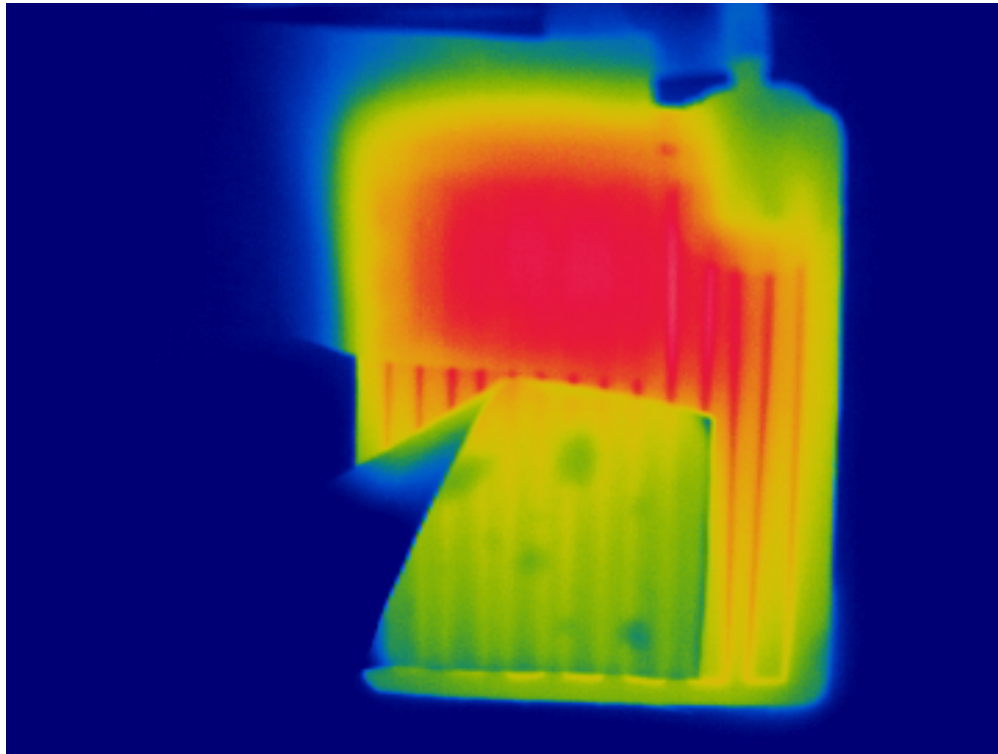


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Conductive material within Temperature Management

Master's Thesis in Applied Physics

by JOHANNA TERNSTRÖM

Supervisor: Anna Ramström
Mölnlycke Health Care

Examiner: Magnus Karlsteen
Chalmers University of Technology

Department of Applied Physics
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden, June 8, 2014

CONDUCTIVE MATERIAL WITHIN
TEMPERATURE MANAGEMENT
THESIS FOR THE DEGREE MASTER OF SCIENCE

JOHANNA TERNSTRÖM

Department of Applied Physics
Applied Physics
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2014

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Johanna Ternström

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Applied Physics
Department of Applied Physics
Chalmers University of Technology
SE-412 96 Gothenburg, Sweden
Telephone:+46 (0)31 772 1000

Cover: IR-picture showing the heat distribution in a Heat Sink and a hydrogel on a electrical heater.

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Abstract

This report deals with the choice of material for a thermal management product at Mölnlycke Health Care. The aim with the product is to prevent hypothermia during surgery. The goal with this project was to investigate which material parameters that was of interest. The material parameters that were found most interesting were the thermal conductivity, the thermal diffusivity and the ability to keep a stable temperature over time. A model was built in Comsol to study the impact of different materials on the temperature on and in human skin. The simulations showed that water based materials could not spread the heat outside of the heater. In an environment that was not thermally and water isolated, the use of a water based material even led to a decrease in skin temperature. Measurements showed that different types of heaters had different requirement on the interface material. Some different commercial materials were tested and Hollywog, Medema and Tflex were found to be most suitable on an iron heater and Hollywog, Medema and Heat sink were found to be most suitable on a an electrical heater. A hydrogel containing 67% water could also be used on the electrical type of heater if the water was not allowed to evaporate. Different types of conductive particles could be used to increase the thermal conductivity and thermal diffusivity in the material. Of the evaluated conductive particles, Carbon Black and Potassium Chloride were most suitable.

This study is a master thesis in applied physics at Chalmers University of Technology. The results in this thesis will be a part in developing a new product at Mölnlycke Health Care. There have been more people involved in this thesis than me, Johanna, and I would like to take the opportunity to thank them for their help and support. First of all, thanks to my supervisors Magnus and Anna for all support for help and inspiration.

Thanks to Angelica Andresen for allowing me to do my thesis in her group at Mölnlycke. Thanks to Johan Andersson from SP Technical Research Institute of Sweden and Anna Grou from Mölnlycke for helpful discussions about thermodynamics and to Gunnar Westman for the crash course in polymer chemistry. Thanks to Oskar Danielsson for support with Matlab and Illustrator and to Anna Sarwe for helpful comments on the report. Finally, a thank to the group of Anna Ström at the Department of signals and systems at Chalmers for materials for the gel making and a special thanks to Jenny Nilsson for all the support and help during the process.

Johanna Ternström, Gothenburg June 8, 2014

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1

Introduction

HYPOTHERMIA is a common side effect occurring during surgery and is defined as a body core temperature below 35°C . [1] The consequences of hypothermia can be huge, and are for example a three times higher risk for surgical wound infections, prolonged postoperative recovery and hospital stay, triple risk of morbid myocardial outcome and increased patient discomfort and anxiety. This increases both the costs for the health care system and human suffering. Mölnlycke Health Care is developing a device for preventing hypothermia by putting an external heat source on the skin. This project is a part in the development of this product.

The product consists of three main parts, a heat source, a protecting shell and a conductive material on the skin. This study deals with the choice and evaluation of this conductive interface material. The results in this report is mainly based on a theoretical study of the thermoregulation system in the human body, a theoretical study of the physics behind thermodynamics, a scanning of the materials available on the market, calculations using Comsol Multiphysics and measurements on materials and humans using a heat camera.

2

Background

THE CHOICE of interface material is a part of the development of a new product at *Mölnlycke Health Care*. It is also a part of further develop one of Mölnlycke Health Care's already existing products, the blanket *Easy warm*. In this chapter, the prior work and expectations of Mölnlycke health Care will be described.

2.1 The product

The product developed at Mölnlycke Health Care is a product that serves to decrease the risk for hypothermia during anesthesia. This could be made by using a thermal self heating blanket that serves to prevent hypothermia preoperatively, i.e. pre- and post operatively. A further development of the blanket consists of a thermal insulating material, focusing the heat towards the patient, heaters (electrical or chemical) and a conducting material that transfer the heat from the heater towards the human body.

2.1.1 Delimitations

In this report only the thermal interface material will be tested and evaluated. This report will serve as a guideline for Mölnlycke while choosing a suitable material for there products.

2.2 Different types of Heaters

Three different kinds of heating devices are considered for the application. Since the material criteria differ for the different types of heaters, tests will be performed on both types of heaters.

2.2.1 Iron Heater

The heat source in the iron heater is an oxidation process of iron described in Equation 2.1. This means that the materials used on this type of heater have to be transparent to air. Since the heating is based on a chemical process the temperature can differ between different heaters and also on different places of a given heater.



2.2.2 Electrical Heater

Two different types of electrical heaters could be used as the heat source. These are heaters that generate heat with a given power or heaters that keep the surface temperature of the heater constant. In this study tests will only be performed on the first type of heater. To study the effect of the second type of heater, calculations will be made by using Comsol Multiphysics.

2.3 Material Criteria

Mölnlycke Health Care are developing disposable products used in the health care industry. This means that the material used for the product needs to be cost effective and easy to dispose. The material also needs to have some specific thermal properties. To avoid "hot spots" on the skin surface, the material has to be able to spread the heat evenly and away from the warmest parts of the warmer. To reduce the size of the heaters, it is also preferable if the material can spread the heat effectively between different warmers or part of warmers. The material also needs to have good contact with the heaters and the human skin. For more information about the materials, see Chapter 6.7.

2.3.1 Even temperature

Thermal spreading is an important aspect of the material. To minimize the risk for *hot spots* on the skin the thermal spreading needs to be high if the temperature from the heat source is uneven. A high thermal spreading also allows the heat to spread away from the heat source.

2.3.2 Contact between material and skin and the material and heat source

Air normally works as an insulator. To get as high as possible thermal transfer between the material and the skin and the material and the heat source, the contact between the parts should be as high as possible and the air in between should be minimized.

2.3.3 Price

The final product is intended to be a so called "one-time use" product. This means that that the price for all components has to be cost effective.

2.3.4 Nontoxicity

Since the material will be used on humans, this means that the material chosen needs to be nontoxic both for humans and the environment.

2.4 Prior material tests

By the start of this study, some prior material testing have been performed and evaluated. The impact of the amount of water in hydrogels has been evaluated to see what properties that most fulfilled the material criteria. Hydrogel as a commonly used product in wound care and has before this study been the only used material in prior tests of the product.

2.4.1 Hydrogels with different amount of water

Some prior tests have been done to evaluate if different types of hydrogels could be used as a conductive material between the heater and the skin. Hydrogels containing 30% and 67% of water had been tested. No significant heat distribution was obtained outside the heater in any of the experiments. The hydrogel with 67% water was at this time considered the best option since the hydrogel containing 30% water got dried out after being heated for 7 hours.[2] Therefore hydrogel containing 67% water will be used as a reference in all measurements.

3

Theory : Body Heat Balance

TO UNDERSTAND the need for the heating device, it is important to understand the mechanisms controlling the temperature in the human body. In this chapter, the main parts controlling the body heat balance will be described.

3.1 Hypothermia

Hypothermia is defined as a body core temperature below 35 °C and develops when the body heat loss is higher than the heat production.[1] For definition of the core, see Chapter 3.2. When the body loses heat, the human body activates different mechanisms to prevent the cooling. This leads to an increase in stress hormones such as adrenalin, noradrenalin and cortisol and peripheral vasoconstriction.[1] Hypothermia is commonly associated with decrease in overall body function and increase in the mortality among patients, a greater need for blood transfusion, longer hospital stay and longer recovery time after operation. Studies have shown that treatment of hypothermia is associated with higher patient outcome, shorter hospital stay, less blood transfusion and higher survival rate.[3]

3.1.1 Different kinds of hypothermia

Hypothermia can occur for a lot of different reasons such as a person being exposed to a cold environment or being kept under water. Hypothermia can be both local and general. General hypothermia is the type connected to the highest risks.[1] This theory section will mainly cover hypothermia due to anesthesia.

3.2 The body Heat Balance

The body can, in words of thermodynamics, be described as being a core with peripheral compartments. The core consists of the head and the chest. The normal temperature in this part of the body is 37°C and rarely differs more than a few tenths of a degree between different parts of the core. In the peripheral parts of the body, the temperature is much lower (normally between 2-4°C less than the core) and varies a lot both in time and between different parts of the arms and legs. Differences in the environmental temperature leads to different temperature in the peripheral components. A temperature difference between the core and the peripheral parts leads to a temperature gradient.[4] According to the second law of thermodynamics, saying that the entropy of a system always increases[5], this mean that, without any external force, the heat will flow from the core out to the peripheral pars. In contrast, high temperature in the peripheral parts leads to a low temperature gradient and a lower heat flow to arms and legs. Under normal circumstances this temperature gradient is maintained by tonic thermoregulatory vasoconstriction of arteriovenous shunts in the fingers and toes.

All body tissue produce heat proportional to their metabolic rate. The brain and the organs are the parts that are the most metabolic active and produce most metabolic heat. These parts are located in the core. Metabolic heat is normally the only internal heat source. The main part of the heat loss on a human body is normally radiation, even though conduction, convection and evaporation plays an important role. [4] There are different ways to study the heat flow in the human body. A commonly used equation to simulate the heat flow in an arm was described by Pennies in 1948. The heat flow in an arm can be described as Equation 3.1. This equation will be used in the calculations using Comsol Multiphysics to study the heat transfer in the skin. Where T is the temperature in the operation area, T_b the temperature in the surrounding blood vessels, ρ_t is the density of the blood, c_t is the specific heat for the blood, k is the thermal conductivity for the tissue, ω_b throughput rate for the blood and $q_e + q_m$ are terms corresponding to electromagnetic heating and metabolism.[6] The temperature flow in the tissue can be increased both by adding electromagnetic heating or increase the metabolism, but most external heat sources used an increase in the operation temperature T by adding an external heat source on the skin.

$$\rho_t c_t \frac{\partial T}{\partial t} = \nabla \cdot k \nabla T - \omega_b c_b (T - T_b) + q_e + q_m \quad (3.1)$$

3.3 Body Heat Balance during General Anesthesia

Almost all patients who undergogeneral anesthesia become hypothermic. Initially the core temperature decrease quite rapidly (1-1,5 °C in the first hour). After the first hour, the temperature will continue to decrease slower and linear for a couple of hours. This will be followed by a stable plateau in which the temperature will remain constant. [4] The first rapid decrease in core temperature is mainly due to redistribution of blood between the core and the peripheral pars of the body. The normal core-to- peripheral

temperature gradient is maintained by tonic thermoregulatory vasoconstriction of arteriovenous shunts in the fingers and toes. During anesthesia, the limit for these contractions decrease, thereby precluding the temperature gradient, allowing the blood to flow from the core to the peripheral parts, as described in Section 3.2. For a picture showing the process, see Figure 3.1.

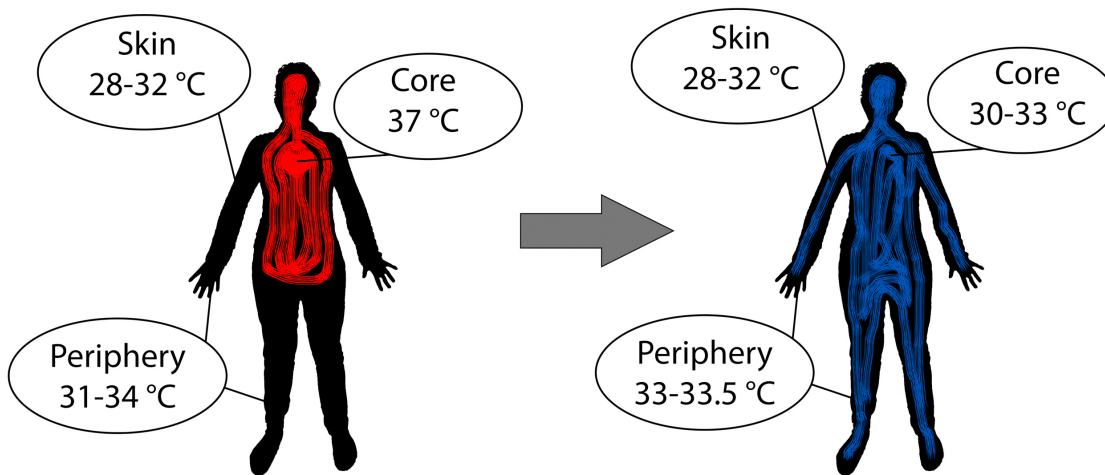


Figure 3.1: Picture describing heat distribution in an human body during general Anesthesia.

3.4 Preventing Hypothermia during Anesthesia

There are a number of ways to prevent hypothermia during anesthesia. Studies have shown that pre-warming of patients significantly reduce the risk for a decline in the body core temperature. Even 10 minutes of pre-warming is sufficient to prevent hypothermia. [7] [8]

3.5 Body Heat Sensitivity

The thermal threshold for pain is shown to be around 43 °C. [9] To avoid burned skin and discomfort, it is important that heating devices don't increase the skin temperature above this limit. The heat applied to the skin is conducted away because of the latent heat transfer properties of the skin and an increase in skin blood circulation. [10]

4

Theory: Heat Transport

TO UNDERSTAND the heating process and the criteria for the material, it is important to understand all different heat transport concepts. In this chapter, some main concepts will be described.

4.1 Radiation

Radiation is the transfer of heat from one surface to another via photons. The heat transfer is not due to movement of atoms and can therefore occur even in vacuum. Heat transport is possible in all materials that allows electromagnetic waves to move (e.g. transparent materials). Depending on the surface characteristics, these waves will be more or less fully reflected, transmitted or absorbed by the material. The sum of these ratios is always equal to 1, see Equation 4.1. [11]

$$a + r + t = 1 \tag{4.1}$$

Where a is the fraction of absorbed waves, r the fraction of reflected waves and t the fraction of transmitted waves. To maximize the heat transfer from the radiation, the reflection component should be minimized and the transmitted component should be maximized.

4.1.1 Emissivity

Emissivity is a number for how well a body reflects incoming electromagnetic radiation and is the fraction between the amount of radiation the body emits compared to a black body at the same temperature. A black body has the emissivity $\epsilon = 1$. All materials have $0 < \epsilon < 1$. [5]

4.2 Conduction

Heat conduction can be described as transfer of thermal energy from a hot part to a cold part of the body. This heat transfer can be provided both from free electrons or free phonons in the material. In metals, the heat transport is dominated by free electrons, but in a perfect electronic insulator, the heat transfer is provided by phonons in the material. [12]

4.3 Convection

Thermal convection deals with the heat transfer between a surface and a moving fluid or between two different fluids. The main source for heat transfer in cooling a cup of tea by blowing on the surface, is due to convection. Convection is the heat transport due to movement in a gas or a liquid and is described as Equation 4.2. Natural convection refers to the movement in a fluid which is not effected by external parameters. This movement is only due to a temperature gradient in the air. In natural convection, the heat transfer coefficient h is between $5Wm^{-2}K^{-1}$ and $25Wm^{-2}K^{-1}$. Forced convection refers to the movement due to an external force such as a pump. In forced convection, the heat transfer coefficient h is between $25Wm^{-2}K^{-1}$ and $250Wm^{-2}K^{-1}$. [13]

4.3.1 Newtons law of cooling

Newtons law of cooling could be describes as:

"The rate at which a body loses heat is proportional to the difference in temperature between the body and the surroundings."[5]

Mathematically this could be described as Equation 4.2.

$$Q = hA(T_{warm} - T_{cold}) \quad (4.2)$$

Were Q is the heat flow rate, h is the heat transfer coefficient, A is the surface area and T_{warm} and T_{cold} are the temperatures in the different warts of the body. [14] This describes that heat flows from a warmer to a colder part of the material with a rate proportional to the difference between the temperatures times the surface area. To maximize the heat transfer in steady state due to conduction, the contact area A should be maximized.

4.4 Evaporation

Evaporation heat transfer occurs through evaporation of water. To evaporate water, energy is needed. This energy is taken from the object, resulting in a cooling of the object. The amount of energy needed to transform a given amount of water into gas is called *enthalpy of Vaporization* or *heat of evapourisation*. This also means that if the

water in a material is free to evaporate, some of the energy from the heat source will be taken to evaporate the water instead of increase the temperature in the material. [4]

4.5 Thermal diffusivity in materials

The thermal diffusivity for different kinds of materials will be used to evaluate whether the material spread the heat evenly or not. In the case those values are not tabulated, the values will be calculated using other material constants according to Equation 4.3. If no material properties are known, the diffusivity will be approximated from the measurements.

$$\alpha = \frac{k}{\rho C_p} \quad (4.3)$$

Where α is the thermal diffusivity, k the thermal conductivity, ρ the density and C_p the specific heat capacity. [15]

4.6 Thermal energy

The thermal energy is the part of the total energy that result from the temperature of the system. A change in thermal energy can be described as Equation 4.4.

$$\Delta E = m \cdot C_p \cdot \Delta T \quad (4.4)$$

Where ΔE is the difference in thermal energy, m the mass of the object, C_p the specific heat capacity and ΔT the difference in temperature. [5] This means that, if the available energy is limited, both the mass m and the specific heat C_p of the material should be minimized.

5

Method

THE METHOD used in the study is a combination of theoretical calculation, simulations, basic lab testing in a fixed environment and tests on humans.

5.1 Calculations in Comsol Multiphysics

The simulation program *Comsol Multiphysics* has been used to evaluate the possible behavior of some different materials as *Thermal interface materials* in the bag and in a blanket. A numerical 2D-model has been constructed. The model has been used to evaluate thermal conduction, thermal diffusivity, the heating of the skin and the evaporation of water.

5.2 Thermal Measurements

Some different kinds of thermal measurements was been done to evaluate the properties of the materials.

5.2.1 Heat camera

A heat camera was used to analyze the thermal transfer in the different materials. The camera was used to get an understanding of how well the material spread and transferred the heat. Measurements were done both using iron warmers and electricity as a heat source to evaluate what materials to choose for the different methods. All measurements were performed during 30 minutes for each type of material and type of heater. Pictures of the thermal distribution were taken every 10 minute. A heat camera measures the radiation temperature as a function of the emissivity. If the heat camera is set to measure a inaccurate emissivity, the measured values for the temperature will be incorrect. Since

it is often hard to know the exact value of the emissivity, a heat camera is not the most accurate way to measure a precise number of the the temperature. Since the emissivity for the different materials and the surface of the heaters were unknown, the emissivity was approximated to be $\epsilon = 0.96$. This is a very rough approximation, but could at least give a rough value of the temperature for most materials.

5.3 Setup and Manufacturing of materials and equipment

Three main setups have been used during the study. The first setup was a computer based simulation and the two other were done using a thermal camera. An insulated bag and some different gels were manufactured to implement the measurements.

5.3.1 Setup: Development of method in Comsol

A model of skin, conductive interface material and electrical heater was made in *Comsol Multiphysics*. The model used the set up *Thermal heat transfer in solids* to study the heat transfer and *Transfer of diluted spices* to study the evaporation of water from a hydrogel. A Report from Comsol showing the different parameters and variables can be seen in Appendix B.

5.3.2 Setup: Heat camera

The setup consists of a thermal camera (*FLIR, ThermoVision A20M*) put on a tall stand and connected to both a computer and an external screen. The heater was placed on a table. A picture showing the measurement set up can be seen in Figure 5.1.

5.3.3 Setup: Human testing

Human tests were made on a hand to evaluate the impact of the conductivity of the material. The measurements were done in an insulated bag, applying the interface material between the skin and the heater. All measurements were performed using the iron heater. Two series of measurements were done. The first serie applying a pressure between the hand and heater, by putting the hand on top of the heater. The other one was preformed the other way around, keeping the heater on top.

5.3.4 Manufacturing of the thermal bag

An isolating thermal test bag, that could be used for thermal testing on humans, was manufactured. The aim with this bag was to get a well insulated environment for tests of different materials. The bag is made of a nonwoven fabric and silica aerogel (*Thermal Wrap*) used as an insulator. Small pockets for keeping the heaters in place were placed on the inside of the bag.

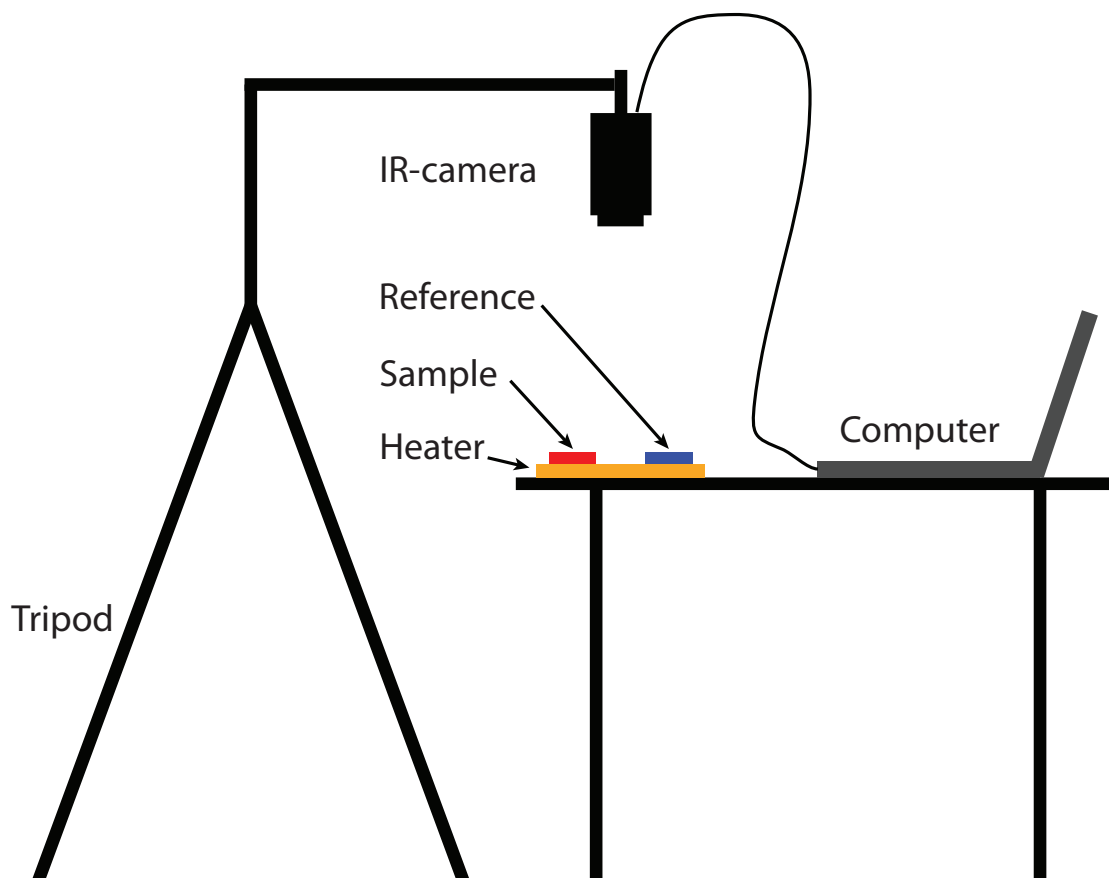


Figure 5.1: Measurement setup for the heat camera.

5.3.5 The making of hydrogels

To be able to study a material with high water content, a hydrogel consisting of 98 % water was made. The gel was made of a combination of Xanthan and LGB polymers in miliQ water. For the recipe for the polymer solutions and a description of the gel making, See Appendix A.

5.3.6 A closer study of the impact of particles in hydrogels

To examine if it was possible to add conducting particles to a hydrogel in order to make the gel more conductive and try to increase the thermal diffusivity, some different gels were produced. The gels were produced with the Xanthan/LGB polymer solutions as a base. The recipe is given in Appendix A. Salts and other particles were added in different concentrations.



Figure 5.2: Thermal bag made of non-woven fabric and the material *Thermal Wrap* as an insulator.

5.3.7 Human testing

Tests on human skin was made using only a chemical heater and the combination material and chemical heater. The tests were performed on three different materials. The material was applied to the skin on the hand, then a heater was put on top of the material. Finally the hand, material and heater was put into the isolating bag for 30 minutes. IR pictures using the heat camera was taken both before and after the heating in the insulating bag. Tests were made both with the hand facing up with the heater on top and facing down with the heater against the table.

6

Materials Tested

IN THIS CHAPTER the different tested materials will be described. Many of the materials are commercial, without any material data sheet available. This means that for some of the materials, the conductive ingredients and properties are unknown.

6.1 Hydrogels

Gels behave like a sticky adhesive which could be useful to get a good connection between the material and the skin. Gels could also be manufactured in a lot of different ways, including different amount of water, consistent, and particles, adapting the gel to requested properties.

6.1.1 Commercial hydrogels

- **First-water hydrogel**
First - water hydrogel containing 67% water is the hydrogel that has been used in tests prior to this study and as a reference in all measurements. Any specific information about the material properties and the material has not been found.
- **WiTouch hydrogel gel pads (Hollywog)**
WiTouch are electrically dispersive hydrogel pads used for electrical pain relief bought from Hollywog. Both sides of the gel are covered with adhesive. The manufacturer claim that ” *The composition of the gel-pads is common materials found in the electrode industry.* ”
- **Axelgaard hydrogel Valuetrode lite (Medema)**
Valuetrode is a stimulation hydrogel manufactured by Axelgaard and bought from Medema. Axelgaard claims that the gel contains; Glycerin, non-tallow Water-Poly(acrylate) Co-polymer and Potassium Chloride.

6.2 Home made Hydrogels with salt

A home made hydrogel containing 98% of water was made using Xanthan and LBG polymers. The recipe can be seen in Appendix A.

- **Gel with Silver Carbonite**

Silver Carbonite was added to the gel solution to study if this could increase the thermal conductivity, thermal diffusivity and/or the stability of the gel.

- **Gel with Copper Sulfate**

Copper Sulfate was added to the gel solution to study if this could increase the thermal conductivity, thermal diffusivity and/or the stability of the gel.

- **Gel with Potassium Chloride**

Potassium Chloride is commonly used as an added substance in gels and other materials to increase the electrical conductivity in the material. The idea was to evaluate whether it could be used to increase the thermal conductivity in the hydrogel as well.

- **Gel with Calcium chloride**

Since Calcium and Potassium ions have similar properties the idea was to study if Calcium Chloride could be used to increase the thermal conductivity in the material. Since Calcium has double bonding instead of single bonding the idea was to study if this could increase the stability of the gel more than Potassium Chloride.

- **Gel with Sodium Chloride**

Sodium Chloride was added to the gel solution to study if this could increase the thermal conductivity, thermal diffusivity and/or the stability of the gel.

6.3 ECG-pads

Some different commercial ECG-electrodes from *AJ MEDICAL* and *3M* have been tested and evaluated for their thermal properties. The idea was to use the fact that both electricity and heat can be transported by conductive particles and evaluate whether the different conductive gels in the different ECG-pads could be used as thermal interface material as well.

- **Skintact FS RB4**

Skintact are ECG electrodes from AJ medical which use a conductive gel (Aqua-Wet) together with foam rubber. The gel consists of Alcohol ethoxylate, glycol ether, fatty acids and Ag/AgCl.

- **Red Dot 2660-3**

Red Dot 2660-3 from 3M uses a conductive gel pad consisting of acrylic polymer, peg monoethyl ether polymer, water, propylene glycol and potassium chloride

- **Red Dot 2560**

Red Dot 2560 from 3M uses a small conductive gel pad consisting of Polyethylene film, Ag/AgCl eyelet, stainless steel or radiolucent stud, foam backing, nonwoven polypropylene scrim, acrylate Adhesive and Polyethylene glycol dimethacrylate.

- **Red Dot 2228**

Red Dot 2228 from 3M uses a small conductive gel pad consisting of Polyethylene film, Ag/AgCl eyelet, stainless steel or radiolucent stud, foam backing, nonwoven polypropylene scrim. Acrylate Adhesive, Polyethylene glycol dimethacrylate. This gel is the same as Red Dot 2560.

6.4 Textiles

Textiles are often insulators, but by applying a coating on the textile fiber, some different kinds of properties such as conductivity can occur. This type of textiles are called *Smart Textiles*.^[16] The conductive silver coated fabric *Medtex* could be ordered from *Shieldtex*.

- **Conductive textile (Medtex)**

There are different kinds of conductive textiles on the smart textile market. The textiles are often made of polyester fiber coated with 99.99 % silver. The fibers are then knitted or woven to a fabric. In this study the woven textile *Medtex P-180* is used. 99.99% silver has a thermal diffusivity of $195.63 \text{ mm}^2/\text{s}$. This is 1158 times higher than water.

- **Conductive textile (Medtex) and water**

To be able to use a material for heating a patient, the material not only has to have a high thermal diffusivity constants, but also a good contact with the human skin. The textile MedTex was used wet to evaluate if the material could get a good connection to both the heater and the body and also conduct the heat fast and evenly.

- **Conductive textile (Medtex) and grease**

The textile MedTex was used together with grease (hand cream) to evaluate if the material could get a good connection to both the heater and the body and also conduct the heat fast and evenly.

6.5 Carbon based materials

Carbon is highly thermally conductive. This makes carbon based materials attractive as thermal interface materials.

- **Carbon rubber**

Silicon rubber with carbon particles which is thermally conductive are commonly used as stimulation electrodes in electro stimulation. A carbon rubber electrode

bought from Medema has been used to evaluate if carbon rubber could be used as a suitable interface material.

- **Pyrolytic Graphite Interface sheet (PGIS)**

Graphite is highly thermally conductive and also has a high thermal diffusivity. PGIS as a lightweight graphite sheet manufactured by Parmasonic with a thermal conductivity between 700 and 1750 W/(m-K).

- **Hydrogel with carbon black**

A hydrogel containing 98% of water was also used as a base to evaluate if carbon black could be added to a gel to increase the thermal conductivity and diffusivity. Carbon black was added to the gel in concentrations of 0.01 wt% and 0.1 wt%. For information about the making of the gels, see Appendix A.

6.6 Heat sinks

Heat sinks are commonly used as thermal interface materials in the electronic industry. Measurements were done on three different types of heat sinks to evaluate if they could be used in this health care application as well.

- **Laird Tgard**

Tgard is a thin thermally conductive pad from Laird used for different types of electronic applications. Tgard consists of a Silicone Polymer coated on both sides of fiberglass.

- **Laird Tflex**

Tflex is a silicon polymer based material from Laird that uses carbon as the thermally conductive particles.

- **T-global L37-5S Ultra Soft Thermally conductive pad (Heat sink)**

T-global Thermally conductive pad is a silicone based pad using Aluminum Oxide as the thermally conductive component.

6.7 Water based materials

- **Burnshield**

Burnshield dressing is a wound dressing used for skin burns. Burnshield is a foamed rubber surrounded by hydrogel mainly consisting of water.

- **Water Bolus**

A water bolus is a plastic bag containing water. The water bolus was used together with gel to stick to the heater.

7

Results

BOTH CALCULATIONS and measurements were performed. The results will be shown in this chapter.

7.1 Calculations

To get a number for the thermal diffusivity for some of the different materials some calculations had to be made. Values are only stated for the materials with enough available information.

7.1.1 Thermal Diffusivity

Since the thermal diffusivity of many of the materials was not known, the values had to be calculated or approximated. The diffusivity for the hydrogel was calculated using approximated values for the conductivity, density and specific heat capacity. The values were calculated as a weighted mean value. The conductivity for the thermal conductive pad (Heat sink) was calculated from values given by Liard. The smart textile Medtex was approximated to have the same diffusivity as silver. The values can be seen in Table 7.1. Since both hydrogel 98% of water and the burn dressing Burnshield contained mostly water, the diffusivity was approximated as water. The diffusivity for the ECG electrodes, Liard Tgard and Tflex, Medema and Hollywog was initially unknown.

7.2 Calculations using Comsol Multiphysics

Calculations using Comsol Multiphysics were performed both simulating the skin, heater and interface material in an isolated- and an non insulated environment. The model was build using Comsols model systems *Heat transfer in Solids* and *Transport of diluted*

| | Hydrogel 67% water | Water | Thermally conductive pad | Medtex | Carbon | PGIS |
|---------|-----------------------|----------------------|--------------------------------|----------------------|----------------------|----------------------|
| m^2/s | $1.27 \cdot 10^{-7}$ | $1.47 \cdot 10^{-7}$ | $8.56 \cdot 10^{-7}$ | $1.66 \cdot 10^{-4}$ | $2.16 \cdot 10^{-4}$ | $1.22 \cdot 10^{-3}$ |

Table 7.1: Tabulated and calculated values for some of the tested materials. A higher value of the diffusivity means a higher spreading of the heat in the material.

pieces. In all simulations, the right and left edges were set as being symmetry edges, simulating a continuous piece of skin. The lower edge was set to the fixed temperature of 25 °C. The material in the heater was chosen to be copper like the electrical heater and the temperature was set to 40 °C. The heater temperature was chosen to be fixed, instead of heaving a fixed power to stimulate the last type of heater *Mölnlycke Health Care* is investigating. Probe points, used to study the temperature change in a specific point was placed both in the skin area and in-between the skin and the materials as shown in Figure 7.1.

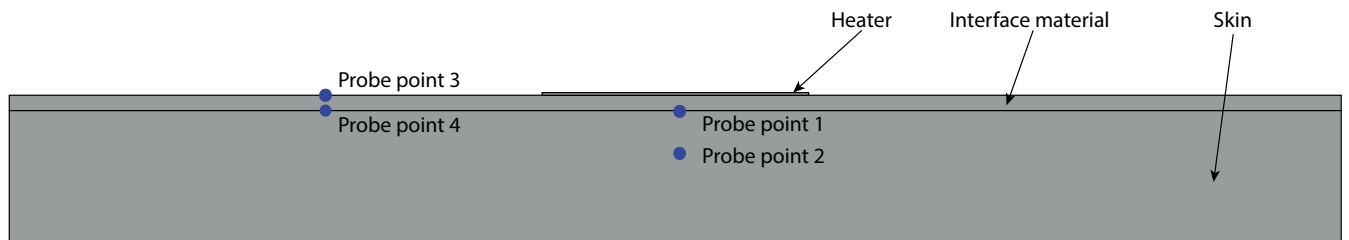
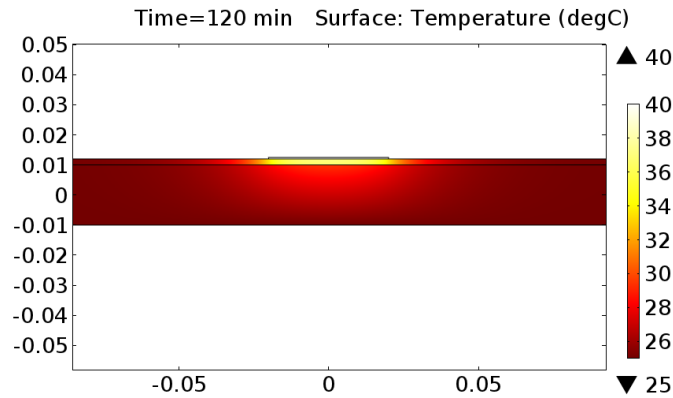


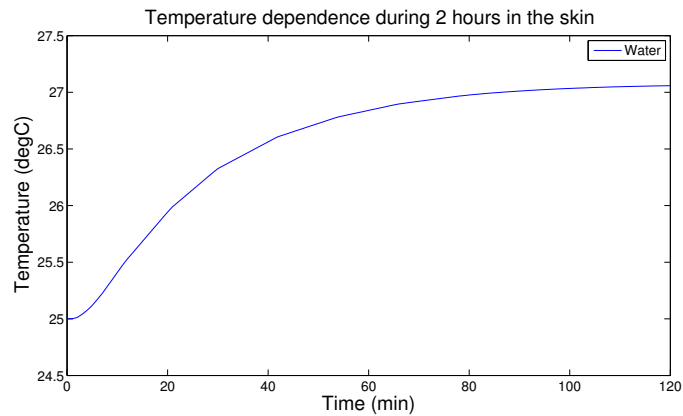
Figure 7.1: Drawing showing the position of the four probe points.

7.2.1 Isolated system

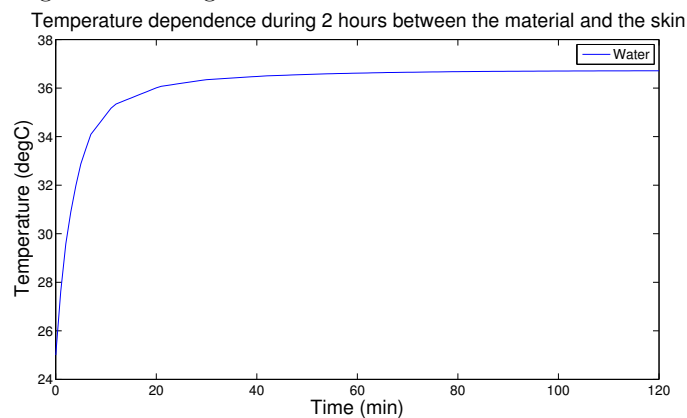
A thermally and water isolated system was simulated by keeping the top part of the material insulated from the environment. Figure 7.2 - 7.5 shows the thermal spreading over time for some different materials in an thermal and water insulated system. All simulations were done for two hours. Figure 7.2 shows the heat distribution and temperature change in a material mainly based on water. This part illustrates the heat distribution in a water bolus or Burnshield burn dressing. Figure 7.3 shows the distribution in Medtex. Medtex is modeled by a layer of silver. Figure 7.4 illustrates the heat distribution from a highly conductive pad such as Heatsink, Tflex or Tgard and is modeled by *Highly conductive silicone rubber*. Figure 7.5 shows the impact from a hydrogel containing 67% water. Finally Figure 7.6 and Figure 7.7 shows the temperature in the skin and between the material and the skin for all the calculations.



(a) Graphical illustration of the heat distribution after 2 hours using water as the interface material.

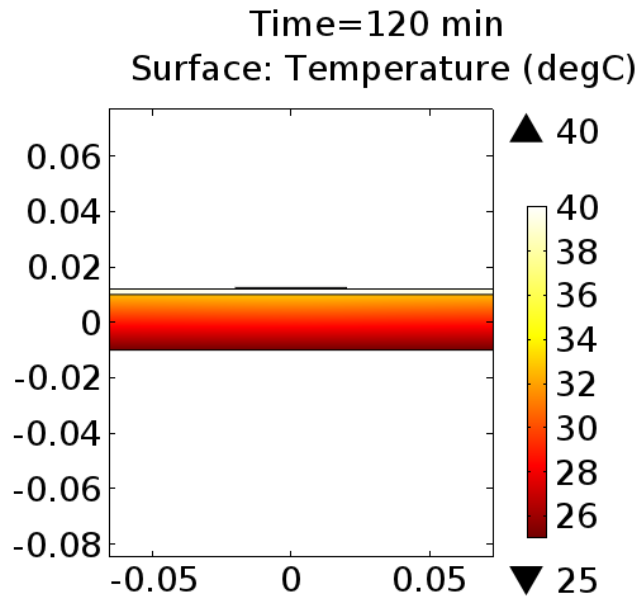


(b) The change in temperature in one point in the skin (Probe point 2) during 2 hours using water as the interface material.

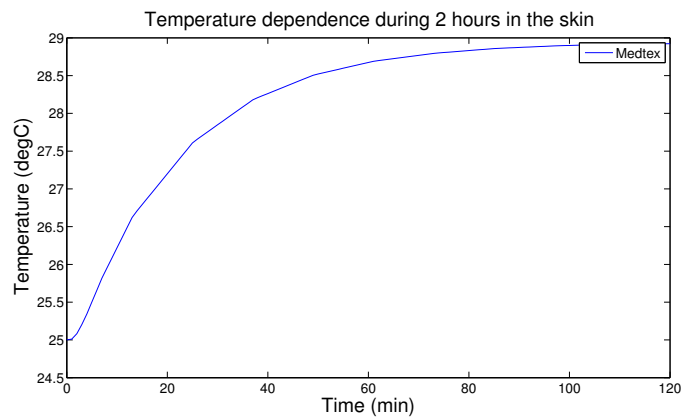


(c) The change in temperature in one point in-between the conductive material and the skin (Probe point 1) using water as the interface material.

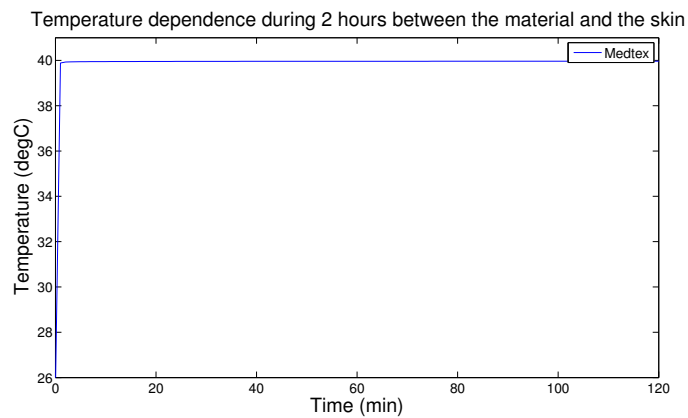
Figure 7.2: A graphical illustration of the heat distribution from an electrical copper heater on skin with water as the conductive medium after 2 hours in an isolated system.



(a) Graphical illustration of the heat distribution after 2 hours using Medtex as the interface material.

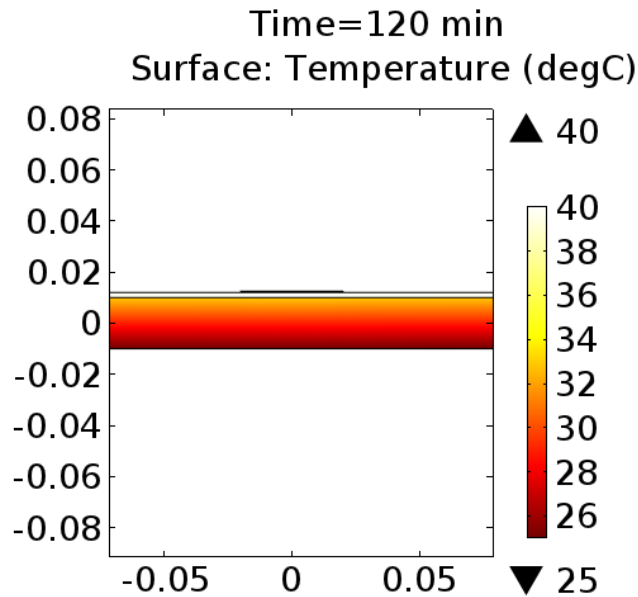


(b) The change in temperature in one point in the skin (Probe point 2) during 2 hours using Medtex as the interface material.

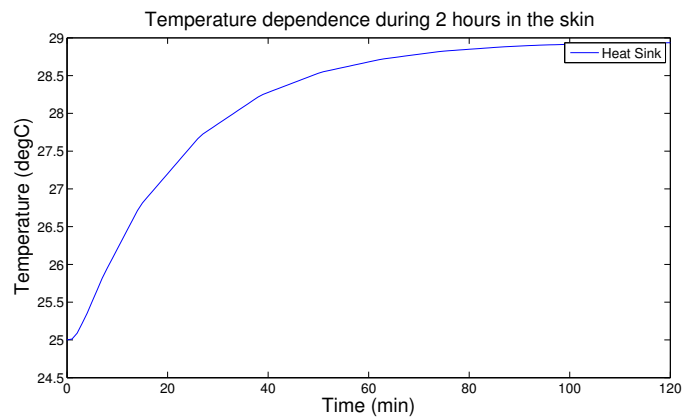


(c) The change in temperature in one point in-between the conductive material and the skin (Probe point 1) using Medtex as the interface material.

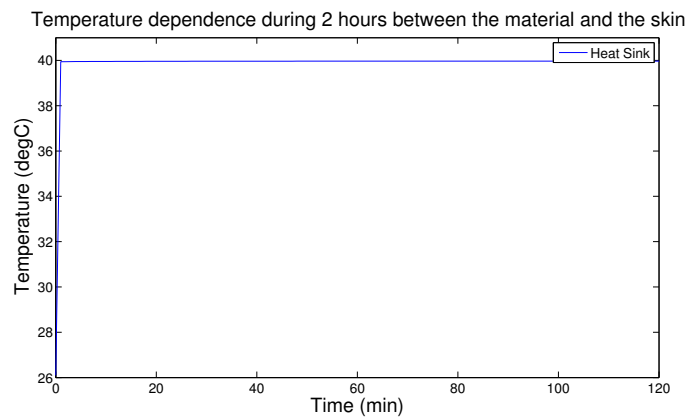
Figure 7.3: A graphical illustration of the heat distribution from an electrical copper heater on skin with Medtex (Silver) as the conductive medium after 2 hours in an isolated system.



(a) Graphical illustration of the heat distribution after 2 hours using a heat sink as the interface material.

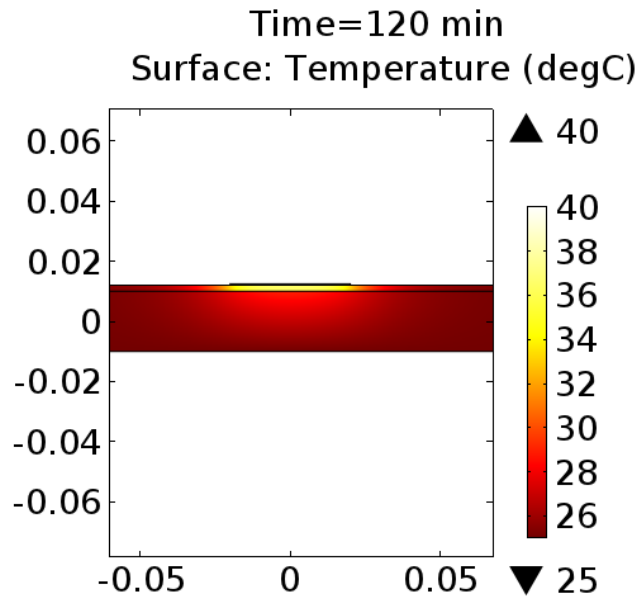


(b) The change in temperature in one point in the skin (Probe point 2) during 2 hours using a heat sink as the interface material.

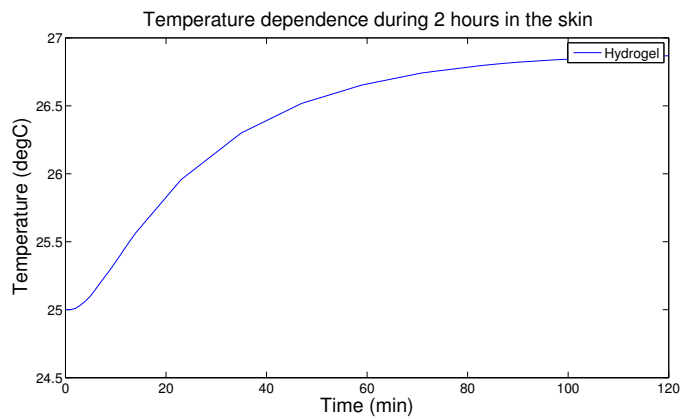


(c) The change in temperature in one point in-between the conductive material and the skin (Probe point 1) using a heat sink as the interface material.

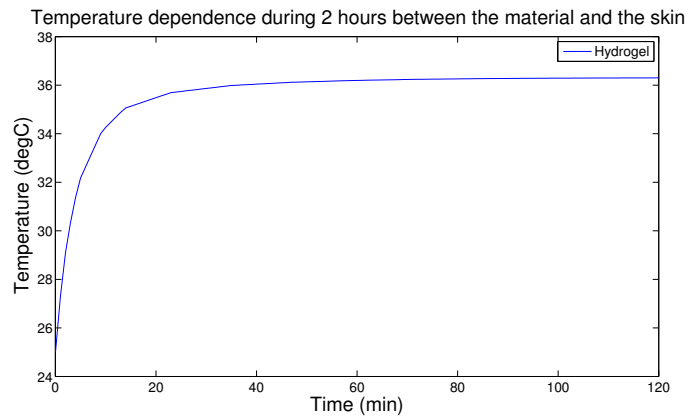
Figure 7.4: A graphical illustration of the heat distribution from an electrical copper heater on skin with highly conductive silicone rubber as the conductive medium after 2 hours in an isolated system.



(a) Graphical illustration of the heat distribution after 2 hours using a hydrogel containing 67% water as the interface material.



(b) The change in temperature in one point in the skin (Probe point 2) during 2 hours using a hydrogel containing 67% water as the interface material.



(c) The change in temperature in one point in-between the conductive material and the skin (Probe point 1) using a hydrogel containing 67% water as the interface material.

Figure 7.5: A graphical illustration of the heat distribution from an electrical copper heater on skin with First water hydrogel 67% water as the conductive medium after 2 hours in an isolated system.

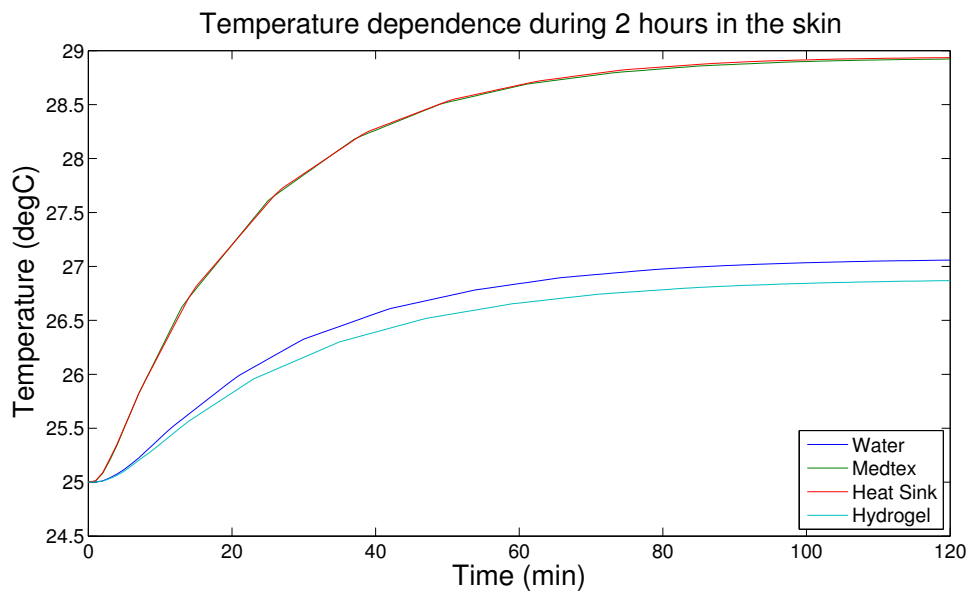


Figure 7.6: A picture showing the impact of all materials on the temperature in a point (Point Probe 1) in the skin. The graphs for Heat sink and Medtex overlap.

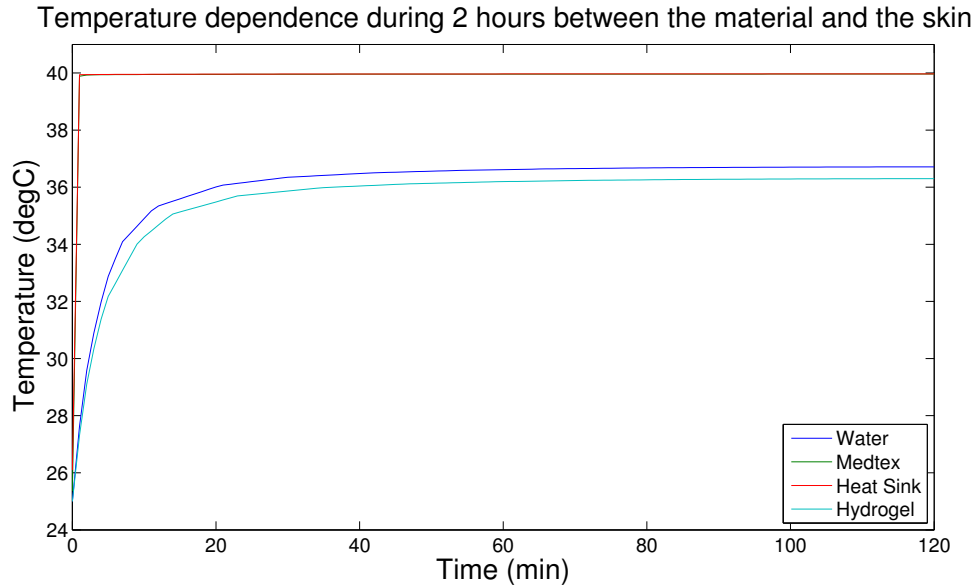
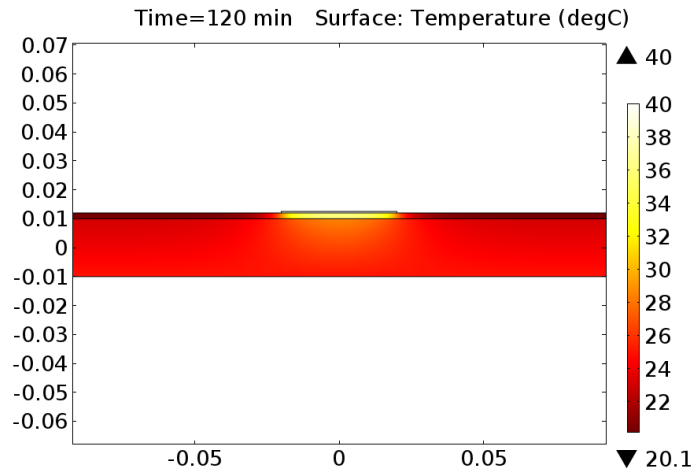


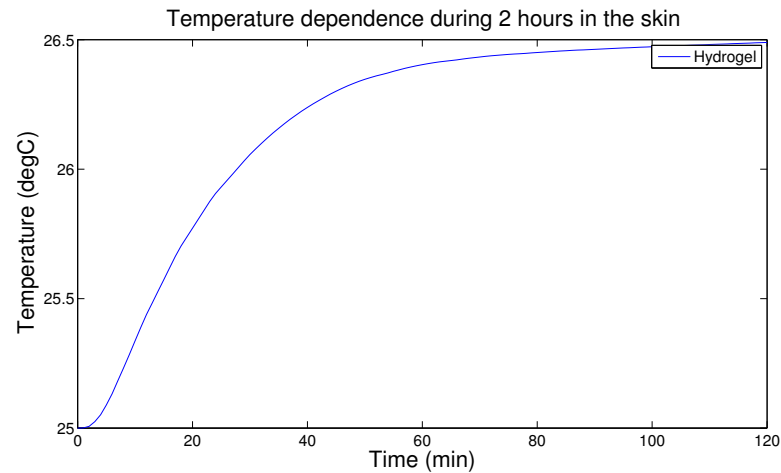
Figure 7.7: A picture showing the impact of all materials on the temperature in a point (Point Probe 2) between the material and the skin. The graphs for Heat sink and Medtex overlap.

7.2.2 Impact of a non isolated system

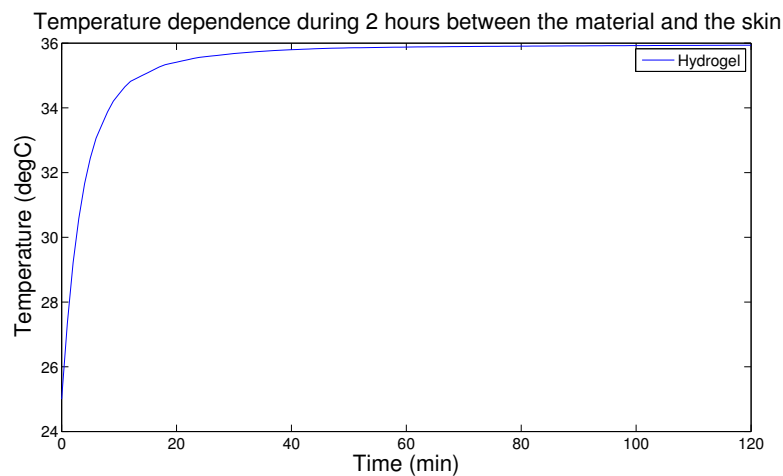
A simulation of the heat distribution in the material and skin and the water concentration in hydrogel containing 67% of water was made. This simulation used the Comsol model *Transport of diluted spices* to simulate the movement of water in the material. Since the heating process is intended to take place in an operation room it was assumed that only natural convection was present. Point probes were placed both in the middle of the skin under the heater and in between the material and the skin both under the heater and 5 cm away from the heater. For a more detailed description of the simulation and all chosen parameters for the material, see Appendix B. Figure 7.8 shows the thermal spreading over time in a system that is not thermally and water insulated. Figure 7.9 shows the change in water concentration in the hydrogel due to evaporation, and the change in temperature due to this change.



(a) Graphical illustration of the heat distribution after 2 hours using a hydrogel containing 67%water as the interface material in a non-isolated system.

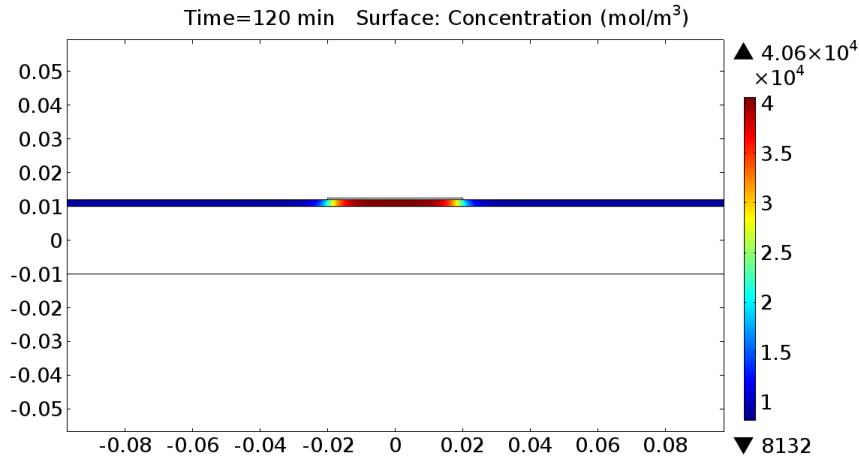


(b) The change in temperature in the skin (Point 2) during 2 hours using a hydrogel containing 67%water as the interface material in a non-isolated system.

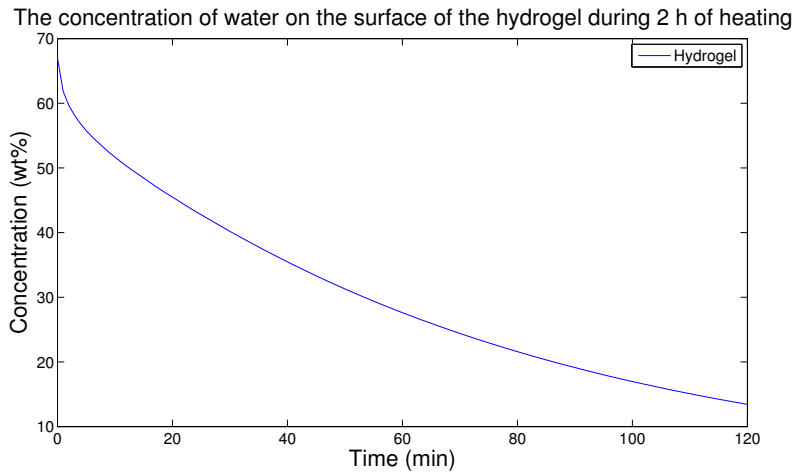


(c) The change in temperature in one point in-between the conductive material and the skin (Point 1) using a hydrogel containing 67%water as the interface material in a non-isolated system.

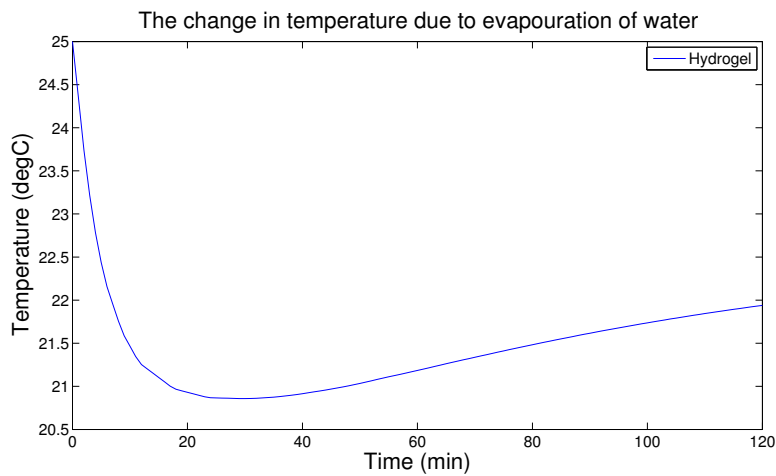
Figure 7.8: A graphical illustration of the heat distribution from an electrical copper heater on skin with First-water hydrogel 67% as the conductive medium after 2 hours in an non-isolated system.



(a) Graphical illustration of the water concentration after 2 hours using a hydrogel containing 67% water as the interface material in a non-isolated system.



(b) The change in concentration in one point at the surface of the hydrogel (Probe point 3) during 2 hours using a hydrogel containing 67% water as the interface material in a non-isolated system.



(c) The change in temperature in one point in-between the conductive material and the skin (Probe point 4) using a hydrogel containing 67% water as the interface material in a non-isolated system.

Figure 7.9: A graphical illustration of the water concentration in First-water hydrogel 67% as the conductive medium after 2 hours in a non-isolated system and the impact of the skin temperature.

7.3 Heat camera

Measurements using a heat camera was preformed on the materials. The findings will be presented here.

7.3.1 Thermal diffusivity and conductivity in the materials

Using the calculations and measurement it can be seen that non of the materials based on water are able to spread the heat much outside the area of the heat source. In the measurements the only material that was able to spread the heat evenly outside the heat source was the PGIS.

One of the other desired properties of the material was the ability to spread the heat evenly to avoid *hot spots* from the heat source. To evaluate the ratio between heater and material, the heat distribution on the material surface and the temperature stability in time, measurements were done during 30 minutes on all materials. Temperature indicators were placed on the reference hydrogel (indicator nr 1), on the tested material (indicator nr 2) and on the heater (indicator nr 3). All tests were performed on both the electrical heater and the iron heater. The spreading of heat in some of the materials on the electrical heater can be seen in Figure 7.14-7.16. Since a precise value of the thermal diffusivity wasn't known, the value was approximated by comperation by hydrogel 67% water. Figure 7.10 shows an example taken with the heat camera which shows the difference in thermal diffusivity between Tglobal Thermally conductive pad and hydrogel 67%. The results for all materials was tabulated together with the other thermal properties in Table 7.3. The ECG electrodes were too small to study if the thermal diffusivity was higher or lower than hydrogel.

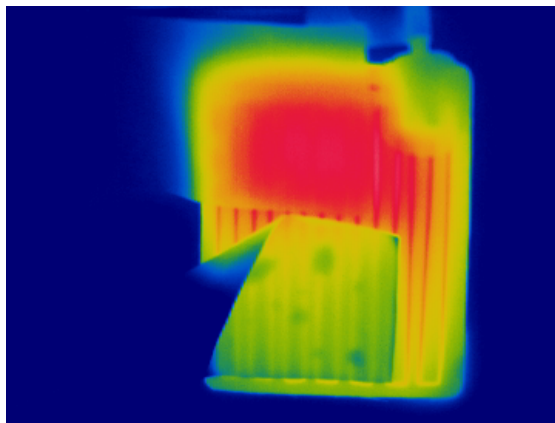


Figure 7.10: Thermal comprehension of a thermal conductive pad (L37-3S), on top, and a hydro gel (FW732-298).

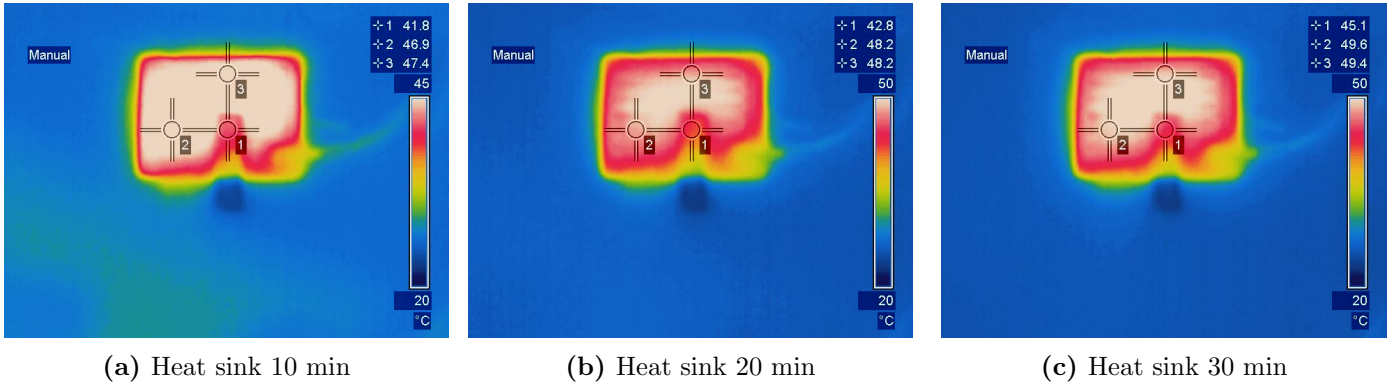


Figure 7.11: The measurement on tglobal heat sink. #1 Shows first water hydrogel 67%, #2 shows global heatsink and #3 the electrical heater.

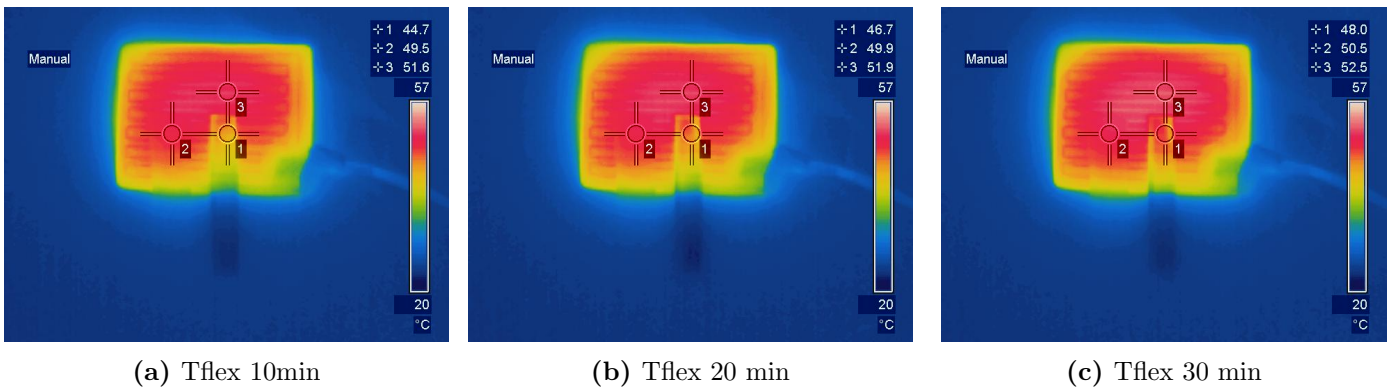


Figure 7.12: The measurement on Tflex. #1 Shows first water hydrogel 67%, #2 shows Tflex and # 3 electrical heater.

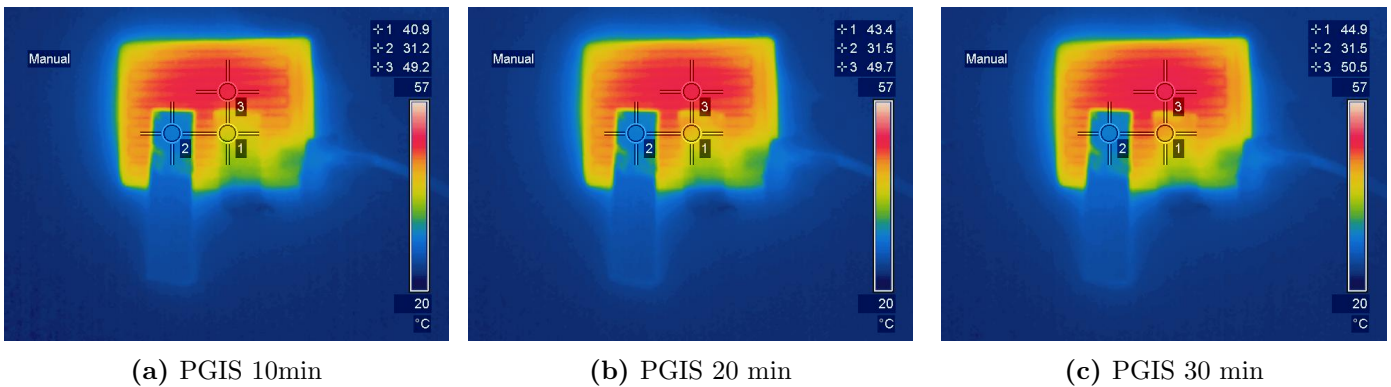
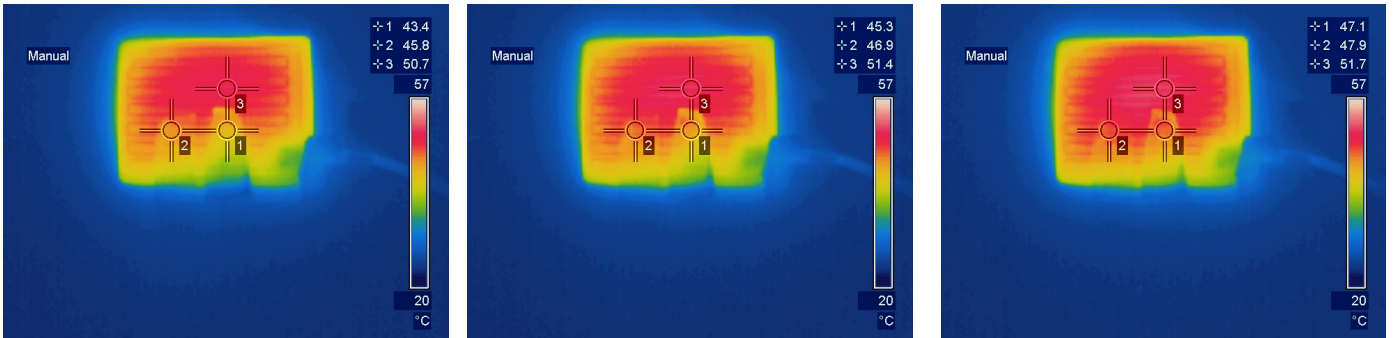


Figure 7.13: The measurement on PGIS (Pyrolytic Graphite Interface sheet). #1 Shows first water hydrogel 67%, #2 shows PGIS and and # 3 the electrical heater.

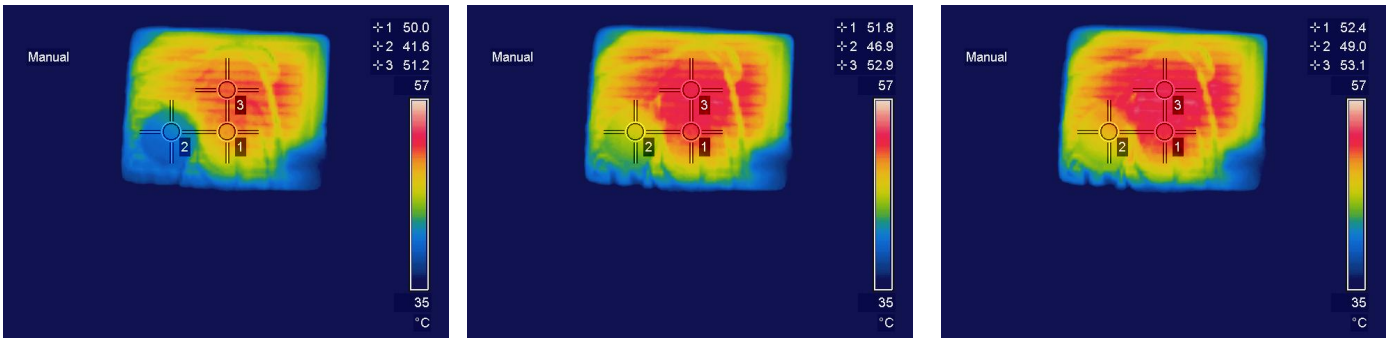


(a) Hollywog 10min

(b) Hollywog 20 min

(c) Hollywog 30 min

Figure 7.14: The measurement on Hollywog gel pad. #1 Shows first water hydrogel 67%, #2 shows Hollywog and #3 the electrical heater.

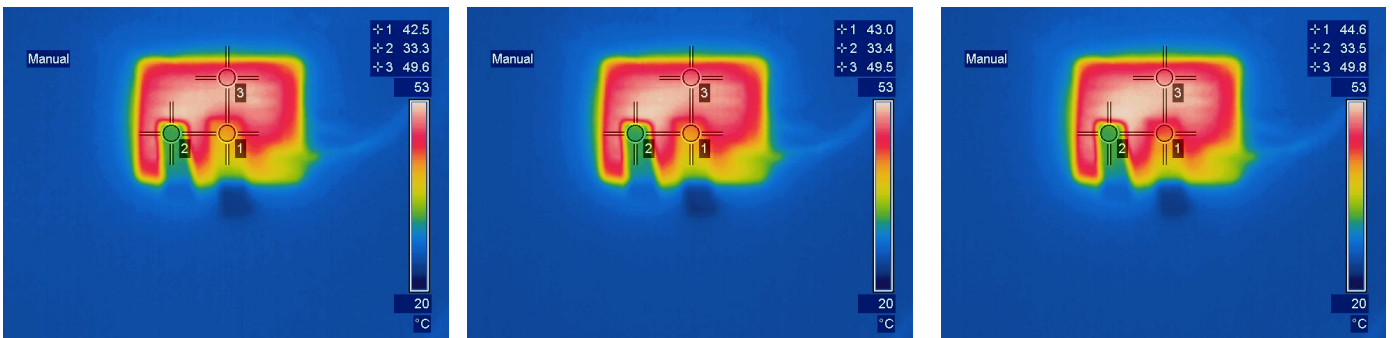


(a) Hydorgel 98% water 10min

(b) Hydorgel 98% water 20 min

(c) Hydorgel 98% water 30 min

Figure 7.15: The measurement on Hydorgel 98% water. #1 Shows first water hydrogel 67% and #2 shows the hydrogel 98% water #3 shows the electrical heater.



(a) Medtex 10min

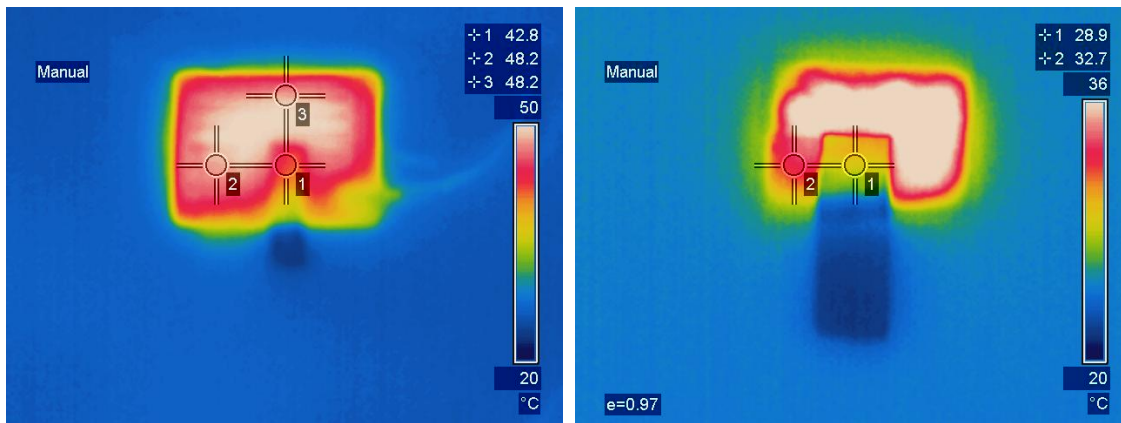
(b) Medtex 20 min

(c) Medtex 30 min

Figure 7.16: The measurement on Medtex. #1 Shows first water hydrogel 67%, #2 shows Medtex and #3 the electrical heater. The camera mood is set at $\epsilon = 0.97$ meaning the measured temperature on medtex is lower than the actual value. Using $\epsilon = 0.65$ gives a value of the temperature that is similar of the temperature of the heater.

7.3.2 Comparison between different warmers

Measurements were done on each material and on both the electrical heater and the iron heater during 30 minutes. IR-pictures were taken every 10 minutes. The materials performed differently on the different materials. An example showing the comparison between the performance of Heat sink and Hydrogel 67% water can be seen in Figure 7.17. The fraction between the heater and the material for all materials can be seen in Table 7.2. A graph arranging the different material after maximal temperature can be seen in Figure 7.18 and Figure 7.19.



(a) A hydrogel containing 67% water (Number 1) and Heat sink (Number 2) on the electrical heater. (b) A Hydrogel containing 67% water (Number 1) and Heat sink (Number 2) on the iron heater.

Figure 7.17: Hydrogel 67% water (Number 1) and Heat sink (Number 2) on the two different heaters.

| Time passed | Iron Heater | | | Electrical Heater | | |
|---------------------------------------|-------------|--------|--------|-------------------|--------|--------|
| | 10 min | 20 min | 30 min | 10 min | 20 min | 30 min |
| Hydrogel 67% water | 75% | 73 % | 71% | 88% | 89 % | 91% |
| Hydrogel 67% plastic | 94% | 96% | 97% | 100% | 100 % | 100% |
| Water bolus | 70% | 70 % | 79% | 70% | 81 % | 83% |
| Water bolus with gel | 79% | 83% | 86% | 71% | 74% | 75% |
| Burn dressing | 79% | 74% | 75% | 76% | 77% | 78% |
| Heat sink | 90% | 87% | 84% | 100% | 100% | 100% |
| Medtex | 70% | 71 % | 71% | 67% | 67% | 67% |
| Medtex and water | 74% | 72% | 72% | 69% | 64 % | 66% |
| Medtex and grease | 82% | 83% | 82% | 69% | 72% | 72% |
| Skintact | 73% | 72% | 74% | 75% | 76% | 76% |
| Red-Dot 2660 | 76% | 79 % | 78% | 81% | 84 % | 85% |
| Red-Dot 2560 | 78% | 79% | 78% | 86% | 87% | 92% |
| Red-Dot 2228 | 76% | 78 % | 80% | 73% | 77% | 75% |
| Hollywog | 98% | 98 % | 100% | 90% | 91% | 93% |
| Carbon rubber | 95% | 92 % | 97 % | 83% | 83 % | 83% |
| Tflex | 100% | 100 % | 100% | 96% | 96% | 96% |
| Tgard | 96% | 96 % | 96% | 93% | 94 % | 94% |
| Medema | 95% | 95 % | 95% | 92% | 92 % | 93% |
| PGIS | 71% | 71 % | 74% | 62% | 63% | 62% |
| Thick hydrogel 98% water with plastic | 79% | 84 % | 89% | 81% | 89% | 92% |
| Thin hydrogel 98% water with plastic | 85% | 88 % | 90% | 88% | 92 % | 93% |

Table 7.2: Temperature fraction between the material and the heat source. This table shows the values measured by the heat camera using the emissivity $\epsilon = 0.96$ on both the material and heater. This means the the fraction only should be considered rough approximations.

Iron Heater

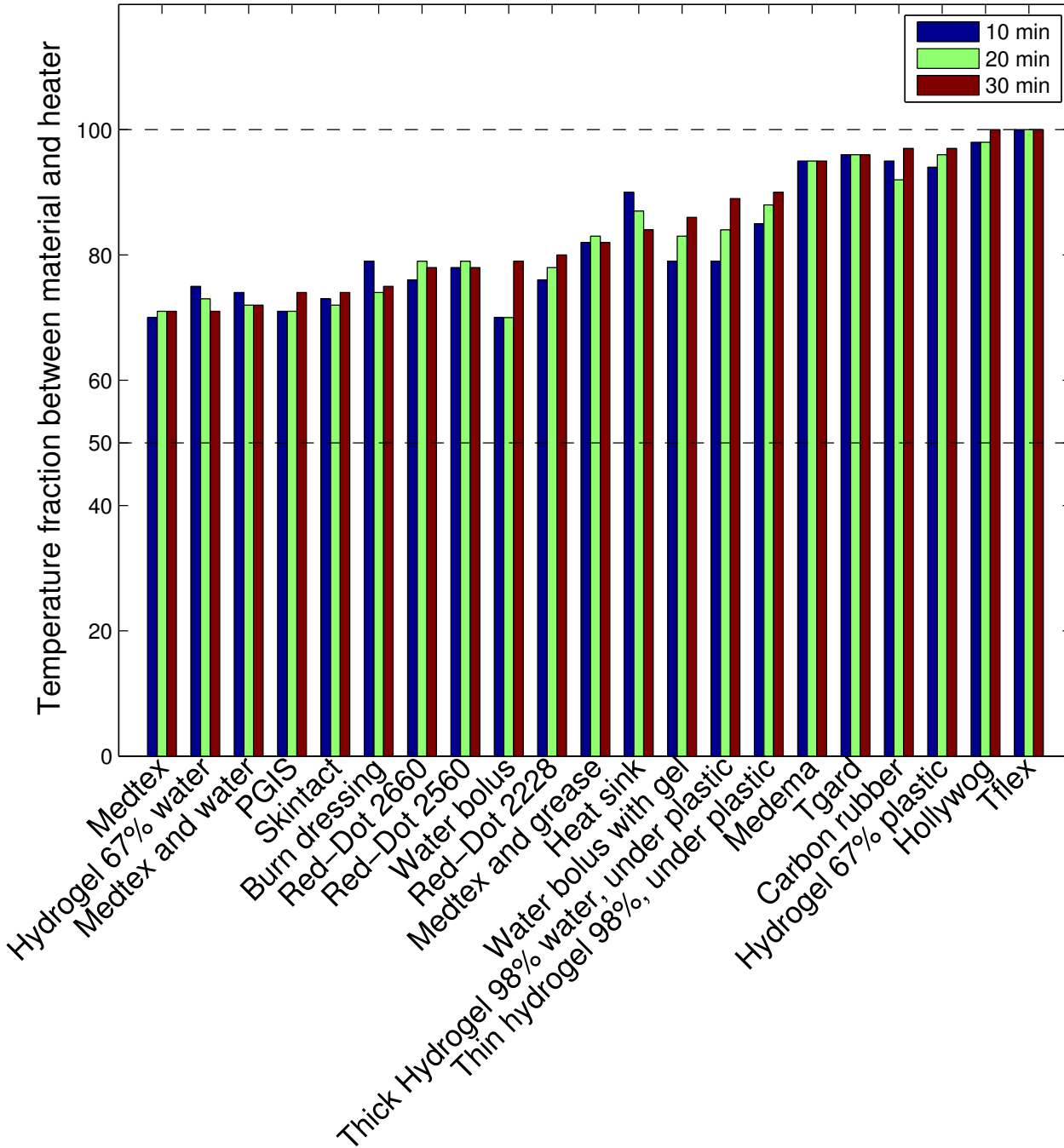


Figure 7.18: The fraction between the temperature on the surface of the commercial material and the heater on the iron heater sorted by maximal temperature.

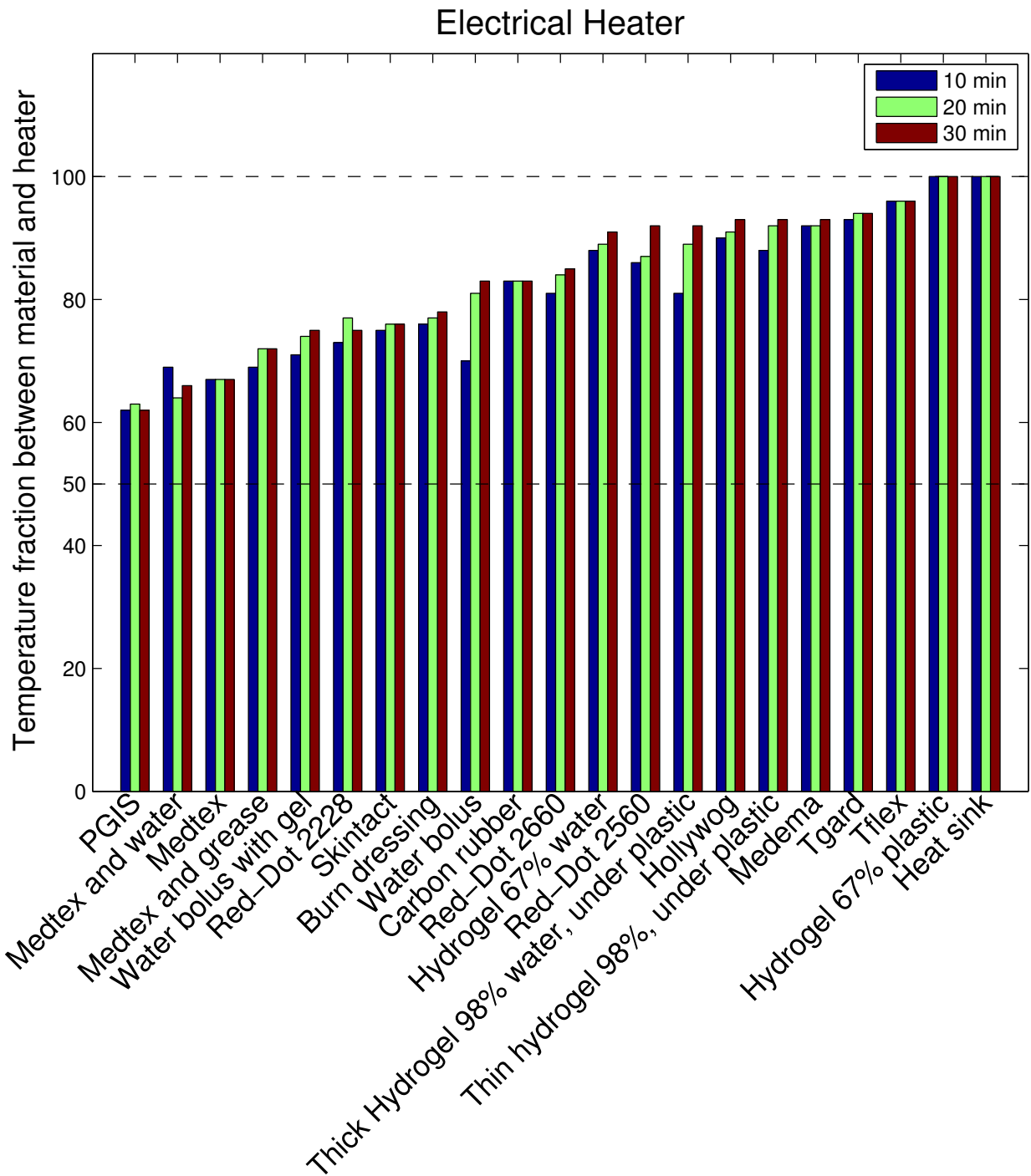


Figure 7.19: The fraction between the temperature on the surface of the commercial material and the heater on the electrical heater sorted by maximal temperature.

| Material | Even temperature in time | | Even temperature on surface | | High thermal diffusivity | High contact area | Water loss during measurement |
|--|--------------------------|------------------|-----------------------------|------------------|--------------------------|-------------------|-------------------------------|
| | <i>Iron heater</i> | <i>El heater</i> | <i>Iron heater</i> | <i>El heater</i> | | | |
| First-water hydrogel 67% | No | No | No | Yes | No (Reference) | Yes | Yes |
| First-water hydrogel 67% with plastic | No | Yes | No | Yes | No | Yes | No |
| T-global Heat Sink | No | Yes | Yes | Yes | Yes | Yes | No |
| Silver coated textile fibre (Medtex) | Yes | Yes | Yes | Yes | Yes | No | No |
| Silver coated Textile (Medtex) with water | No | No | Yes | Yes | Yes | Yes | Yes |
| Silver coated Textile (Medtex) with Grease | Yes | No | No | Yes | Yes | Yes | Optional |
| Burn dressing | Yes | No | Yes | No | No | Yes | Yes |
| Red-Dot 2560 ECG-gel | Yes | No | No | Yes | Unknown | Yes | No |
| Red-Dot 2660-3 ECG-gel | No | No | No | Yes | Unknown | Yes | No |
| Red- Dot 228 ECG-gel | No | No | No | No | Unknown | Yes | No |
| Skintact ECG-gel | Yes | Yes | Yes | No | Unknown | Yes | Yes |
| Carbon rubber | No | Yes | Yes | Yes | Yes | No | No |
| Pyrolyt Graphite Interface Sheet | Yes | Yes | Yes | Yes | Yes | No | No |
| Hydrogel 98% water | No | No | Yes | No | No | Yes | Yes |
| Liard Tgard | Yes | Yes | Yes | Yes | Yes | No | No |
| Liard Tflex | Yes | Yes | Yes | Yes | Yes | Yes | No |
| Medema | Yes | Yes | Yes | Yes | Yes | Yes | No |
| Hollywog | Yes | Yes | Yes | Yes | Yes | Yes | No |

Table 7.3: Summary of the different aspects of the commercial materials. All answers are based on the measurements, calculations and MSDS of the materials. If *Unknown* is stated, not enough information from the MSDS, calculations or the measurements have been available.

7.3.3 The impact of conductive particles

To study the impact of conductive particles in different materials a hydrogel containing 98% of water was manufactured. Some different salts and other conductive particles was then added in different concentrations to the gel. The particles were chosen from available substances with known thermal conductive properties. All salts were added in the concentration of 20 mM, 200mM and 2M. Carbon black particles were added in 0,01wt% and 0,1wt%. The solutions that was able to gel is shown in Table 7.4. The gels that didn't melt during the testing are shown as a graph in Figure 7.20. All materials were assumed to have a emissivity of $\epsilon = 0.96$. Since the gels contained a high amount of water, all measurements were performed under a water isolating plastic.

| Particle and koncentration | Fraction between temperature of the material and the heater | | | Comments |
|---------------------------------------|---|--------|--------|-----------------|
| | 10 min | 20 min | 30 min | |
| No Particles | 81% | 89% | 92% | |
| KCl 20 mM | 92% | 94% | 94% | Stable gel |
| KCl 200 mM | 95% | 98% | 100% | Stable gel |
| KCl 2M | 92% | 93% | 93% | Gooey gel |
| CaCl 20 mM | 92% | 95% | 95% | Almost Melted |
| CaCl 200 mM | 94% | 95% | 94% | Melted |
| Ag ₂ SO ₃ 20 mM | 90% | 92% | 92% | Very stable gel |
| CuSO ₄ 20 mM | 92% | 97% | 97% | Melted |
| NaCl 200 mM | 95% | 97% | 96% | Melted |
| Carbon black 0,01 wt% | 90% | 93% | 94% | very stable gel |
| Carbon black 0,1 wt% | 94% | 97% | 96% | very stable gel |

Table 7.4: Temperature fraction between the material and the heat source for hydrogels with different amount of conducting particles.

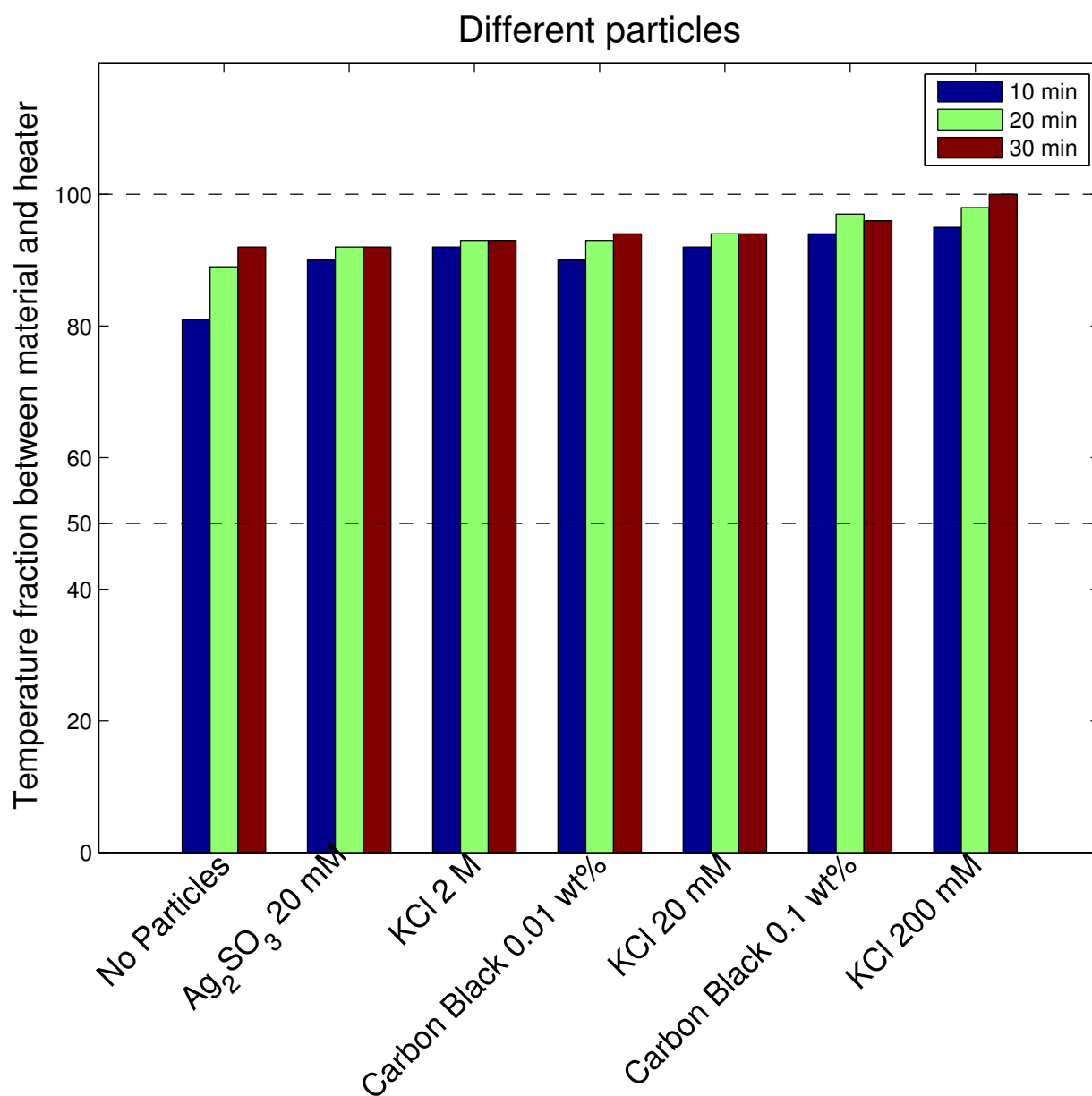


Figure 7.20: The fraction between the temperature on the surface of the different gels and the heater on the electrical heater sorted by maximal temperature.

7.3.4 The impact of water

To study the impact of water, measurements were performed on each commercial material containing a high amount of water with and without protective plastic on top. The plastic was thin and not thermally isolated. The results can be seen in Table 7.5. All measurements were done only on the electrical heater.

| Time passed | 10 min | 20 min | 30 min |
|----------------------------------|--------|--------|--------|
| Hydrogel 67% water | 88% | 89 % | 91% |
| Hydrogel 67% water under plastic | 100% | 100 % | 100% |
| Burnshield | 76% | 77% | 78% |
| Burnshield under plastic | 89% | 92% | 92% |
| Skintact | 75% | 76% | 76% |
| Skintact under plastic | 91% | 91 % | 91% |
| Medtex and water | 69% | 64% | 66% |
| Medtex and water under plastic | 92% | 93 % | 93% |
| Medtex and grease | 69% | 72% | 72% |
| Medtex and grease under plastic | 85% | 81 % | 77% |

Table 7.5: Temperature fraction between the material and the heat source for materials containing water, without or with protective plastic.

7.4 Human testing

To evaluate whether the conductivity is an essential parameter for the interface material, some human testings were made. The position of the indicators were places as Figure 7.21. To minimize the impact from movement of the indicators, the mean value of the three temperatures was also compared.

7.4.1 Thermal isolated system applying pressure

Measurements were done on one hand in the conductive bag. The tests were performed with the hand over the heater applying a pressure. A temperature comparison between the temperatures before and after heating can be seen in Table 7.6.

7.4.2 Thermal isolated system without pressure

Measurements were done on one hand in the conductive bag. The tests were performed with the heater over the hand minimizing the pressure. A temperature comparison between the temperatures before and after heating can be seen in Table 7.7.

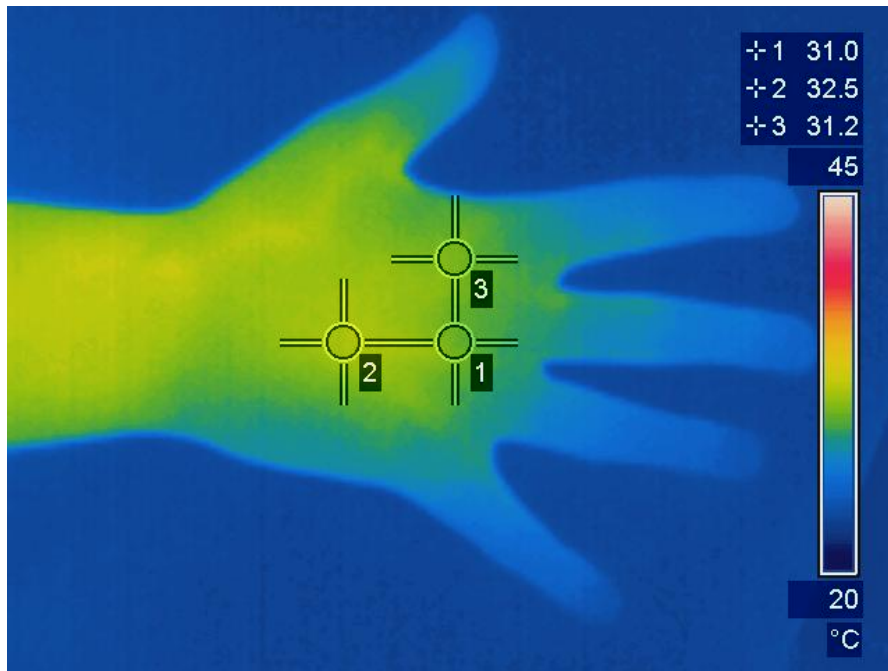


Figure 7.21: The position of the three different markers on a human hand.

| Position | No interface material | Hydrogel | Heat sink | Medtex |
|------------|-----------------------|----------|-----------|--------|
| # 1 | 117% | 117% | 117% | 115% |
| # 2 | 110% | 114% | 114% | 118% |
| # 3 | 120% | 114% | 120% | 121% |
| Mean value | 116% | 115% | 118% | 118% |

Table 7.6: Temperature fraction between a hand before and after being heated for 30 minutes with the iron heater in the isolated bag and the hand before heating.

| Position | No interface material | Hydrogel | Heat sink | Medtex |
|------------|-----------------------|----------|-----------|--------|
| # 1 | 111% | 117% | 111% | 117% |
| # 2 | 108% | 114% | 117% | 120% |
| # 3 | 110% | 116% | 112% | 120% |
| Mean value | 110% | 116% | 113% | 119% |

Table 7.7: Temperature fraction between a hand before and after being heated for 30 minutes with the iron heater in an insulated bag without applying pressure.

8

Evaluation of the Results

TO EVALUATE the different commercial materials, a Pugh matrix has been used. The results have been analyzed separately for the different heaters. First Water Hydrogel 67% water has been used as a reference. If the studied material better fulfilled the criteria when the reference material it was displayed with a "+", if the materials fulfilled the criteria equally it was displayed with an "S" and if the evaluated material fulfilled the criteria less than the reference it was displayed with a "-". Table 8.2 shows a Pugh matrix for the commercial materials on an electrical heater using hydrogel as a reference. Since the diffusivity of the ECG electrodes was unknown the value for the diffusivity was set to "S". The materials found most interesting is Heat sink, Medema and Hollywog. If the surface temperature of the heater is very even and the thermal diffusivity is found less important, Hydrogel containing 67% of water could also be suitable.

| Criteria | Material | Thin hydrogel 98% water | Thick hydrogel 98% water | Hollywog | Medema | Liard Tflex | Liard Tgard | Pyrolyt Graphite Interface sheet | Carbon rubber | Skintact | Red-Dot 2228 ECG-gel | Red-Dot 2660 ECG-gel | Red-Dot 2560 ECG-gel | Burnshield | Medtex with grease | Medtex with water | Medtex | T-global thermally conductive pad (heat sink) | First water Hydrogel 67% water with plastic | Hydrogel 67% water (reference) | |
|--------------------------|----------|-------------------------|--------------------------|----------|--------|-------------|-------------|----------------------------------|---------------|----------|----------------------|----------------------|----------------------|------------|--------------------|-------------------|--------|---|---|--------------------------------|---|
| | | + | - | - | + | - | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S |
| High temperature | | + | - | - | + | - | - | + | + | + | + | + | + | + | + | + | - | + | + | + | + |
| High thermal diffusivity | | + | - | - | + | - | - | + | + | + | + | + | + | + | + | + | + | + | + | + | + |
| No evaporation of water | | + | - | - | + | - | - | + | + | + | + | + | + | + | + | + | + | + | + | + | + |
| Even surface temperature | | + | - | - | + | - | - | + | + | + | + | + | + | + | + | + | + | + | + | + | + |
| Even temperature in time | | + | - | - | + | - | - | + | + | + | + | + | + | + | + | + | + | + | + | + | + |
| Big skin contact area | | + | - | - | + | - | - | + | + | + | + | + | + | + | + | + | + | + | + | + | + |
| Numbers of + | | 5 | 5 | 5 | 5 | 5 | 5 | 4 | 5 | 3 | 2 | 2 | 3 | 2 | 3 | 3 | 4 | 4 | 3 | 3 | |
| Numbers of S | | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 2 | 2 | 2 | 3 | 1 | 3 | 1 | 0 | 1 | 3 | 3 | |
| Numbers of - | | 0 | 0 | 0 | 0 | 0 | 1 | 2 | 1 | 1 | 2 | 2 | 0 | 3 | 0 | 2 | 2 | 1 | 0 | 0 | |
| Total | | 5 | 5 | 5 | 5 | 5 | 4 | 2 | 4 | 2 | 0 | 0 | 3 | -1 | 3 | 1 | 2 | 3 | 3 | 0 | |

Table 8.1: Pugh matrix for the commercial materials on iron heater using hydrogel as a reference.

| Criteria | Material | Thin hydrogel 98% water | Thick hydrogel 98% water | Hollywog | Medema | Liard Tflex | Liard Tgard | Pyrolyt Graphite Interface sheet | Carbon rubber | Skintact | Red-Dot 2228 ECG-gel | Red-Dot 2660 ECG-gel | Red-Dot 2560 ECG-gel | Burnshield | Medtex with grease | Medtex with water | Medtex | T-global thermally conductive pad (heat sink) | First water Hydrogel 67% water with plastic | Hydrogel 67% water (reference) | |
|--------------------------|----------|-------------------------|--------------------------|----------|--------|-------------|-------------|----------------------------------|---------------|----------|----------------------|----------------------|----------------------|------------|--------------------|-------------------|--------|---|---|--------------------------------|----|
| | | + | - | + | + | + | + | + | - | - | - | S | S | S | - | - | - | - | S | S | S |
| High temperature | | + | + | + | + | + | + | - | - | - | - | - | + | - | - | - | - | + | + | + | |
| High thermal diffusivity | | - | - | + | + | + | + | + | + | S | S | S | S | - | + | + | + | + | S | S | |
| No evaporation of water | | - | - | + | + | + | + | + | + | - | + | + | + | - | + | + | + | + | + | + | |
| Even surface temperature | | - | - | + | + | + | + | + | + | + | - | + | - | S | + | + | + | + | + | + | |
| Even temperature in time | | - | - | + | + | + | + | - | + | + | - | S | - | + | + | + | + | + | + | + | |
| Big skin contact area | | S | S | S | S | S | - | - | - | S | S | S | S | S | S | - | - | S | S | S | |
| Numbers of + | | 4 | 4 | 4 | 5 | 5 | 5 | 4 | 4 | 2 | 1 | 2 | 2 | 1 | 4 | 2 | 4 | 5 | 4 | 4 | |
| Numbers of S | | 2 | 2 | 2 | 1 | 0 | 1 | 0 | 0 | 2 | 3 | 3 | 3 | 2 | 1 | 0 | 0 | 1 | 2 | 2 | |
| Numbers of - | | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 2 | 2 | 1 | 1 | 1 | 3 | 1 | 4 | 2 | 0 | 0 | 0 | |
| Total | | 0 | 0 | 4 | 5 | 5 | 5 | 4 | 2 | 3 | -2 | 1 | 1 | -2 | 3 | -2 | 2 | 5 | 4 | 4 | -3 |

Table 8.2: Pugh matrix for the commercial materials on electrical heater using hydrogel as a reference.

9

Discussion

ACCORDING TO THE CALCULATIONS it is possible to spread the heat outside the heat source using a material with a high thermal diffusivity such as silver (Medtex) or heat sink if it is applied with high contact to a heater with constant surface temperature instead of constant power. This would give the same effect as using a larger heat source. Thus during the measurements this behavior was only obtained by PGIS. The calculations also simulated the temperature increase in the skin depending on different heaters. From the pictures it can be seen that the temperature is significantly higher for the materials with high thermal diffusivity, but since the temperature on the heater is stable this actually means that having a bigger area of the heater will lead to a higher temperature in the skin. Another conclusion drawn from the calculations is that a material with high diffusivity will lead to an almost instant temperature increase on the surface of the skin, while for a material with lower thermal diffusivity, the temperature increase will take longer. At last, the calculations showed that using a material containing water will not just lead to a decrease of water concentration in the material, but also decrease the temperature of the skin.

In the measurements on the human hand there are no correlations between a high conductivity of the interface material and increase in surface temperature on the hand. This could mean that a small difference in thermal conductivity of the interface material does not give a big temperature change on the temperature of the skin surface if the hand is placed in a well insulated environment. This could be due to some different factors such as that the blood transports the heat away from the skin or that *a high as possible* thermal conductivity is not a vital parameter in the material. According to the human testing using different interface materials without applying external pressure, the contact area doesn't seem to be vital either in an insulated environment. This could be due to that the thermal energy is being kept inside the thermal bag minimizing the impact of slow heat transfer between the heater and the skin. The results could possibly have been different using shorter test periods and making more measurements on each

material creating a mean value to correct for the difference in the different iron heaters. The properties could also be found to be of greater importance in an environment that is less well insulated.

From the study using different conductive particles in a gel, it can be seen that the presence of conductive particles can increase the thermal conductivity within the material. The particles found most interesting are Potassium Chloride and carbon black.

9.1 Reliability

Since the measured temperature using the heat camera depends on the emissivity and the precise value of the emissivity is unknown, the value of the fraction between the material and heater is just a rough approximation. Since the emissivity of Medtex was hard to approximate, the temperature of these measurements are even more unreliable. Since Medtex did not qualify as one of the more suitable materials, no further studies was found to be necessary. In the evaluation of different conductive particles there is also an issue concerning the making of the gels. Since it was hard to manufacture gels with the same thickness all the time, the mass of the different gels differed. This means that the amount of energy needed to heat the gels to a given temperature differs between the different samples. This is also a problem in the measurements on the commercial materials, since the materials have different sizes and different thickness, this will also effect the results.

9.2 Further studies

If the temperature ratio between the material and the heat source will be found essential, more accurate measurements should be done using for example thermo couples or covering the materials with full black paint using the heat camera. Depending on the positioning of the heaters, it could also be of interest to study the pressure sensibility of the materials to evaluate the risk for hot spots on the skin if an external pressure is put on the heater. It could also be of interest to study if it is possible to develop another type of hydrogel or silicone gel containing conductive particles but less water.

10

Conclusion

ACCORDING TO THE STUDY and the evaluation using a Pugh matrix some suitable interface material suggestions were found. The best choice of material depends on the type of heater chosen. Both Medema and Hollywog could be used successfully both on the electrical heater and the iron heater. On the iron heater, Liard Tflex could also be of interest. On the electrical type of heater T-global thermally conductive pad (Heat sink) is a suitable material. If the heater have an even surface temperature, a hydrogel could also be suitable.

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A

The making of hydrogels

Making of Polymer solutions

Xanthan polymer solution:

99% miliQ water

1% Xanthan mash-sh from Grinsted

Slowly stir the polymer powder into the water using a magnetic stirrer. Heat the solution to approximately 85 °C during 30 minutes.

LGB polymer solution:

99% miliQ water

1%LGB 246 from Grinsted

Slowly stir the polymer powder into the water using a magnetic stirrer. Heat the solution to approximately 85 °C during 30 minutes.

The making of gels

Mix Xanthan and LBG 1:1. Heat the solution to above 80 °C for about 15 minutes. Pour the solution in a suitable container. Let the gel cool down.

B

Report from Comsol

The following report is generated directly from Comsol MultiPhysics.

Hud Material

**Date**

May 17, 2014 4:52:08 PM

Contents

- 1. [Global Definitions](#)**
 - 1.1. [Parameters 1](#)
- 2. [Component \(comp1\)](#)**
 - 2.1. [Definitions](#)
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 - 2.4. [Heat Transfer in Solids \(ht\)](#)
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- 3. [Study](#)**
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 - 4.3. [Tables](#)
 - 4.4. [Plot Groups](#)

1. Global Definitions

1.1. Parameters 1

Parameters

| Name | Expression | Description |
|-----------|---------------------------|--|
| T_air | 20[degC] | Surrounding temp |
| conc | 0.67 | weight percent water concentration in hydrogel |
| rho_hydro | 1090[kg/m ³] | density hydrogel |
| M_H2O | 18[g/mol] | water molucular weight |
| c0 | conc*rho_hydro/M_H2O | initial moistor concentration of water |
| D | 2.3e-9[m ² /s] | Selfdiffusion water |
| C_m | 0.003 | specific moisture capacity |
| h_T | 25[W/(m ² *K)] | Heat transfer coefficient |
| c_b | 0.02*rho_hydro/M_H2O | Air moisture concentration |
| k_m | 1.29e-9[kg/(m*s)] | Moisture conductivity |

| | | |
|-----|---------------------------------|---|
| h_m | 1.67e-6[kg/(m ² *s)] | Mass transfer coefficient in mass units |
| k_c | h_m/(rho_hydro*C_m) | mass transfer coefficient |
| D_m | 5e-10 [m ² /s] | Surface moisture diffusivity |
| Ida | 2.3e6[J/kg]*M_H2O | Molar latent heat of vapourisation |

2. Component (Comp1)

2.1. Definitions

2.1.1. Variables

Variables 1a

Selection

| | |
|------------------------|--------------|
| Geometric entity level | Entire model |
|------------------------|--------------|

| Name | Expression | Description |
|------|----------------------|------------------------|
| dT | (T - 0[degC]) [1/K] | Temperature difference |

2.1.2. Probes

Domain Point Probe 1

| | |
|------------|--------------------|
| Probe type | Domain point probe |
|------------|--------------------|

Domain Point Probe 2

| | |
|------------|--------------------|
| Probe type | Domain point probe |
|------------|--------------------|

Domain Point Probe 3

| | |
|------------|--------------------|
| Probe type | Domain point probe |
|------------|--------------------|

2.1.3. Selections

Explicit 1

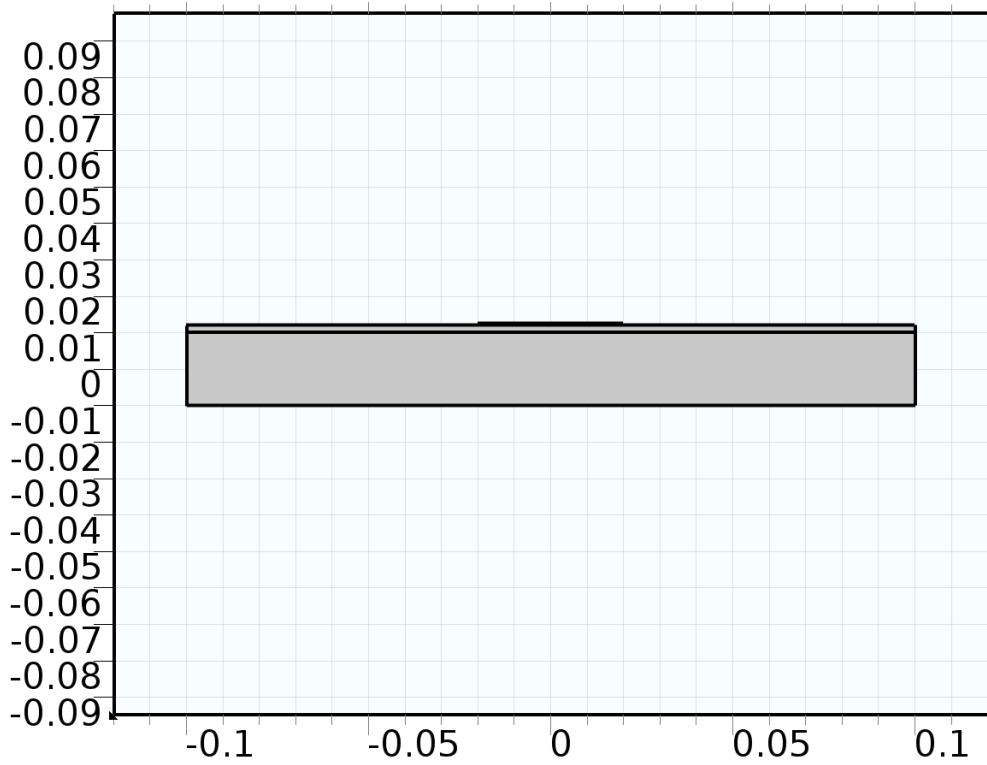
| |
|-----------------------|
| Selection type |
| Explicit |
| Selection |
| Boundary 12 |

2.1.4. Coordinate Systems

Boundary System 1

| | |
|------------------------|-----------------|
| Coordinate system type | Boundary system |
| Identifier | sys1 |

2.2. Geometry 1



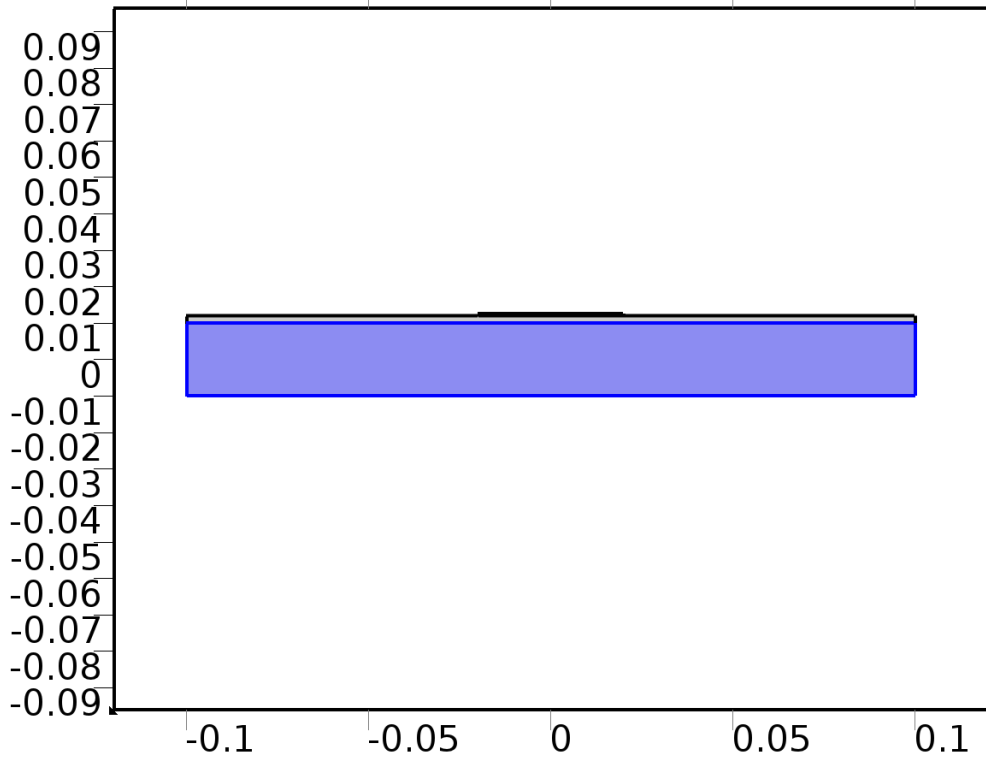
Geometry 1

Units

| | |
|--------------|-----|
| Length unit | m |
| Angular unit | deg |

2.3. Materials

2.3.1. Skin

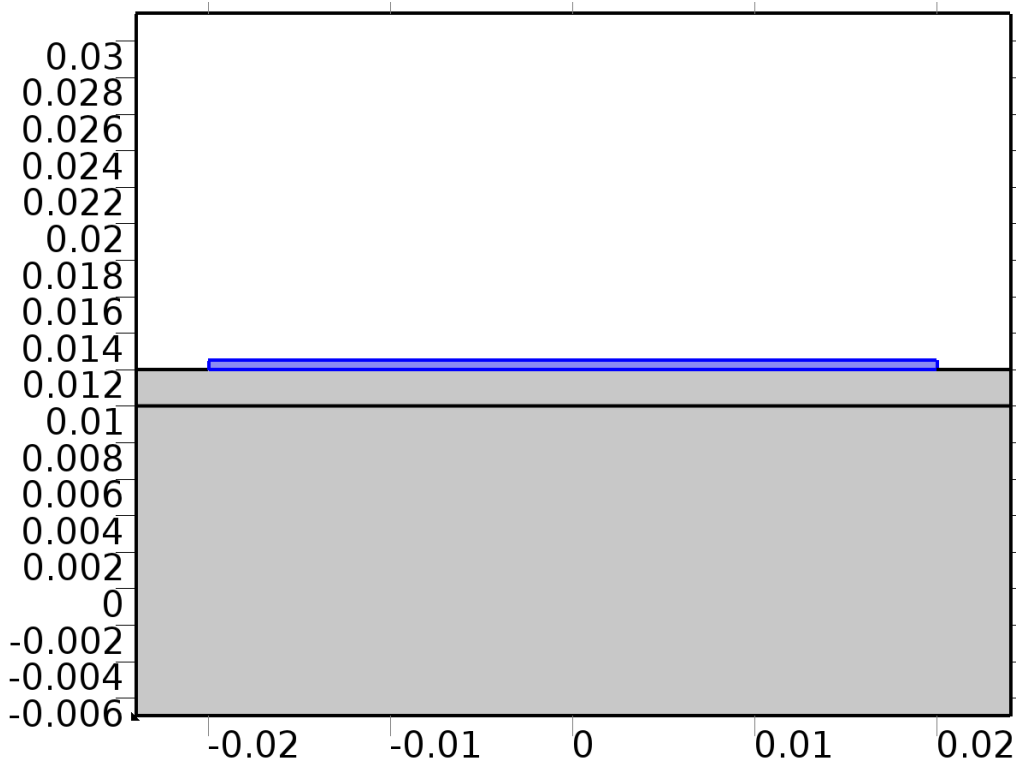


Skin

Selection

| | |
|------------------------|----------|
| Geometric entity level | Domain |
| Selection | Domain 1 |

2.3.2. Copper

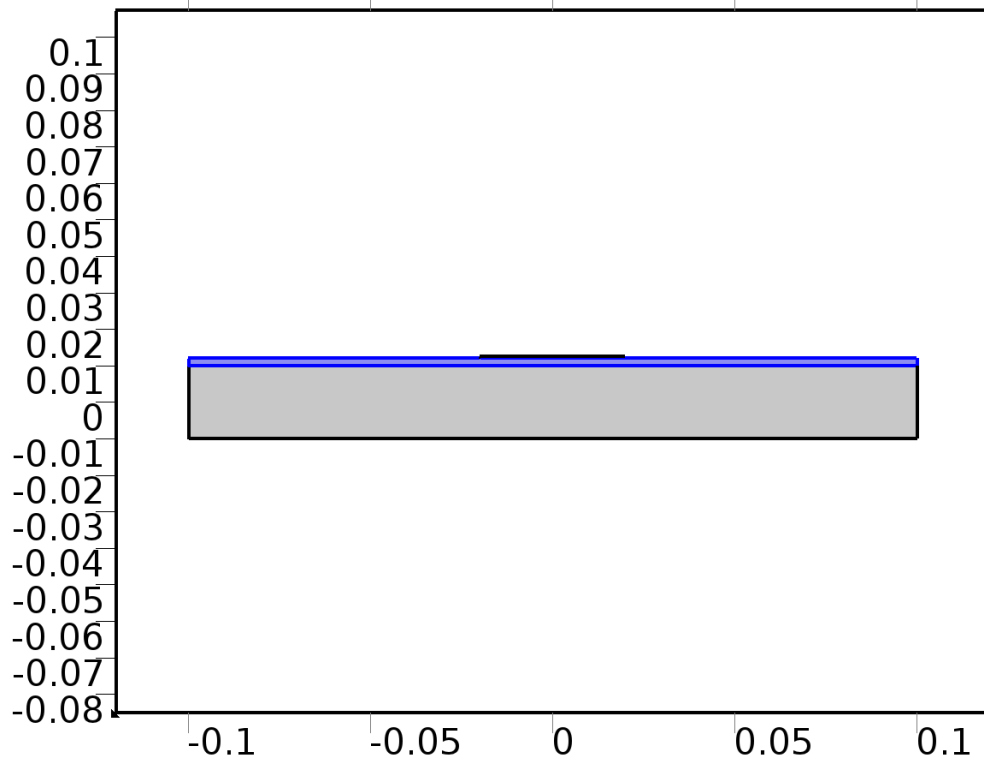


Copper

Selection

| | |
|------------------------|----------|
| Geometric entity level | Domain |
| Selection | Domain 3 |

2.3.3. Hydrogel 67

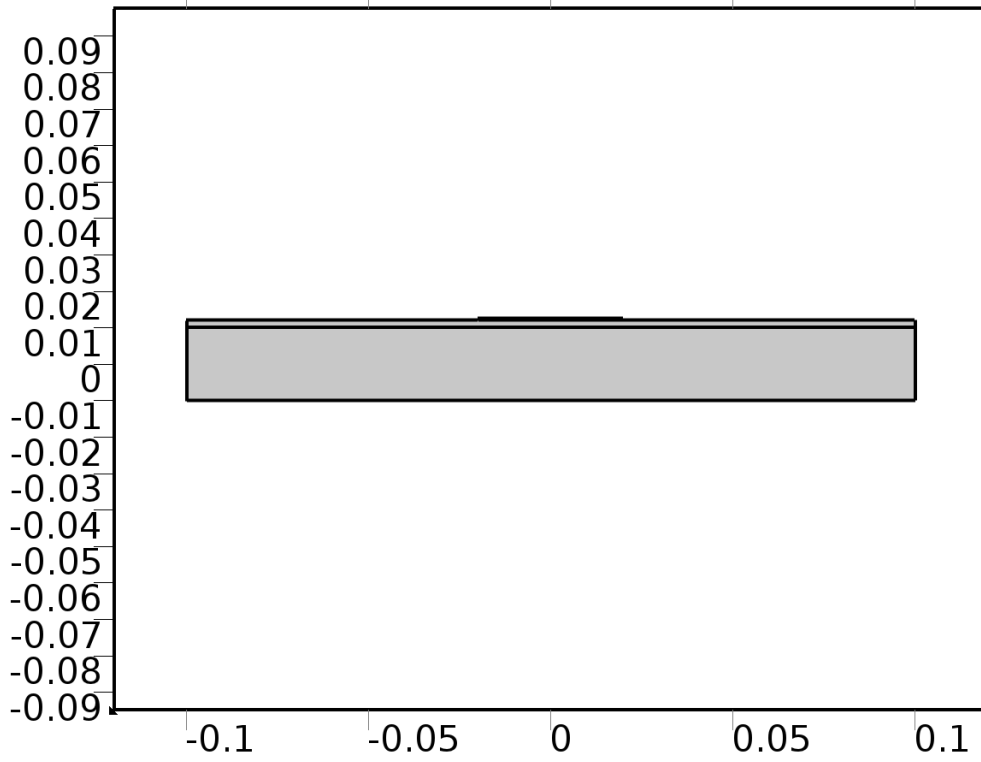


hydrogel 67

Selection

| | |
|------------------------|----------|
| Geometric entity level | Domain |
| Selection | Domain 2 |

2.3.4. Air

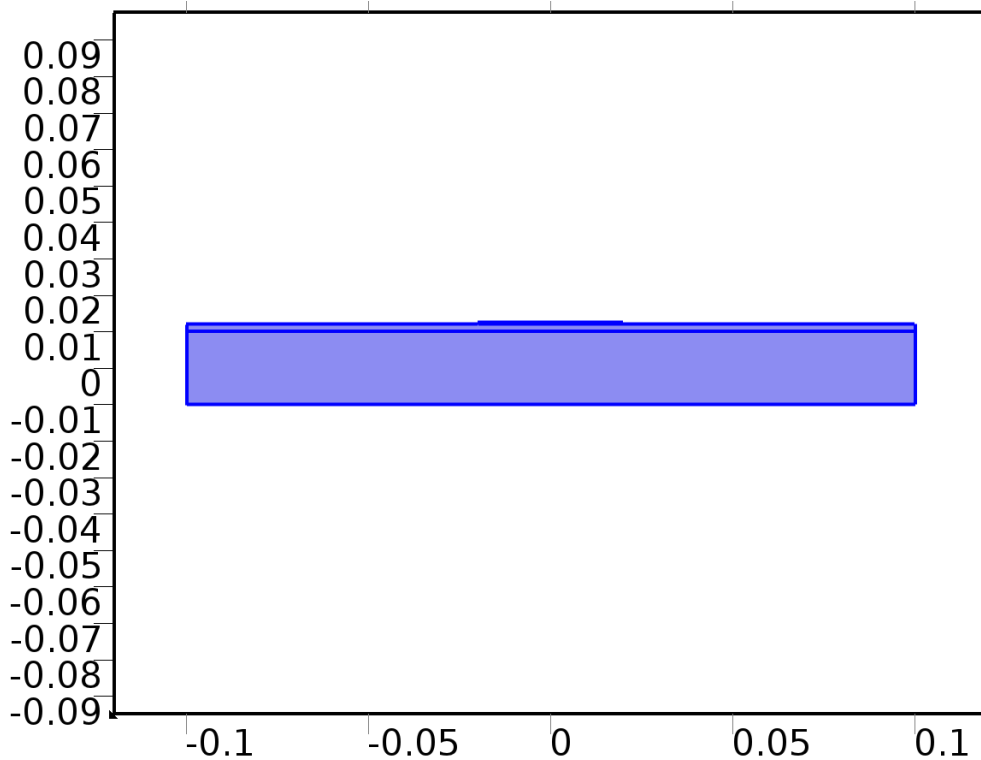


Air

Selection

| | |
|------------------------|------------|
| Geometric entity level | Domain |
| Selection | No domains |

2.4. Heat Transfer in Solids (Ht)

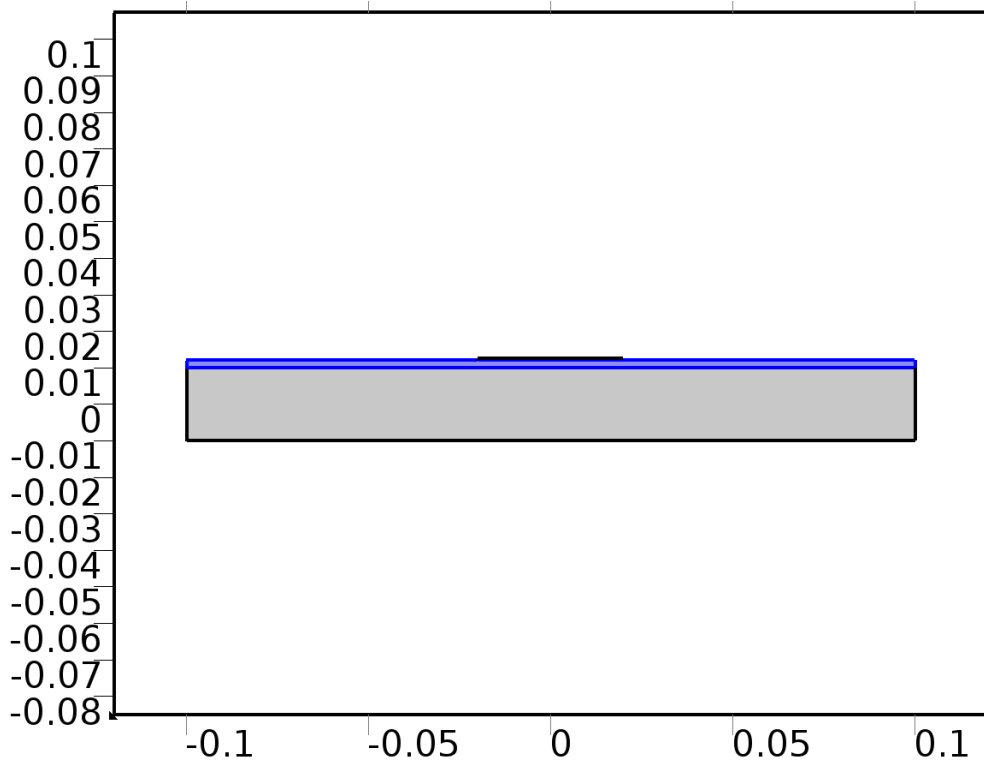


Heat Transfer in Solids

Features

| |
|---------------------------|
| Heat Transfer in Solids 1 |
| Thermal Insulation 1 |
| Initial Values 1 |
| Symmetry 1 |
| Outflow 1 |
| Initial Values 2 |
| Thermal Contact 1 |
| Heat Flux 1 |
| Temperature 1 |
| Temperature 2 |

2.5. Transport of Diluted Species (Chds)

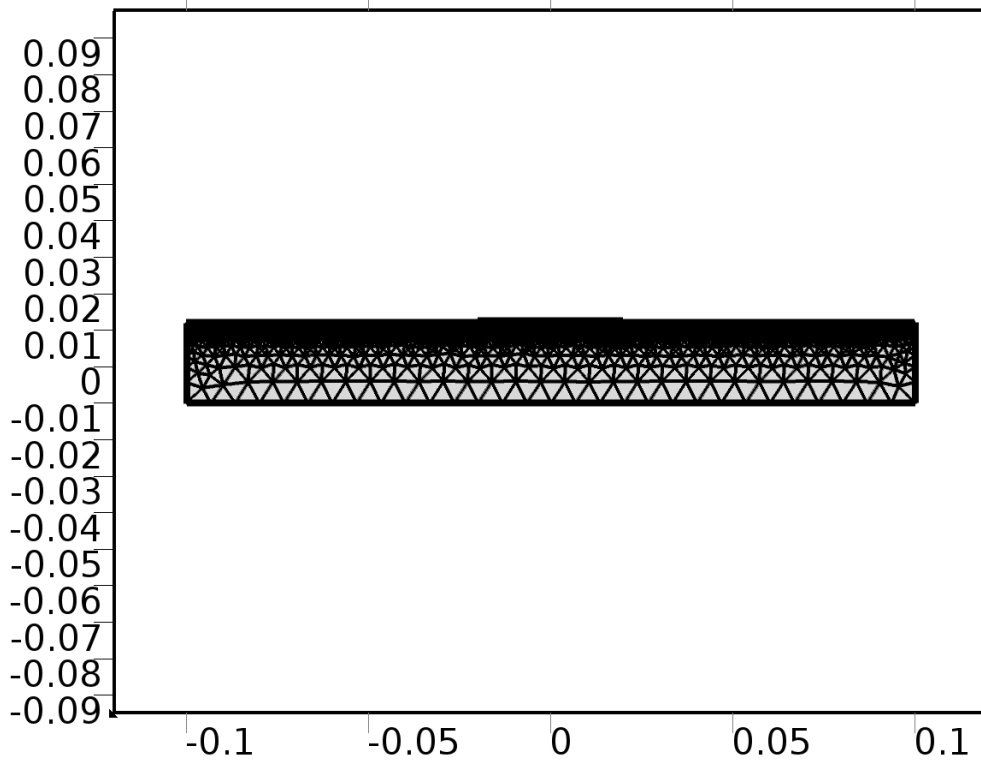


Transport of Diluted Species

Features

| |
|----------------------|
| Diffusion |
| No Flux 1 |
| Initial Values 1 |
| Flux 1 |
| Periodic Condition 1 |

2.6. Mesh 1



Mesh 1

3. Study

3.1. Stationary

Study settings

| Property | Value |
|--------------------------------|-------|
| Include geometric nonlinearity | Off |

Mesh selection

| Geometry | Mesh |
|--------------------|-------|
| Geometry 1 (geom1) | mesh1 |

Physics selection

| Physics | Discretization |
|-------------------------------------|----------------|
| Heat Transfer in Solids (ht) | physics |
| Transport of Diluted Species (chds) | physics |

3.2. Time Dependent

Study settings

| Property | Value |
|--------------------------------|-------|
| Include geometric nonlinearity | Off |

Times: range(0,1,120)

Mesh selection

| Geometry | Mesh |
|--------------------|-------|
| Geometry 1 (geom1) | mesh1 |

Physics selection

| Physics | Discretization |
|-------------------------------------|----------------|
| Heat Transfer in Solids (ht) | physics |
| Transport of Diluted Species (chds) | physics |

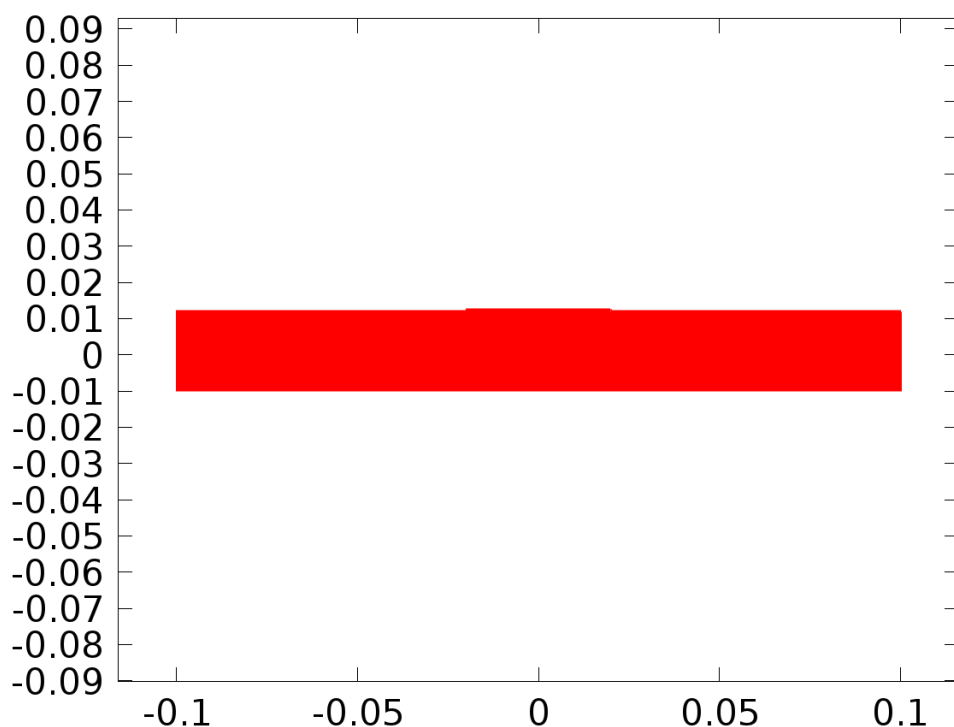
4. Results

4.1. Data Sets

4.1.1. Solution 1

Solution

| Name | Value |
|-----------|-----------------------|
| Solution | Solver 1 |
| Component | Save Point Geometry 1 |

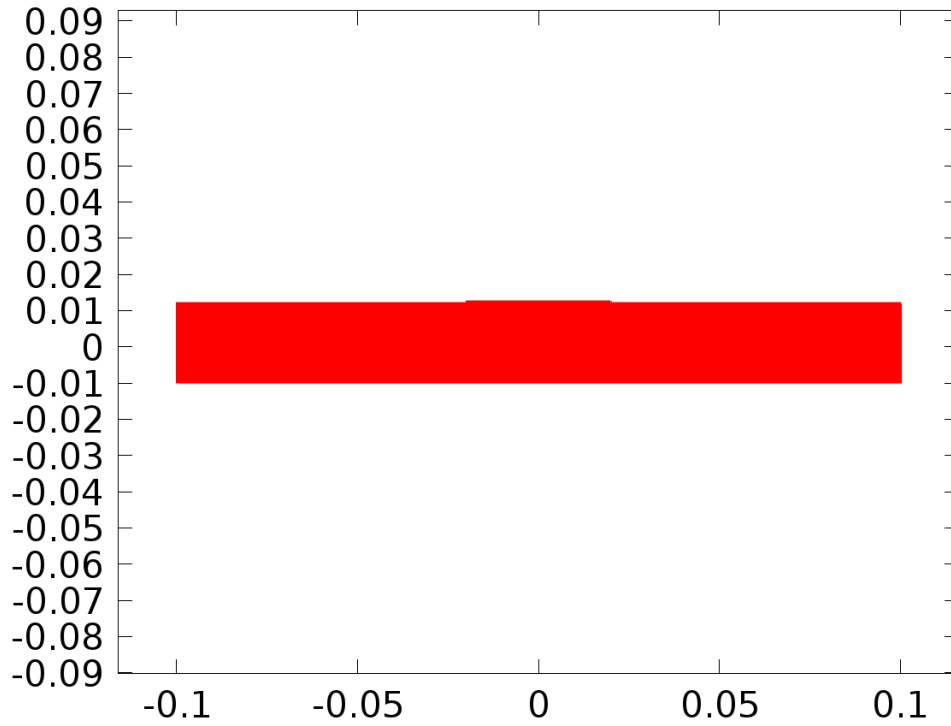


Data set: Solution 1

4.1.2. Probe Solution 2

Solution

| Name | Value |
|-----------|-----------------------|
| Solution | Solver 1 |
| Component | Save Point Geometry 1 |
| Frame | Spatial (x, y, z) |

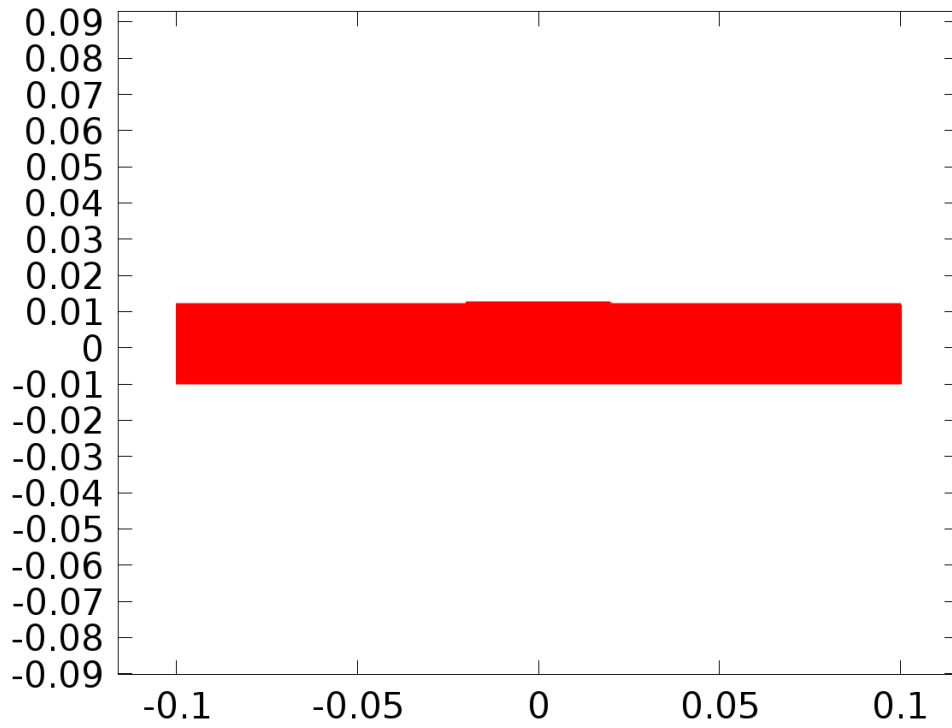


Data set: Probe Solution 2

4.1.3. Solution 1

Solution

| Name | Value |
|-----------|-----------------------|
| Solution | Solver 1 |
| Component | Save Point Geometry 1 |



Data set: Solution 1

4.1.4. Cut Point 2D 1

Data

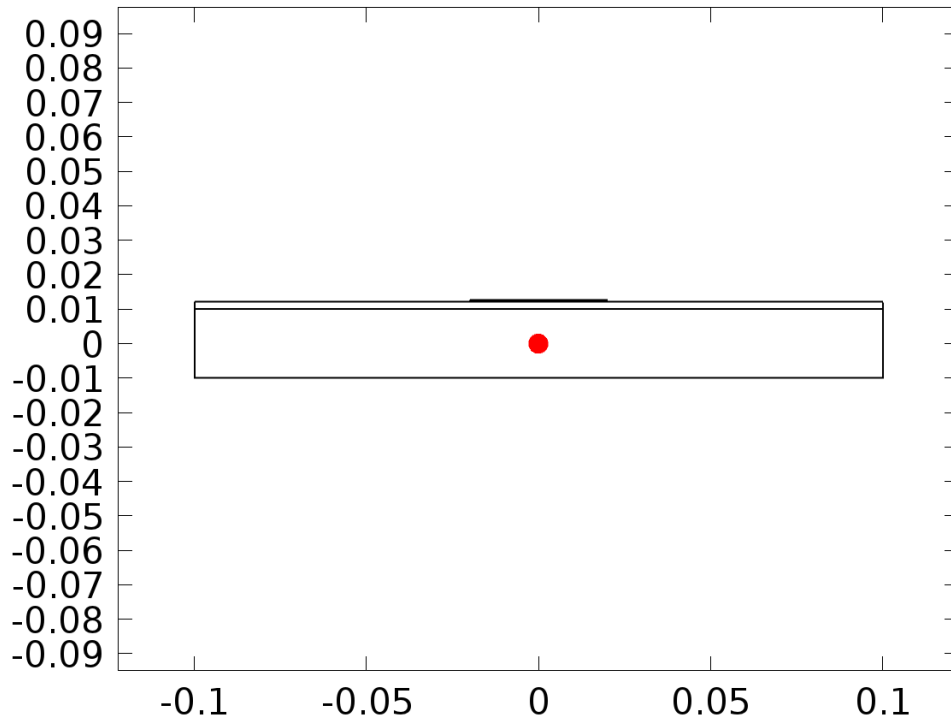
| Name | Value |
|----------|------------|
| Data set | Solution 1 |

Point data

| Name | Value |
|--------------|-------------|
| Entry method | Coordinates |

Settings

| Name | Value |
|------|-------|
| x | 0 |
| y | 0 |

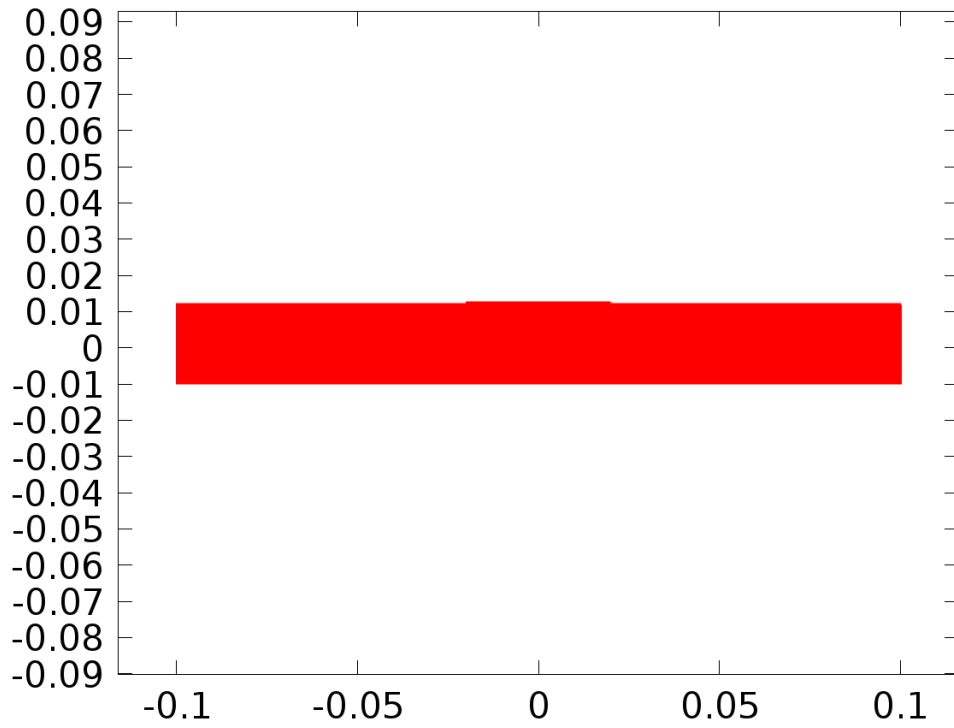


Data set: Cut Point 2D 1

4.1.5. Solution 1

Solution

| Name | Value |
|-----------|-----------------------|
| Solution | Solver 1 |
| Component | Save Point Geometry 1 |



Data set: Solution 1

4.1.6. Domain Point Probe 1

Data

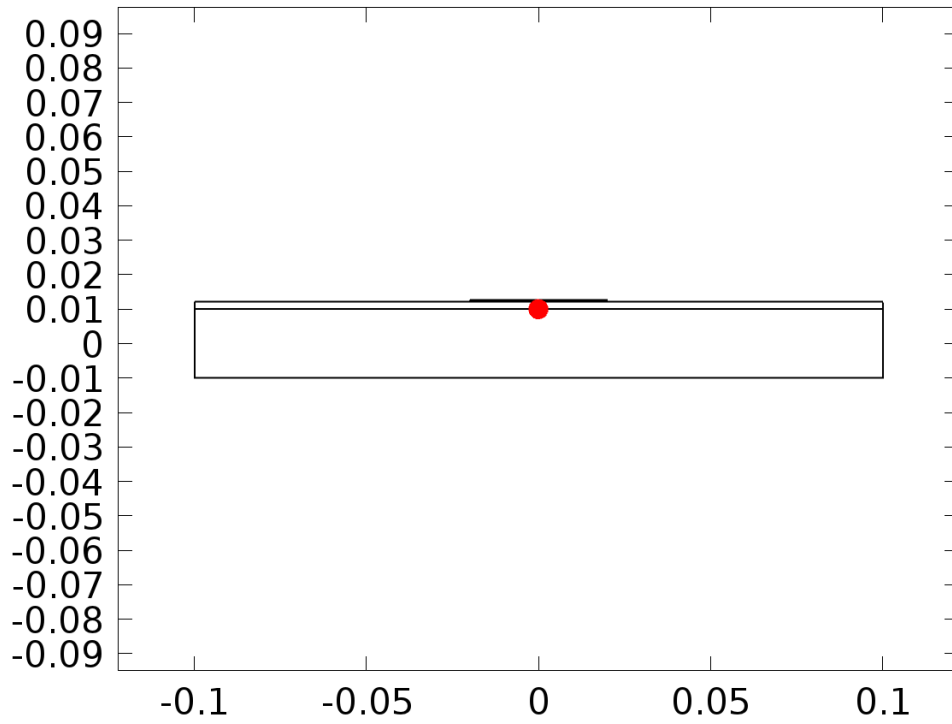
| Name | Value |
|----------|------------------|
| Data set | Probe Solution 2 |

Point data

| Name | Value |
|--------------|-------------|
| Entry method | Coordinates |

Settings

| Name | Value |
|------|-------|
| x | 0 |
| y | 0.01 |



Data set: Domain Point Probe 1

4.1.7. Domain Point Probe 2

Data

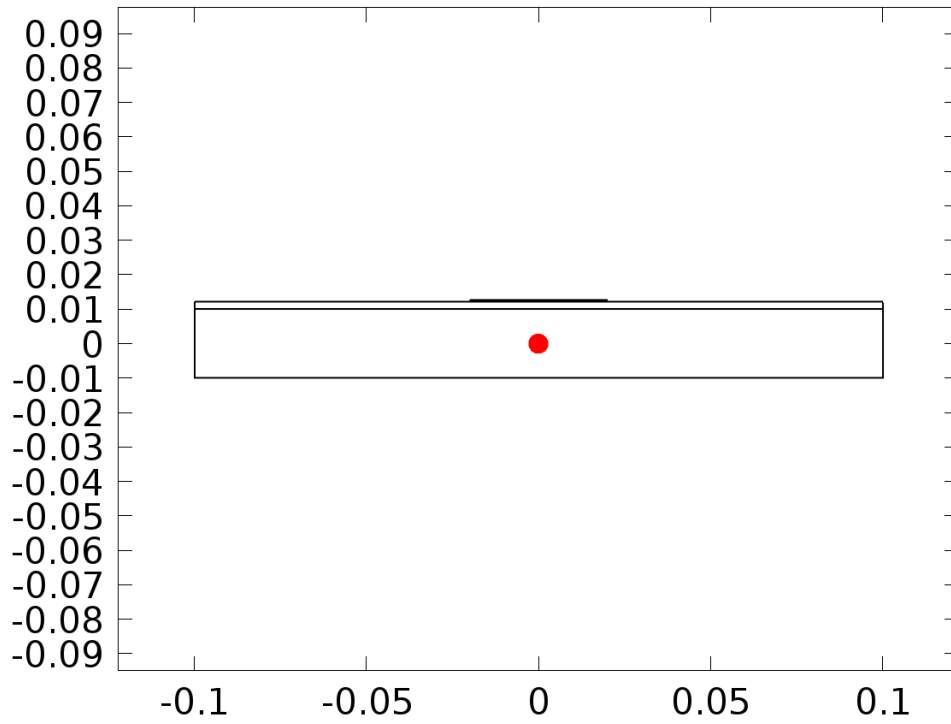
| Name | Value |
|----------|------------------|
| Data set | Probe Solution 2 |

Point data

| Name | Value |
|--------------|-------------|
| Entry method | Coordinates |

Settings

| Name | Value |
|------|-------|
| x | 0 |
| y | 0 |

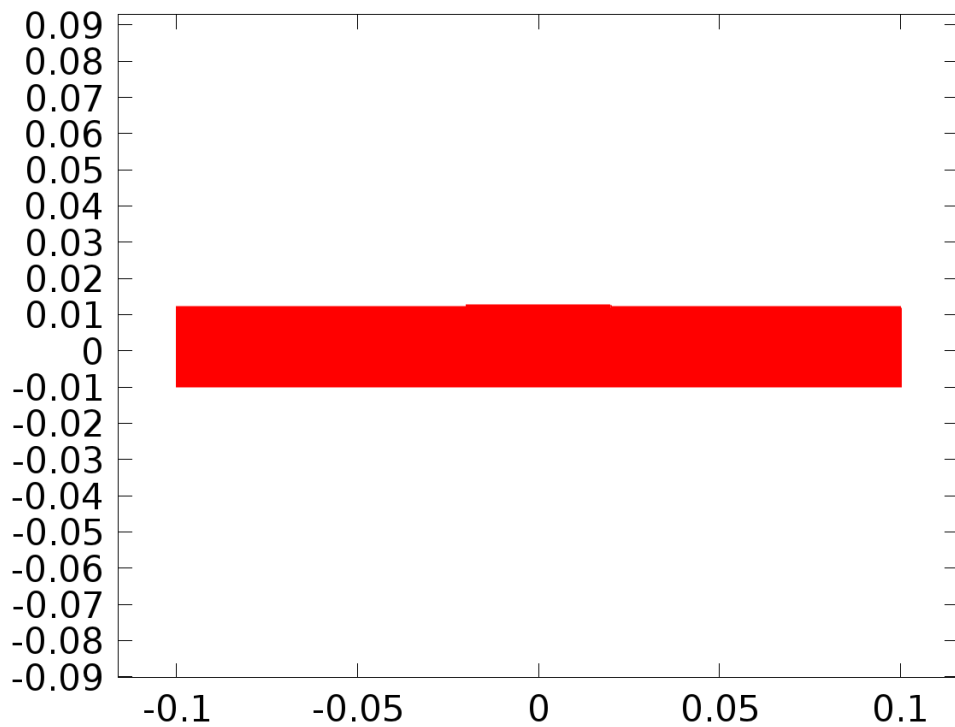


Data set: Domain Point Probe 2

4.1.8. Solution 1

Solution

| Name | Value |
|-----------|-----------------------|
| Solution | Solver 1 |
| Component | Save Point Geometry 1 |

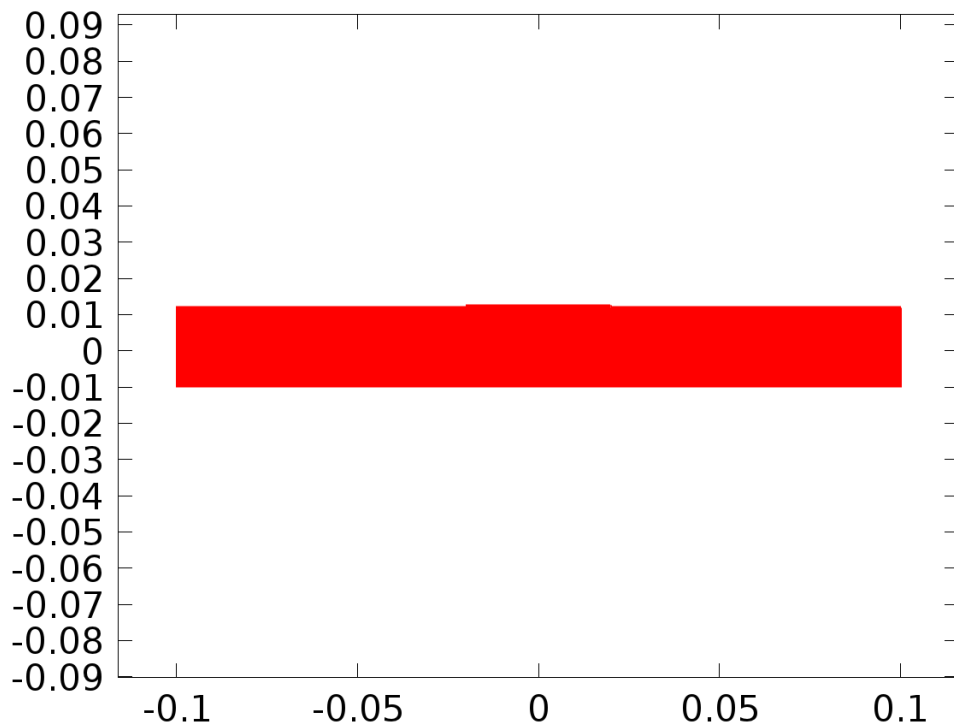


Data set: Solution 1

4.1.9. Solution 1

Solution

| Name | Value |
|-----------|-----------------------|
| Solution | Solver 1 |
| Component | Save Point Geometry 1 |



Data set: Solution 1

4.2. Derived Values

4.2.1. Point Probe Expression 1

Data

| Name | Value |
|----------|----------------------|
| Data set | Domain Point Probe 1 |

Expression

| Name | Value |
|-------------|-------------|
| Expression | T |
| Unit | K |
| Description | Temperature |

4.2.2. Point Probe Expression 2

Data

| Name | Value |
|----------|----------------------|
| Data set | Domain Point Probe 2 |

Expression

| Name | Value |
|------------|-------|
| Expression | T |
| Unit | K |

| | |
|-------------|-------------|
| Description | Temperature |
|-------------|-------------|

4.3. Tables

4.3.1. Probe Table 1

Probe Table 1

| t | Temperature (K), Point Evaluation | Temperature (K), Point Evaluation | Temperature (K), Point Evaluation | c/c0*conc (1), Point Evaluation |
|------------|--------------------------------------|--------------------------------------|--------------------------------------|------------------------------------|
| 0 | 298.15002 | 298.15 | 298.15 | 0.66997 |
| 0.35088 | 298.15004 | 298.15 | 298.14999 | 0.66918 |
| 0.70177 | 298.15019 | 298.15 | 298.14997 | 0.66841 |
| 1.40353 | 298.15128 | 298.15 | 298.14981 | 0.6669 |
| 2.80706 | 298.16643 | 298.15 | 298.14733 | 0.66411 |
| 5.61412 | 298.24418 | 298.15 | 298.13356 | 0.65928 |
| 11.22825 | 298.47323 | 298.15 | 298.08733 | 0.65153 |
| 22.4565 | 298.97632 | 298.15 | 297.96729 | 0.64035 |
| 44.91299 | 299.91589 | 298.15013 | 297.70252 | 0.62551 |
| 67.36949 | 300.76722 | 298.15062 | 297.43824 | 0.61444 |
| 112.28249 | 302.16939 | 298.15506 | 296.95744 | 0.59852 |
| 157.19548 | 303.3223 | 298.16442 | 296.53284 | 0.58593 |
| 247.02147 | 304.93455 | 298.20451 | 295.8799 | 0.56692 |
| 336.84746 | 306.05751 | 298.26263 | 295.38456 | 0.55141 |
| 516.49944 | 307.27171 | 298.41308 | 294.78347 | 0.52674 |
| 696.15142 | 307.93264 | 298.5711 | 294.42317 | 0.50536 |
| 1055.45538 | 308.46662 | 298.83905 | 294.1233 | 0.46835 |
| 1414.75934 | 308.70113 | 299.04497 | 294.01885 | 0.43488 |
| 1774.06329 | 308.82001 | 299.19648 | 294.00738 | 0.4041 |
| 2492.67121 | 308.95674 | 299.40904 | 294.08153 | 0.34791 |
| 3211.27913 | 309.0106 | 299.51839 | 294.23933 | 0.29946 |
| 3931.27913 | 309.03664 | 299.5705 | 294.42092 | 0.25793 |
| 4651.27913 | 309.05296 | 299.59643 | 294.59814 | 0.2225 |
| 5371.27913 | 309.06478 | 299.61207 | 294.76034 | 0.19233 |
| 6091.27913 | 309.07421 | 299.62393 | 294.90404 | 0.16664 |
| 6811.27913 | 309.08225 | 299.63419 | 295.02905 | 0.14479 |
| 7531.27913 | 309.08933 | 299.64341 | 295.13668 | 0.12619 |

4.3.2. Evaluation 2D

Interactive 2D values

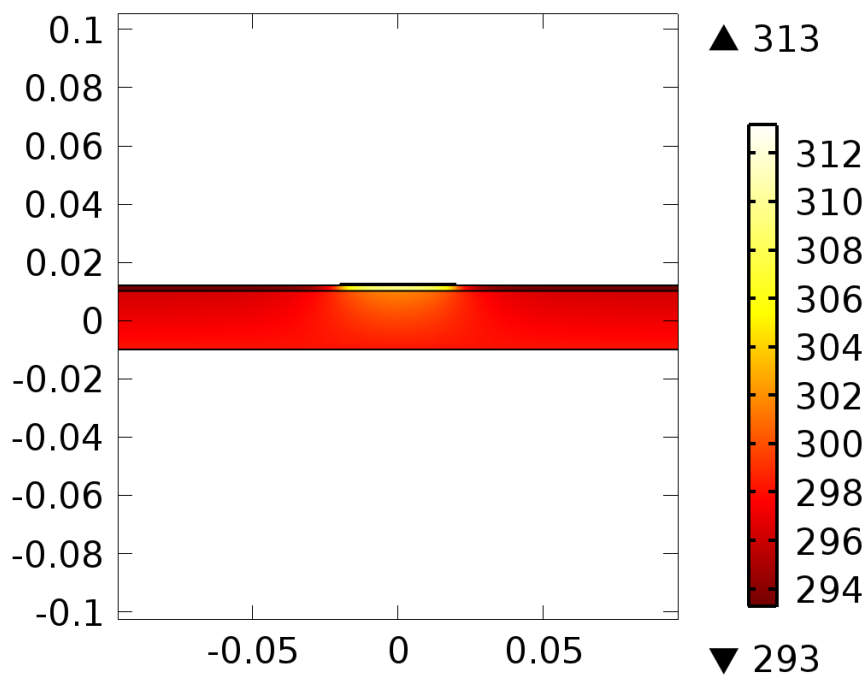
Evaluation 2D

| x | y | Value |
|----------|---------|-------------|
| -0.0718 | 0.0103 | 31699.40378 |
| -0.07382 | 0.01004 | 31890.10552 |
| -0.07298 | 0.0103 | 31699.15719 |
| -0.07298 | 0.01063 | 31273.40203 |

4.4. Plot Groups

4.4.1. Temperature (Ht)

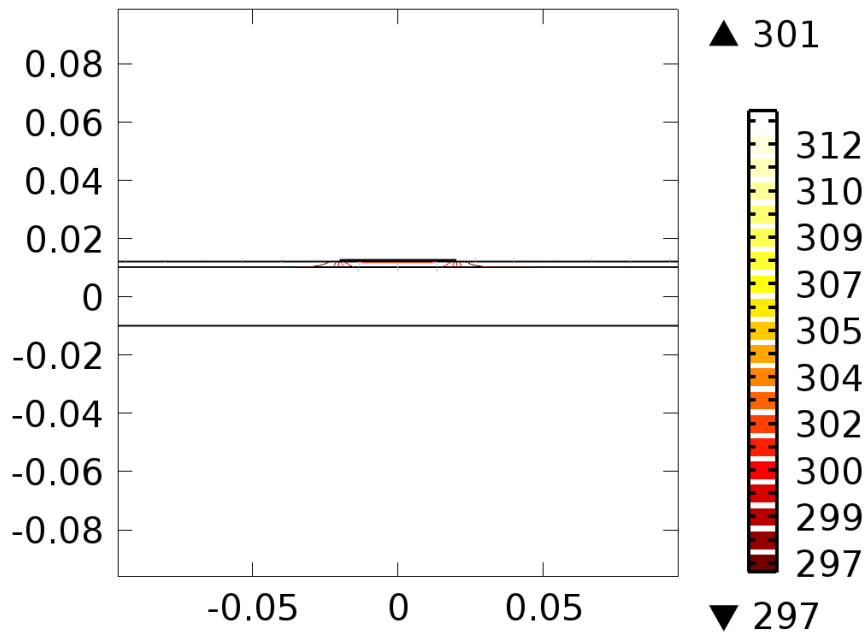
Time=120 min Surface: Temperature (K)



Time=120 min Surface: Temperature (K)

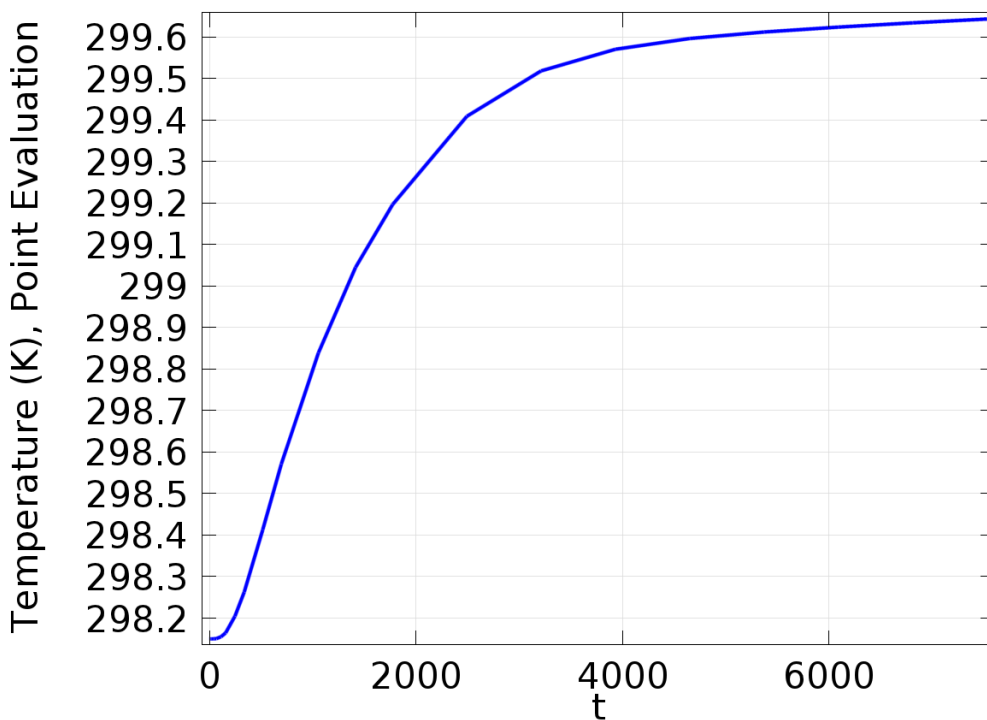
4.4.2. Isothermal Contours (Ht)

Time=1 min Contour: Temperature (K)
 Arrow Surface: Total heat flux



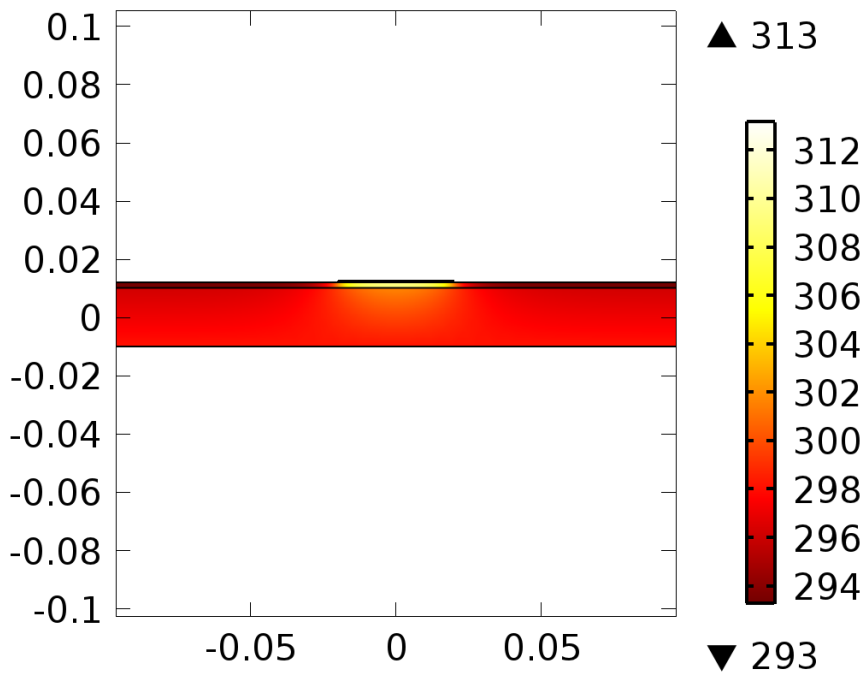
Time=1 min Contour: Temperature (K) Arrow Surface: Total heat flux

4.4.3. Probe 1D Plot Group 6



4.4.4. Temperature (Ht)

Time=120 min Surface: Temperature (K)

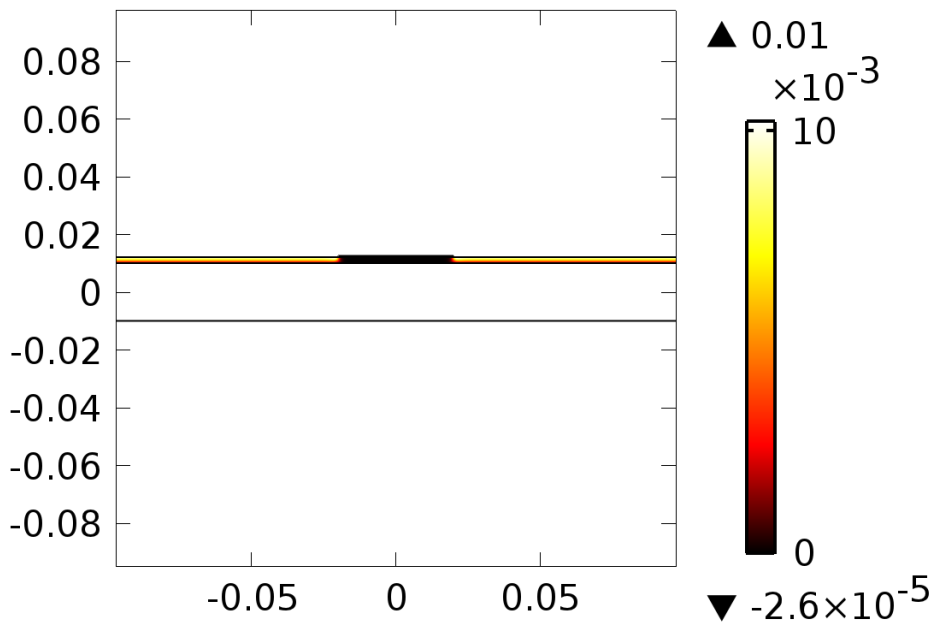


Time=120 min Surface: Temperature (K)

4.4.5. 2D Plot Group 8

Time=41 min

Surface: Diffusive flux, y component (mol/(m²*s))



Time=41 min Surface: Diffusive flux, y component (mol/(m²*s))

4.4.6. 2D Plot Group 9