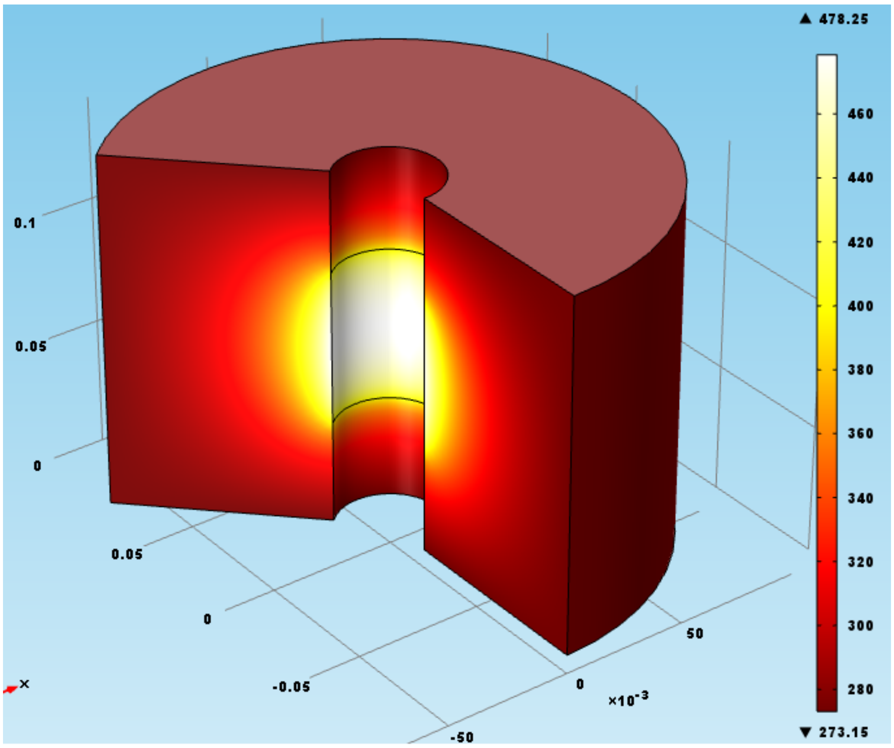


FIGURE 5.2: 3D cylinder validation

Chapter 6

Recommendations for further work

Appendix A

Simulation log

Case:	Verification model Cylinder conduction		
Filnavn:	Filnavn.mph		
Modules:	Heat transfer in Solids		
Physics			
Time step	Stationary	Heat conduction	Heat equation
Boundary conditions			
Heat transfer		Heat flux	
Influx			
Outflux			
Wall			
Initial			
Mesh			
Type	Physics controlled mesh	Number of elements	418
		Average element quality	0.9838
Convergence			
Limit		Stabilization	

Table A.1: Simuleringscase

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