Lappeenranta-Lahti University of Technology LUT
School of Engineering Science
Computational Engineering
Technical Physics

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INTEGRATION OF A HEAT FLUX SENSOR AND AN INFRARED FILTER FOR FIRE DETECTION

Master's Thesis

Examiner: Professor Bernardo Barbiellini

Supervisor: D.Sc. Mikko Kuisma

ABSTRACT

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Integration of a heat flux sensor and an infrared filter for fire detection

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Keywords: infrared filter, heat flux sensor, selective filter, filter integration

Fire detection is based on detecting some key element of a fire, like smoke, flames or temperature. A carbon fire creates high temperature H_2O and CO_2 gases that emit distinctive infrared radiation. These radiation peaks could be detected by using a system consisted of a heat flux sensor and an infrared filter. A heat flux sensor is a passive electrical device that turns temperature gradient into electrical signal. An infrared filter filters desired infrared radiation while blocking unwanted wavelengths. The aim of this research was to examine different solutions of the filter-sensor integration for a fire detection application. Filter-sensor integration was studied using literature review and empirical research. In the empirical research, the distance between the filter and the sensor, the gap, was changed between 0 and 1 mm with 0.1 mm differences. It was found that having the filter further away from the sensor prevented an unwanted baseline rise of the sensor signal. The baseline rise was caused by the filter absorbing heat. It was also found that using air as the medium between the filter and the sensor was a better option than using a thermal interface material between them. The best results came from a filter that had a small air gap, the size between 0.5 mm and 1 mm, between the filter and the sensor.

TIIVISTELMÄ

Lappeenrannan-Lahden teknillinen yliopisto LUT
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Lämpövuoanturin ja infrapunafiltterin integraatio palontorjuntaan

Diplomityö

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67 sivua, 38 kuvaa, 2 liitettä.

Tarkastaja: Professori Bernardo Barbiellini

Hakusanat: infrapunafiltteri, lämpövuoanturi, selektiivinen filtteri, filtterin integraatio

Tulipalon havaitseminen perustuu jonkin tulen tunnusmerkin, kuten liekkien, savun tai lämpötilan muutosten, havaitsemiseen. Tulipalon seurauksena syntyy kuumia H_2O ja CO_2 kaasuja, jotka emittoivat niille ominaisia infrapuna-aallonpituuksia. Näitä kuumille kaasuille ominaisia aallonpituuksia voidaan käyttää tulipalojen havaitsemiseen ja torjuntaan. Tässä diplomityössä tutkitaan mahdollisuutta käyttää lämpövuoanturia ja infrapunafiltteriä infrapuna-aallonpituuksien havaitsemiseen ja testataan erilaisia tapoja integroida filtteri lämpövuoanturiin. Diplomityö tehtiin käyttäen hyväksi kirjallisuuskatsausta aiemmista aiheeseen liittyvistä artikkeleista sekä empiiristä tutkimusta erilaisista tavoista yhdistää filtteri ja anturi. Tutkimuksessa huomattiin, että lähellä sensoria oleva filtteri aiheuttaa lämpövuoanturin signaalin perustason nousua filtterin lämpenemisen takia. Tutkimuksessa kokeiltiin myös termistä kontaktia parantavaa väliainetta sensorin ja filtterin välissä, mutta se aiheutti voimakasta lämpövuoanturin signaalin perustason nousua. Kokeiluista yhdistelmistä tutkimuksen mukaan parhaassa integraatiossa filtterin ja sensorin välissä on 0.5 mm – 1 mm välinen ilmarako.

PREFACE

“Työhön ja toimeen, veljet! Työhön kaikin voimin; sillä tämä elämä maksaa tämän vaivan, ja ihmiskunta, näemme, ei olekkaan tuota pahempi vekkuli; ei, vaan onpa, luulen minä, maailma meille niin kuin maailmalle me;–“

from the novel *Seitsemän Veljestä* by Aleksis Kivi

As this master thesis project is coming to an end I would like to take some time and thank everyone who have been a part of it with me. A great thank you to my supervisors Mikko Kuisma and Bernardo Barbiellini for your academic guidance. Thank you for guiding me throughout this process. A very special thank you goes to Antti, Matias and Henri, who were all an essential part of developing the test setup for this thesis, performing the tests and analyzing the results. Without you, this thesis would have looked very different.

My time in university has been filled with great friendship, fun nights, hard work and experiences that have allowed me to grow as a person. A big thank you to the student union of computational engineering, Lateksii ry. The experiences in Lateksii has allowed me to learn many real-life skills and most importantly, have fun while learning them.

I would like to thank my friends and people who have been by my side on this journey of writing my master thesis. A special thank you to Henna and Ailey, whose company offered an important escape from an occasionally overwhelming project. Your intelligent observations continue to be one of my biggest inspirations in life.

Lastly, I would like to thank my family for being my rock during this stressful time. My wonderful mother and father who are always so proud of me and whom I can always trust to be there for me. A big thank you to my lovely sister, who continues to be my biggest cheerleader in life. A special thank you to Livia, whose wise demeanor, something a person can only dream of, inspires me in my academic pursuits.

Lappeenranta, February 27, 2022

Inka Saarikoski

CONTENTS

LIST OF ABBREVIATIONS

CWL	central wavelength
FEM	finite element model
IR	infrared
LED	light emitting diode
MEMS	microelectromechanical system

1 INTRODUCTION

Fire detection is based on detecting some of the key elements of a fire, including flames, smoke, and temperature rise. Different materials emit characteristic emission spectras and have specific emission peaks as they burn. In this research project, the infrared radiation peaks high temperature H_2O and CO_2 emit are used to detect a fire [1].

Heat flux sensors are electric devices that are used to sense temperature gradients. There is a possibility to use these devices to detect fires. Heat flux sensor fire detection is based on detecting the thermal radiation of the fire.

The fire detection system in this research project consists of a heat flux sensor that converts temperature gradient into voltage and a filter that filters the radiation and leaves the interesting emission peaks. The different parts of the filter-sensor system and its working principle is pictured in Fig. 1.

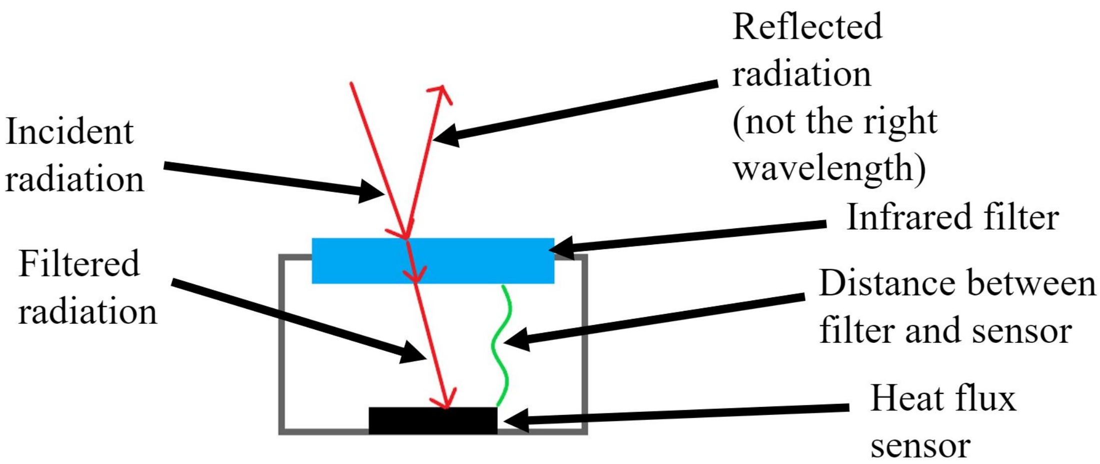

Figure 1. The main parts of the filter-sensor system and its working principle.

The fire emits infrared radiation that has multiple different wavelengths. In order to distinguish between ambient infrared radiation from the environment and the infrared radiation from a fire, the fire detection system needs a filter that only lets the H_2O and CO_2 emission peak wavelength radiation to the heat flux sensor. As the radiation enters the filter, the wavelengths that are of interest should transmit through the filter and the rest of the radiation should reflect from the surface of the filter. The transmitted radiation should then cause a heat gradient on the heat flux sensor, which then converts the heat gradient into an output voltage.

This chain of events is unfortunately not as simple as it seems. The different surfaces between the filter and the heat flux sensor can cause unwanted and unpredictable reflection, absorption, and other phenomena that disrupt the heat transfer.

Thus far, the filter and heat flux sensor have not been tested together. There has not been enough sufficient research about filter integration. Different filter-sensor distances and mediums need to be tested to further the project of fire-sensing gradient heat flux sensors as the filter integration is an essential part of designing the fire detection system.

The properties of the filter material have been studied by Conley et al. [2]. The development of the MEMS heat flux sensor has been described by Immonen et al. [3]. These studies have not included the final integration of filter and heat flux sensor and how one affects the other. Earlier tests and simulations about filter integration with IR detectors have been done by Fonollosa et al. in 2008 [4]. These tests can be used as a guide for our research.

This master thesis concentrates on the integration of the filter and heat flux sensor. The scope of this thesis does not include study of the filter or the sensor and their properties, although they are visited briefly to gain a better understanding of the research problem. The main objective of this research is to understand better how the filter and sensor affect each other.

The research questions of this thesis are:

- How does the filter work?
- How can the heat from the filter transfer to the heat flux sensor?
- How do different surface interfaces affect the heat transfer?
- What would be a good test set up to test the heat transfer between the filter and the sensor?
- How should the filter and the sensor be connected?
- Does the filter and sensor attachment affect the selectivity of the filter?

The aim of this study is to use literature and experimental research to investigate how different parameters affect the heat transfer between filter and sensor and therefore their integration. Investigated parameters include distance between filter and sensor and the medium between filter and sensor (air or thermal interface material).

Chapter 2 discusses the basics of how the two main components of our research, the heat flux sensor and the infrared filter, work, and what the optimal properties of a filter in our application would be. Chapter 2 also summarizes an earlier study that tested the function of a heat flux sensor and filter with different distances. Chapter 3 discusses the heat transfer between filter and sensor and how that can be used to evaluate different filter and sensor attachment methods.

Chapter 4 introduces the test setup designed for filter and sensor integration and goes over the experiment. Chapter 5 presents and analyzes the test results in discussion. Chapter 6 concludes our research.

This master thesis was funded by Academy of Finland THERAD project. This thesis is part of the THERAD project, which means the novel measurement and sensing technologies for thermal radiation of unwanted fires research. THERAD studies the possibility of creating a fire detection system by using an infrared-selective coating on a gradient heat flux sensor [5]. The filters used in this research were provided by the THERAD project. They are a part of the THERAD research of spectrally selective materials.

The methodology of this research includes literature review based on academic studies both from THERAD project and other, non-THERAD related research. A test setup was designed and experimental tests were then done from the basis of literature.

2 THEORY OF HEAT TRANSFER AND A HEAT FLUX SENSOR-FILTER SYSTEM

Heat transfer happens when there is a temperature gradient, which is a temperature difference between two locations, and thermal energy transfers from high temperature to low temperature. There are three main types of heat transfer: conduction, convection and radiation [6].

Conduction is a heat transfer type that happens within the material. Conduction works differently in fluids and solids. In gas, the molecules in higher temperature have higher velocity and these high velocity molecules transfer thermal energy by colliding with lower velocity molecules, causing conductive heat transfer. In solids, conduction occurs in two ways, lattice vibrations and free electrons. Free electrons make materials great thermal conductors in the same way they make materials good electrical conductors. Many materials that are good electrical conductors also make great thermal conductors [6].

Convection is a form of heat transfer that requires a flow. It can only take place in fluid mediums. Convection can be a mixture of diffusion, where higher temperature fluid mixes with lower temperature fluid due to concentration differences, or advection, the flow of fluid causing heat transfer [6].

Heat can also transfer by electromagnetic radiation without any medium material, this is called thermal radiation. All objects that have a temperature emit thermal radiation. The radiation that objects emit is determined by their temperature and material. If the object absorbs and emits all wavelengths of electromagnetic radiation, it is called a black body, and the radiation it emits is called black body radiation [6].

When discussing heat transfer in a filter and heat flux sensor system, it is essential to notice that different heat transfer types are all present in the system. Depending on the application of the heat flux sensor, heat might transfer to the filter by means of conduction, convection or radiation, or as a mixture of them all. An example of the heat transfer from source to the sensor is pictured in Fig. 2. Taking fire as an example, the heat from the flame transfers through air mostly by radiation heat transfer. The flame radiates heat in the same way that it radiates visible light, and these photons radiate to the filter. The filter then transfers the heat from the preferred infrared region and emits it from the other side of the filter. The heat then transfers to the sensor by either radiation or convection.

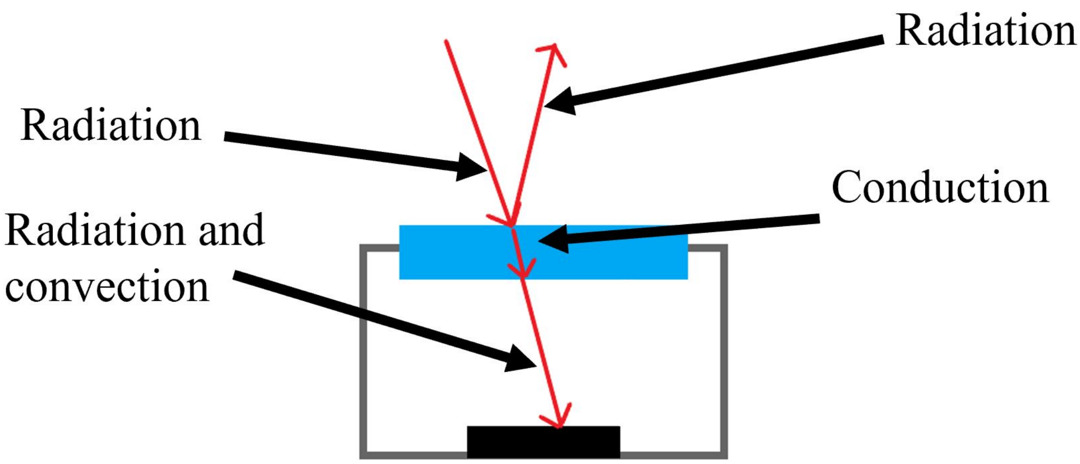

Figure 2. An example of how heat transfers in the filter-sensor system by different heat transfer types.

2.1 Heat flux sensor

Heat flux sensors are electrical systems that are used to measure heat flux, for example thermal energy transfer, by using the Seebeck effect. Seebeck effect is the effect of a temperature gradient inducing a voltage. A heat flux sensor consists of thermopiles, that are made of two different materials. When the materials have a thermal gradient, practically meaning that they have a temperature difference, a voltage is induced in the thermopile. The induced voltage is proportional to the temperature difference and can therefore be used to signal heat flux.

The thermopile materials should have thermal and electrical qualities based on the proposed use of the system. The thermopile used in this research is used to signal changes in heat flux and it's therefore beneficial to use materials that result in a sensitive sensor that responds to even the smallest of changes in temperature.

2.2 Infrared filters and their optical properties

Infrared filters can be made of various different materials for different applications. Their function is to reflect and block certain wavelengths of light while transmitting desired wavelengths. A filter placed on top of the sensor will also act as a protective layer that will shield the thermopile structure against dust and other contamination [7].

The name infrared filter can be used to describe both a filter that blocks infrared light and a filter that passes infrared light. In this thesis infrared filter and IR-filter are used to describe a type of filter that passes infrared wavelengths.

The different effects the filter material can have on the incident radiation include absorption, reflection and transmittance. When it comes to the design of infrared filters suitable for fire safety applications, the optical properties of the filter material are important. The reflection and absorption of photons have to be researched when discussing different filter materials. The phenomena of radiation in material is portrayed in Fig. 3.

The reflectivity of the material is the fraction of the incident radiation that is reflected, absorptivity is the fraction that is absorbed and transmissivity is the transmitted fraction [6]. Therefore

$$\rho + \alpha + \tau = 1$$

where ρ is the reflectivity, α is the absorptivity and τ is the transmittance [6].

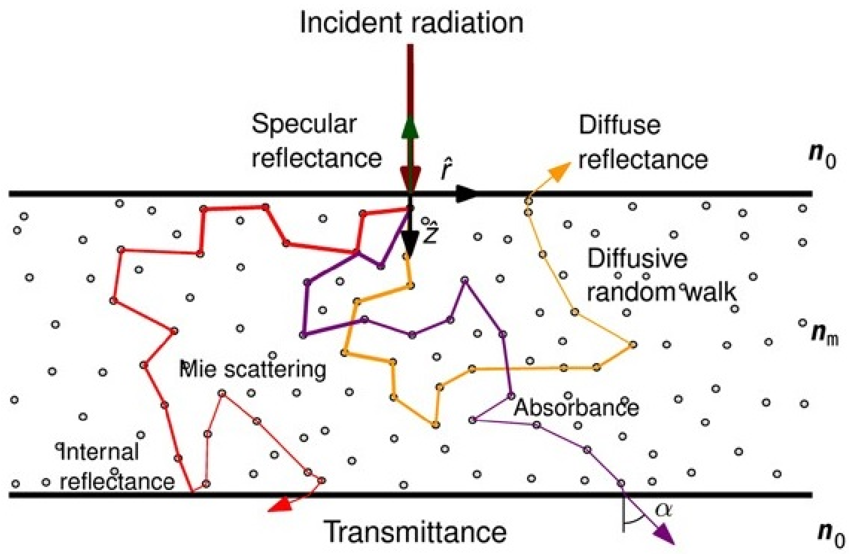

Figure 3. Incident radiation on filter material [8].

There are two types of reflectance; specular reflectance which happens when photons reflect from the surface of the material, and diffuse reflectance which happens when photons inside the material scatter back to the surface [9]. In Fig. 3, the diffuse reflectance is pictured as an orange arrow and specular reflectance as the green arrow overlapping with the incident radiation.

The movement of photons through medium is called transmission [6]. Transmission is pictured in Fig. 3 with the red arrow. Photons can scatter as they are moving through the material and therefore its transmittance angle is not always same as the incident angle. The scattered transmitted photon is pictured in Fig. 3 with the narrowing red arrow, the narrowing of the arrow representing the loss of radiation energy because of absorption. The small dots on the material pictured in Fig. 3 represent the microinclusions in the material that cause the photons to scatter and absorb while moving through the medium.

Pictured in Fig. 3 as a violet arrow is the absorption of photons. Absorption turns photon energy into heat of the medium [9].

Another optical phenomenon that takes place in materials is scattering. Scattering can result in either transmittance by forward scattering, reflection by backscattering or absorbance. High scattering inside the medium makes the photons stay longer in the medium by elongating the optical path length and therefore raises the possibility of absorbance. [2]

A study by Conley and Moosakhani [2] studied the optical properties of compact layers that contained different semiconductor particles in various sizes. By changing the size, material, and coating of the particles the optical properties of the material changed. This can be applied further in infrared filters by using these parameters to modify which wavelengths the filter transmits, reflects, and absorbs. Fig. 3 is an illustration used in Monte Carlo model, which is a method that can be used to approximate the optical spectra of composites. The optical spectra of insulating composites with semiconductor microinclusions was studied with this method in [8].

Filters capability to transmit only the wanted wavelengths is called selectivity. An ideal material for an IR-filter in fire safety would be one that only transmitted infrared radiation that is distinctive for a fire and blocked out the rest. A good IR-filter material would reflect unrelated radiation efficiently while transmitting as much of the fire-related radiation as possible without absorbing it too much. Filter materials should not absorb the radiation, because it causes the temperature of the system to rise. While researching materials and their optical properties it's important to remember that an IR-filter for fire safety is a very specific application and most studies aim for properties that might not support that.

One of the filters used in our experiment is described in the study by Conley and Moosakhani

[2]. This filter material is highly reflective on the near-IR region and its reflectivity increases the thicker it is. This is due to the incident radiation scattering through the micro- or nanoparticles in the filter and reversing back out of the filter. Adding micro- and nano inclusions into the filter material is one way of changing the optical properties of the filter.

2.3 Types of heat loss

In a MEMS thermal sensor there are three types of heat loss [10]. Air transporting heat out of the system is a type of thermal loss called gas convection. Radiative heat loss means the energy lost by radiation through thermally conductive surfaces that are warmer than the environment. Heat loss through thermal conduction is heat dissipation in the substrate material.

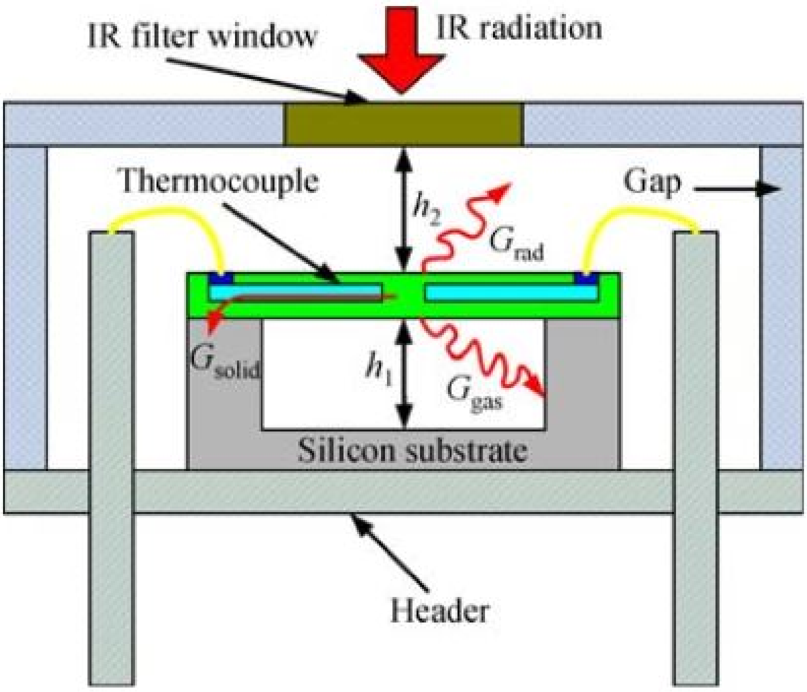

Figure 4. An example of a filter-thermopile configuration showing different types of heat loss. [10]

In our heat flux sensor-filter test system all heat loss types are somewhat relevant. Radiative heat loss can be present if the casing of the system is very thermally conductive. A thermally conductive casing can be used to act as a heat sink to which the cold junctions of the thermopile connect [11]. The casing of the system can also be a thermally insulating material, which lessens the impact of ambient, unwanted radiation influencing the sensor. This ensures that the heat flux only comes through the filter and absorbs through the sensor to the heat sink.

Gas convection could mostly be ruled out as in most sensor systems the sensor and filter are configured in a way that is closed and gas cannot travel in and out of the system. In Fig. 4 the system is closed and gas convection heat loss is pictured happening in the air gap under the thermopile and on to the silicon substrate. In a test setup the sensor system can be more open to allow proper cooling down between individual tests and therefore allow desirable gas convection. In a heat sensing system the filter and the sensor are usually in a closed place to prevent gas convection heat loss.

Thermal conduction heat loss can be prevented, but also amplified with the use of different materials. A material with a high thermal conductivity can be used as a heat sink that aids the heat conduction through the heat flux sensor and to the heat sink below it. This is pictured in Fig. 4 as the red arrow G_{solid} that is shown moving to the silicon substrate. Heat conduction through the heat flux sensor to the heat sink is of course desirable as it promotes the temperature gradient and should not necessarily be considered a type of heat loss. Heat conduction through other surfaces of the system, like the sides of the chamber between the filter and the sensor, is on the other hand not desirable and should be prevented, as it adds to the overall heat loss of the system. This can be prevented by using a case material that is a poor thermal conductor.

2.4 Earlier research by Fonollosa et al.

There is very little studied information about different filter-sensor attachments. One study about filters and their integration on IR detectors is by Fonollosa. [4]. The study used both experiments and simulation to research the performance of the filter-sensor assembly and it is the only study found to use different filter-sensor distances. It provides valuable information to our research as the experiment is very similar to ours. The study by Fonollosa can be used as a guide when examining different possible ways of integrating our filter with a heat flux sensor.

The test setup from the study consisted of sensors, filters and an IR emitter. An array of four micromachined thermopiles were used as the infrared detection unit. Optical filters were connected to the thermopiles by solder joints, which left a 60 μm gap between the filter and the sensor. The filters were multilayer thin-film, consisting of either infrasil or germanium thin film stacked to create a highly selective filter by layering high and low refraction index materials. The filter and thermopile sensor were assembled together using a flip-chip technique.

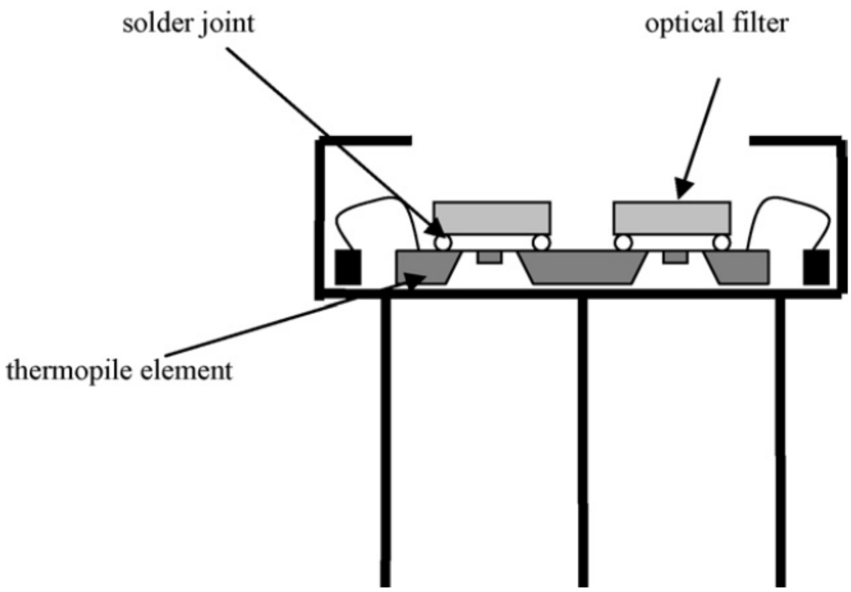

Figure 5. The thermopile element and the filter were connected by a solder joint in the study by Fonollosa et al. [4]

The IR radiation system consisted of an IR emitter, an optical lens that collimated the radiation and an optical shutter that controls the pulse of radiation to the sensor. The IR sensor was placed in a vacuum chamber that had a bushing wall that allowed measuring the output voltage while maintaining vacuum conditions for the filter-sensor assembly.

2.4.1 Results from the study by Fonollosa et al.

The thermopile output voltage was first measured without any optical filter, and then with a 3.95 μm central wavelength (shortly CWL) filter that was placed in front of the shutter. This was done in order to get a measurement without any thermal coupling between the filter and the sensor, in other words to minimize the effect of filter temperature rise on the sensor. The measurement was repeated with the flip-chipped optical filter to test how the filter being closer to the sensor affected the output voltage.

The filters decreased the output voltage in both the flip-chipped and CWL filters. In

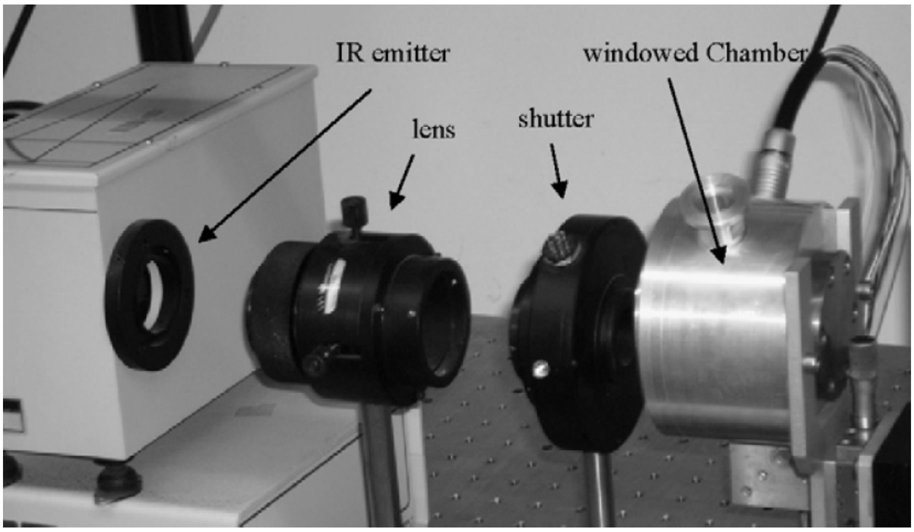

Figure 6. The test assembly used in the Fonollosa experiment. The sensor was included inside a windowed vacuum chamber.

the CWL filter case the output voltage was lower than in the flip-chipped case, but the response was faster in CWL than in flip-chipped filter. In other words, the flip-chipped filter placed right next to the sensor caused a stronger output voltage but responded slower to the change.

The tests were repeated in vacuum conditions. The tests without filter and with the CWL filter in front of the shutter produced larger output voltages in vacuum than they did in air. The decrease in the output signal between no filter and the CWL filter was similar in vacuum than it was in air. In contrast, using the flip-chip filter in vacuum produces a much smaller output voltage but faster response time and has values in both comparable to ones from using the CWL filter.

The signal level is higher and response time is lower when a filter is close to the sensor. This phenomena is not detected in vacuum, so it can be linked to the air gap between the sensor and the filter and the thermal coupling that happens when these parts are close to each other.

The filter integration was further studied with a finite element model (FEM) analysis, which is a method used to numerically model problems like heat transfer. Conduction was the only relevant heat transfer type in the system that consisted of the filter held up by solder joints, membrane, silicon substrate and an air region between the substrate and the filter.

The two parameters that were experimented in simulation were the power absorbed at the silicon absorber and the power dissipated at the filter bulk material. The simulation proved that the filters output voltage is higher and faster if the power is targeted on the silicon absorber than on the filter.

The simulation results were compared to earlier experimental results for both the sensor with and without filter. The simulation values were mostly accurate and followed the experimental results. Some slight differences occurred most likely due to differences between the material properties that were used in the simulation and the real material properties in the experiments.

The output voltage response was slow when most of the power was directed on the filter. The response time decreased and output voltage was larger when the simulation was repeated in vacuum. This mirrors earlier experimental results.

2.4.2 Discussion and relevance of the study by Fonollosa et al.

It was found that increasing the distance between the filter and the sensor decreases both the output voltage value and the response time. This is due to the thermal coupling between the filter and detector when they are placed very close to each other.

The filter naturally absorbs some of the infrared radiation which cannot be completely prevented. Because of infrared absorption, the temperature of the filter rises and if the filter is very close to the sensor, the sensor to heats up. This leads to a rise in the output voltage and as simulated, can be avoided by increasing the distance between the filter and the sensor.

If the filter is already warmer because of absorbed radiation, it can warm up the heat flux sensor, which then shows as an increased baseline in the output voltage. This can cause a faulty output voltage and heat flux. Because of the thermal coupling between filter and sensor and the temperature rise in sensor the heat flux is smaller than it would be with a "cold" sensor. This could mean that the sensitivity of the sensor is compromised as the heat gradient between the IR source and the sensor is smaller.

From both the experimental and simulation results it was concluded that having the filter-sensor system in a vacuum enhanced the output voltage response. This further demonstrates the effect of thermal coupling through air between the filter and sensor. Having the system in a vacuum was not a feasible option, so the height of the solder joints, in other words the distance between the filter and the sensor, was increased to test whether it has an impact on the output voltage and response time.

No difference in selectivity was reported, which was expected, as selectivity was not a focal point of this research.

The study by Fonollosa can be used as a reference when integrating the filter and sensor, but it is important to remember that different applications value different properties of filter integration. In the study by Fonollosa et.al. the response time was an important parameter, and its behavior was studied with different parameters to eventually examine how to optimize it. Even though response time is an important quality of the heat-flux sensor and filter system, it's not a subject of major concern for our research. The parts of the study that are most important for our research discuss the warming up of the filter, what causes it and how it can be managed.

In the study it was found that the thermal coupling between the filter and the sensor was only prominent when the filter was close to the sensor with air between them. As thermal coupling does not occur in vacuum, we can speculate which type of heat transfer causes it in non-vacuum conditions. Radiative heat transfer can be ruled out as it is the only type of heat transfer that doesn't require a medium. Majority of the slow output voltage was caused by the thermal coupling. Air is a poor conductor, so it's fair to assume that the thermal coupling with air mediums happens because of air convection in the medium.

There are some differences between the filters used in the study by Fonollosa et.al. and the filters used in our research. The SiO_2 filters used in our research are dense and have silicon micro- or nanoparticles depending on the filter. They are 3 millimeters thick [2]. As discussed earlier, the filters used by the Fonollosa study were thin-film with thickness measurable in micrometers. The sensor used in the Fonollosa study was also more suitable for detecting IR radiation than the heat flux sensors used in our study, which measure conductive heat.

The research by Fonollosa et.al. put a lot of emphasis on the response time, the size of the output voltage and how different filter integrations changed them. As were discussed earlier, the response time of the sensor is not a major concern in our studies. The reduce in output voltage that the filter causes can be a cause of concern. For a fire-detecting sensor the output voltage does not need to be the largest possible, but it needs to be enough to produce a notable signal in the system. The heat absorption in the filter is a problem when it becomes major enough to attenuate the thermal gradient and hinder the sensing of the heat flux. The temperature rise of the filter causes noise, which makes it hard to detect the signal caused by the actual radiation we want to detect.

3 HEAT TRANSFER BETWEEN FILTER AND SENSOR

The heat transfer from filter to sensor depends on the way the filter and the sensor are positioned and whether there is air between them. In the case where the filter and sensor are right next to each other, the heat conducts straight from the filter to the sensor. If there is air between the filter and the sensor, the heat radiates from the filter surface through air and to the sensor surface, which then conducts heat. The air between the filter and the sensor also absorbs part of the radiation and heats up, causing a delayed temperature change and thermal coupling, which was detected earlier in the study by Fonollosa.

Thermal coupling in this context means that the sensor mirrors the temperature of the filter. It could be argued whether thermal coupling is a phenomenon that should be avoided in the filter-sensor system. The function of the filter is to filter the infrared spectrum and get the filtered radiation to the sensor. The most important part of this system is that the desirable heat transfers through the filter and does not reflect or absorb on its way to the sensor.

When the filter material absorbs incident radiation, the temperature of the system raises and the sensing of a temperature gradient becomes less reliable. Filter temperature rise causes a problem when the temperature of the filter gets so high that it starts to interfere with the sensor output voltage by causing an extra temperature gradient. If the temperature of the filter-sensor system is already higher than room temperature, the temperature gradient caused by a fire would then be smaller compared to what it would be if the filter-sensor system was room temperature. This can potentially make the sensing less accurate. Temperature rise in the filter and heat flux sensor system in testing have to be managed by letting the filter-sensor system cool down between tests.

The difference in the thickness of the filters can produce differences in their thermal function; a thicker filter can absorb more thermal energy and takes longer to cool down. On the other hand, a thicker filter in theory does not heat up as easy as a thin one. This could prevent thermal coupling, with the presumption that it is something we should prevent.

Filter can cause a problem if temperature changes affect it more than the sensor, in which case the filter causes the sensor to signal heat. To combat this problem, the system can be equipped with a temperature sensor placed on the filter [7]. The temperature measurement can be compared to the sensor signal and then be used to correct the sensor signal in case of a temperature rise in the filter.

3.1 Filter and sensor attachment

When picking out a way to integrate the filter to the sensor there are two main issues that need to be navigated; the temperature rise of the filter which heats up the sensor and causes thermal coupling, and the transmissivity of the infrared radiation between the filter and the sensor. The topic of filter integration covers both the problems of filter-sensor attachment and the choice of medium or lack of one between them. To further test and evaluate the different possibilities of filter-sensor integration, different options for attachment and medium need to be explored.

One possible way of attaching the filter to the sensor is by having it directly on. Some existing heat flux sensors have a filter that works as a coating on top of the sensor that is embedded on the sensor assembly. In these cases the filter and sensor can act as one thermal system that is thermally coupled on purpose. If the filter and the sensor are thermally coupled and mimic each other's temperature, the rate of how fast the sensor reacts to the heat flux might be slower and more subdued than in a system where they are further away from each other. This was demonstrated in the study by Fonollosa. In a system where the filter and sensor are not coupled and the filter is more affected by ambient thermal changes than the sensor, the difference in filter temperature can cause an extra signal on the sensor [7].

In a 2017 review of the MEMS-based thermoelectric infrared sensors, the MEMS-based filter-sensor integration was pictured having an air gap between the filter window and the thermocouple [10]. An air medium between the filter and the sensor will heat up by the radiation that makes it through the filter.

The intensity of thermal radiation decreases while traveling in air, because the radiation is absorbed into the air by exciting the air molecules. The air between the sensor and the filter will absorb some of the infrared radiation, which is something to keep in mind when thinking of the filter integration, although compared to the amount of radiation intensity loss between the radiation source and filter, the intensity loss between filter and sensor is very small.

In theory, it should not matter whether the heat that reaches the sensor is radiation or air convection. The heat has transmitted through the filter and therefore would only contain the radiation of interest. The sensor does not differentiate between different heat transfer types, and it is indifferent whether the heat that causes the sensor output voltage is infrared radiation or convection of warm air. If radiative heat is filtered and then warms the air in the gap and the heat flux sensor senses this, it is not a false signal, as the heat that caused the signal originated in the desired radiation.

In reality, some heat transfer types are less effective than others. Conductive heat transfer will show up on the sensor as a slower signal than the radiative heat transfer. There is also no way to determine whether the signal of conductive heat transfer is caused by for example filter temperature rise because of ambient temperature fluctuations or actual desirable infrared radiation going through the filter and causing its temperature to rise.

Because of the reflectance of near-infrared radiation, the filter should not absorb or transmit unwanted heat. The filter heating up due to unwanted non-fire related heat radiation and that causing a signal on the heat flux sensor should therefore in theory not be a concern, but in reality, some heat absorption is bound to happen and cause false signals on the heat flux sensor.

One problem that the air gap proposes is that because of air convection, the warm air escapes from the system as it naturally spreads, causing heat losses in the system. This can be solved by simply insulating the system and making sure that the air inside the gap does not spread outside the system. Another problem that the air convection can pose is that as the air heats up and moves around the gap due to convection, it starts to heat up the sides of the gap instead of the edge of the sensor. This could possibly lead to heat loss and therefore compromising of the sensitivity of the sensor signal.

Using a vacuum between the filter and the sensor is not a feasible option in a fire safety application as it is hard to manufacture and can complicate the package of the heat flux sensor. It is not the most reliable way of ensuring the heat continuity from filter to sensor as any damage to the vacuum can be detrimental to the vacuum conditions.

3.2 Thermal interface materials

Another possible filter-sensor medium is a material that conducts heat. These materials are called thermal interface materials. They are used for example in computers to help cool them by aiding the heat transfer out of the central processing unit to a heat sink.

The heat transfer across an interface of two materials is dependent on thermal interface resistance. When two solid surfaces are joined, the microroughness of the materials causes them to be microscopically separated. The separation of the surfaces causes air to get in between the materials. Because air is a bad thermal conductor, this separation causes thermal insulation and increases the thermal resistance of the interface. The heat transfer across the surface can be severely compromised with a thermally insulating barrier of air between the surfaces. Fig. 7 shows the air gaps between the materials and how the surface roughness causes only some parts of the surface to connect. Because of the microscopic waviness in the material, as much as 99% of the surface can be separated and not transferring heat properly [12].

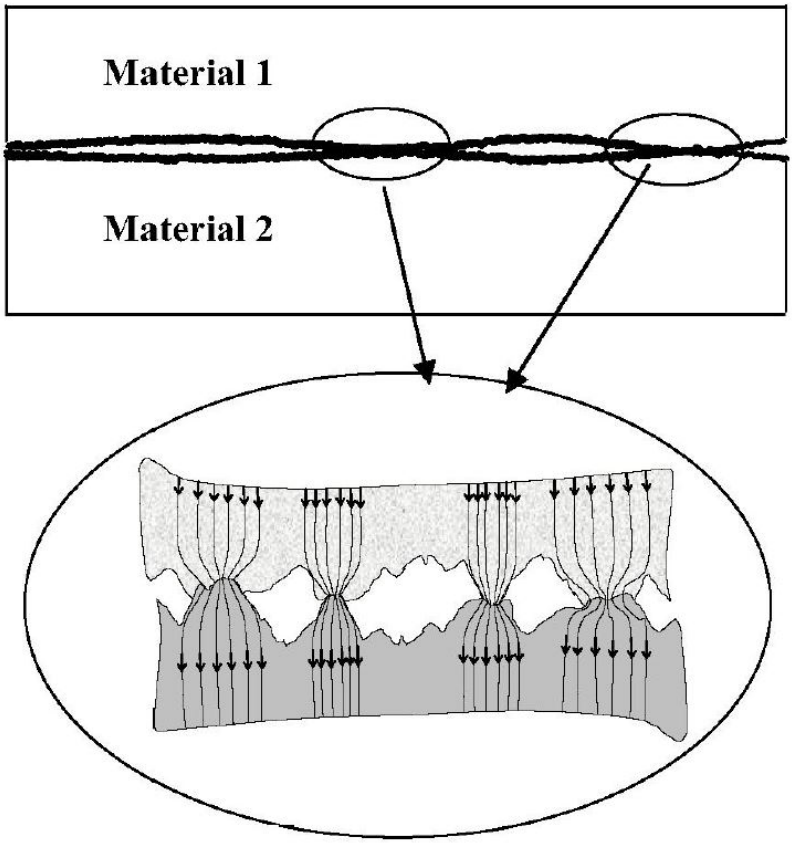

Figure 7. Surface roughness between materials causes only a fraction of the surfaces to be in contact [13].

Thermal resistance of the system consists of the thermal resistance of the assembly and the contact thermal resistance. The use of a thermal interface material helps to decrease the latter. Thermal contact resistance consists of the conduction resistance from the surface points that connect, conduction and radiative resistance of the gaps that do not connect and in the case a thermal interface material is used, the thermal conduction resistance of said material layer [12].

The thermal contact resistance can be reduced by adding pressure on the contact area or buffing it. Both methods aim to flatten and create more contact surface between the materials, but they can be quite rough to delicate electronics and cause damage. Using a thermal interface material that can seep into the microroughness and fill the air gaps without use of excessive pressure will improve the thermal contact resistance without damaging the electronics.

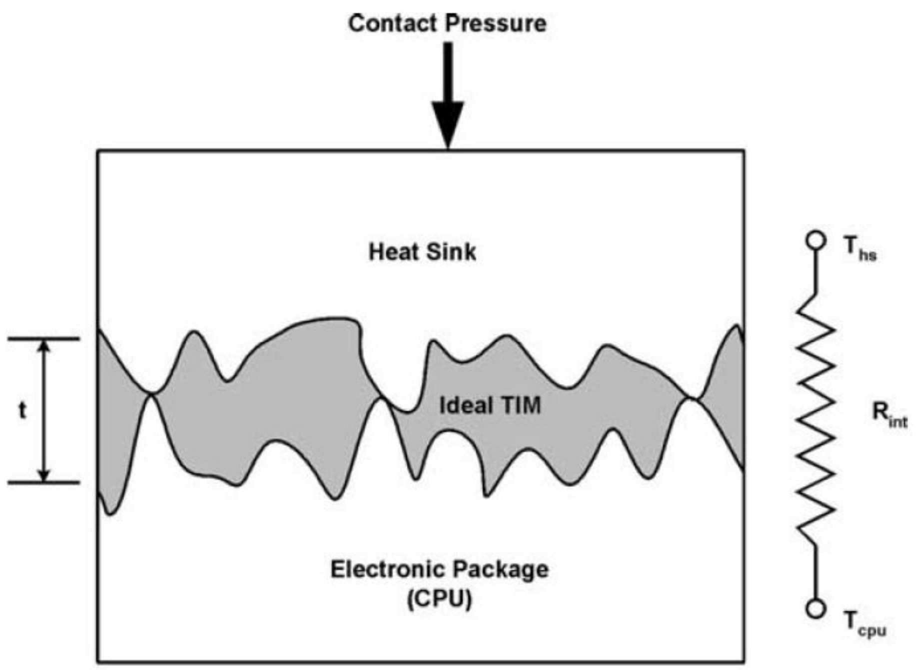

Figure 8. Graph of an ideal thermal interface material [12].

Ideally, the thermal interface material would fill all the gaps between surfaces so that no air would be trapped and the only thermal resistance between the surfaces would be from the thermal interface material, as pictured in Fig. 8. Practically there is always some air that is left in between the surfaces and the thermal interface material, as pictured in Fig. 9. Because of the air gaps, the thermal interface resistance consists of a series of resistances pictured in Fig. 9, including the thermal interface materials conduction resistance and its contact resistances with surfaces on both sides [12].

In a realistic case, the thermal interface material might decrease the amount of air gaps but does not erase them completely. Therefore, there is still some insulation between the

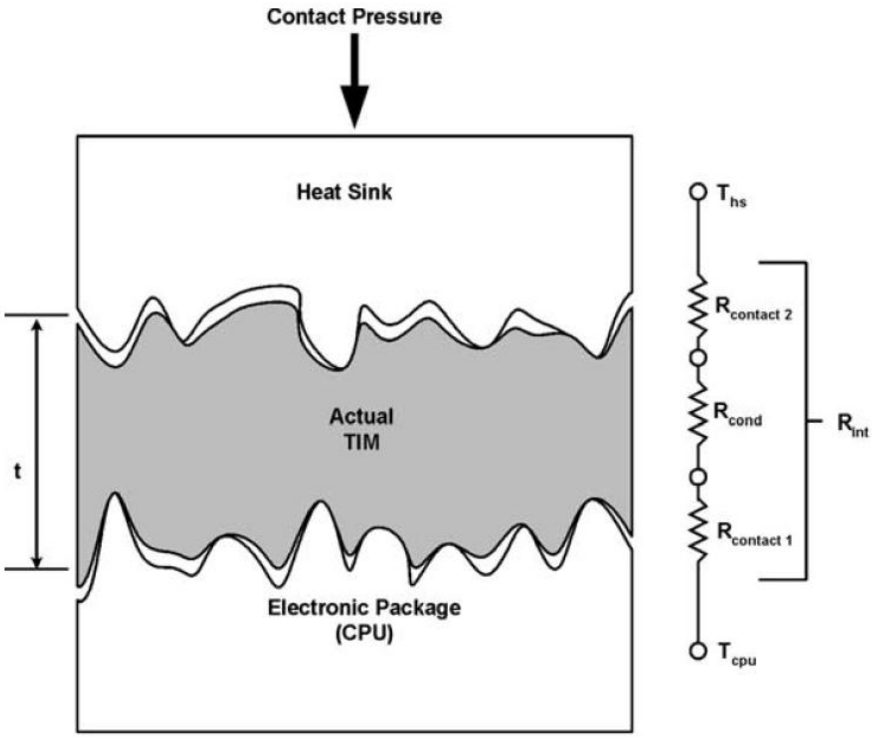

Figure 9. A realistic thermal interface material application [12].

surfaces. Even though most thermal interface materials have a known thermal resistance, the real thermal resistance is application specific and cannot be known beforehand, because all surfaces have unique microroughness and the thermal interface material will fill those gaps differently in each application.

The type of thermal interface material should be chosen so that the qualities fit the application best. Attributes like thermal conductivity, viscosity (leaking, deforming to surfaces), thickness, performance, manufacturing capabilities and toxicity should be considered.

In the case of a filter-sensor system, the use of a thermal interface material has not yet been explored. The material making the heat transfer between the filter and the sensor more efficient seems like a great idea, but the type of heat transfer the material promotes has to be taken into account. The thermal interface material aids the heat transfer mostly by conduction, which is not the desirable form of heat transfer between the filter and the sensor in this case. The most desirable form of heat transfer to the sensor would be heat radiation, which causes short peaks in the sensor output signal. Because of this, using a thermal interface material as a medium between the filter and the sensor might not produce the ideal result. Although the result of such test might not be ideal, it still has experimental value. The test would provide information about the behaviour of the filter-sensor system with a conductive medium, compared to a non-conductive medium like air.

4 TEST SETUP AND EXPERIMENT OUTLINE

There are several things in the design of a test setup that have to be considered. The aim of the study, repeatability of tests, physical constraints and user friendliness have to be taken into account. Requirements for the updated set up were:

- possibility to change the distance between the filter and the sensor with high accuracy
- possibility to change the filter
- possibility to try different infrared wavelengths
- possibility to change the distance between the IR source and the sensors
- possibility to change the medium between the filter and the sensor

These requirements were based on the research questions and the research made in the literature review part of this thesis. The different parts of the setup can be seen in a simplified graph in Fig. 10. where the heat flux sensor is pictured on top of a heat sink, with a variable distance between the sensor and the filter. The IR LEDs are shown on the top of the figure.

The criteria of variable distance between the filter and the sensor is related to the question of how the filter and the sensor should be attached. The impact of sensor-filter distance to the sensor was noted in earlier research by Fonollosa [4]. The goal for these tests is to try whether the results from the simulation by Fonollosa [4], where the distance affected the output voltage, are applicable in a practical setup. The filter and sensor distance can be seen in Fig. 10 as the variable distance.

The possibility of changing the filter is a criteria for the test setup because it allows for a more extensive research. Testing the filter-sensor integration with filters of different materials can help to understand which effects detected in the system originate from specific filter properties and which from the way the filter is integrated to the system. Different filters also have different transmissivities in the infrared region and reflect and absorb heat differently. By using different filters and analyzing their results, it will be easier to isolate the effects of different filter integration from effects that originate from filter properties, like the radiation absorption and temperature rise of the filter.

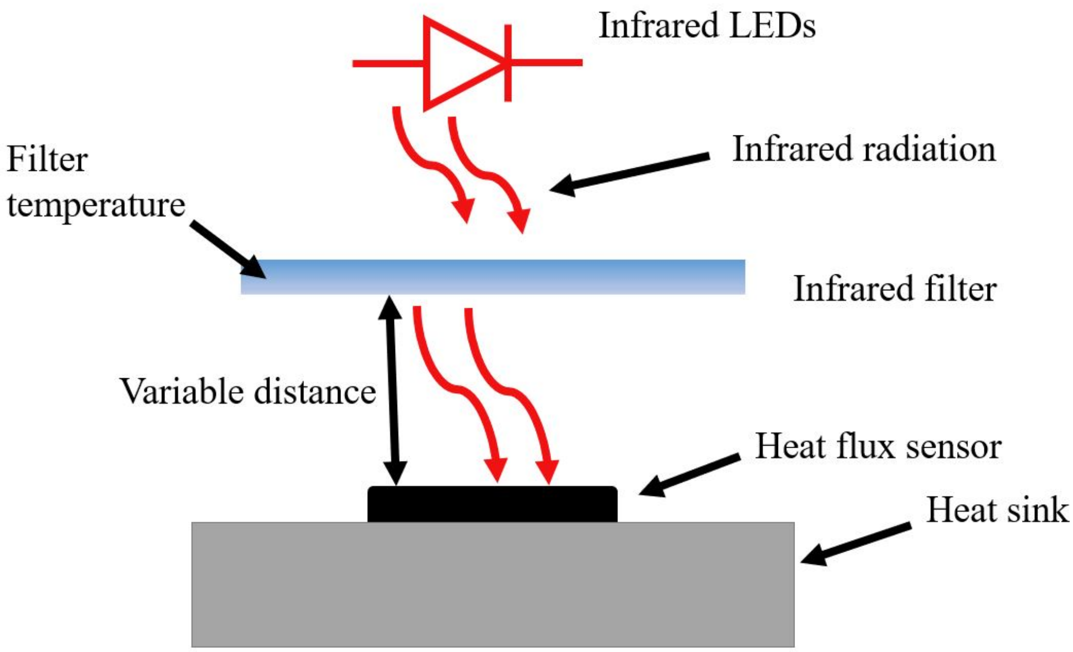

Figure 10. A simplified graph of the filter-sensor test system.

Having the test setup equipped with infrared light sources that emit different wavelengths of IR radiation is essential as we want to study whether the filter integration has an effect on the selectivity of the filter. Different wavelengths of IR radiation are used because the heat flux sensor does not differentiate between different wavelengths of infrared radiation.

The possibility to change the distance between the filter and the IR source is a practical necessity. Even though filter-IR source distance is not a variable in this study, the possibility to adjust it is practical in case the IR source is not effective enough to reach the filter-sensor system. This will be tested before the actual research tests and adjusted accordingly.

The possibility of changing the medium between the filter and the sensor is a test setup criteria that will help answer the research questions “How do different surface interfaces affect the heat transfer?” and “How should the filter and the sensor be connected?” Changing the medium from air to a thermal interface material minimizes the surface areas of air-filter and air-sensor interfaces. By comparing the system behavior between the system with the thermal interface material and the system that uses an air medium we can more effectively isolate the effects that each medium material causes and analyze which would be a better one for fire detection.

A big part of the principles of the test setup is also listing which parameters need to be measured with it. The needed measurements include:

- heat flux sensor output voltage
- infrared led plate temperature
- filter temperature
- heat sink temperature

The measurement places can be seen in the simplified graph Fig. 10.

4.1 Test setup

The test setup was constructed with the principles listed on the previous chapter. For clarity, the test setup means the whole test system, which can be seen in Fig. 11. This includes the measurement devices. The test fixture means the configuration that holds the LEDs, the filter and the heat flux sensor. It is pictured in Fig. 12.

The test fixture is situated inside an aluminum box, similar to the one used in the earlier research setup. The aluminum box can be seen in Fig. 11. The box insulates the test fixture from its environment and protects the system from electromagnetic interference. Even though the aluminum box insulates the test fixture, precautions will have to be made to keep things like differences in the temperature of the test environment and possible sources of electromagnetic interference in check.

The measurement data was acquired by using National Instruments compactDAQ 9198 chassis and National Instruments NI 9219 and NI 9216 modules. A NI 9401 module was used to operate the led pulse. The test was operated with a Matlab code, which automatically saved and plotted the measurement data. A detailed diagram with all of the measurement channels is attached as Appendix A2.1.

The test fixture is pictured in Fig. 12 and Fig. 13. The test fixture was constructed on an aluminum heat sink plate, pictured in light red in Fig. 12. The test chamber that covers the heat flux sensor from the sides is pictured in blue and functions as a shield and covering, minimizing the interference of ambient thermal radiation.

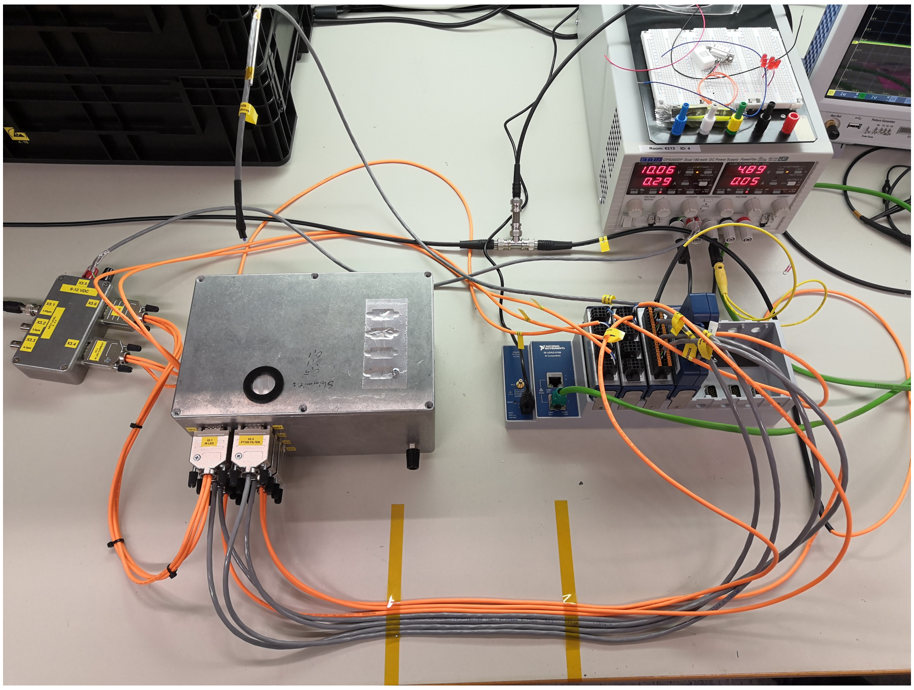

Figure 11. The whole test setup. The aluminum box on the left includes the test fixture inside. The data acquisition tool used in the measurements is on the right.

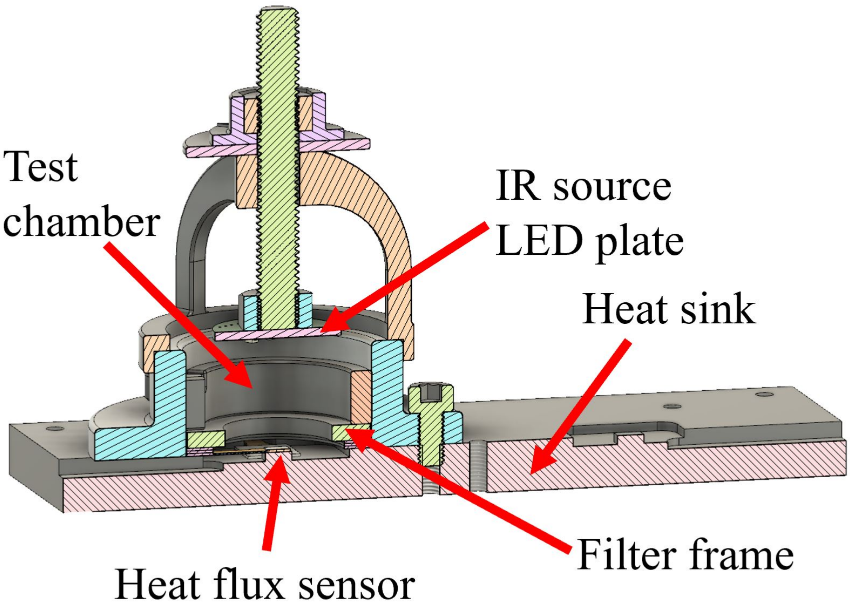

Figure 12. Basic design of the test fixture. The heat flux sensor is pictured in the bottom. The area surrounded by the blue part is referenced to as the test chamber.

One important aspect of the test fixture was figuring out where to attach the LED plate. In this test fixture, the LED plate is held in place by the LED holder, pictured on top of the test chamber in Fig. 13. The LED holder is a 3D-printed cage that holds the LED plate above the sensor chamber on the other end of a screw. The function of the screw is to help adjust the height of the LEDs. The LED holder is designed to be open on the sides in order to allow the infrared radiation reflected from the filter to exit the test chamber, giving the filter a better chance to stay cool and not absorb all of the radiation that reflects back to the filter. If the LED holder and test chamber formed a closed system from the top, the unwanted radiation that was first reflected from the filter could potentially scatter and reflect from the chamber walls back to the filter, now with different, unpredictable wavelengths. The ambient radiation inside the chamber would slowly heat up the filter and cause faulty signaling on the sensor. Therefore, it's beneficial to have an opening beside the LED plate, to allow convection and radiative heat transfer out from the top of the filter.

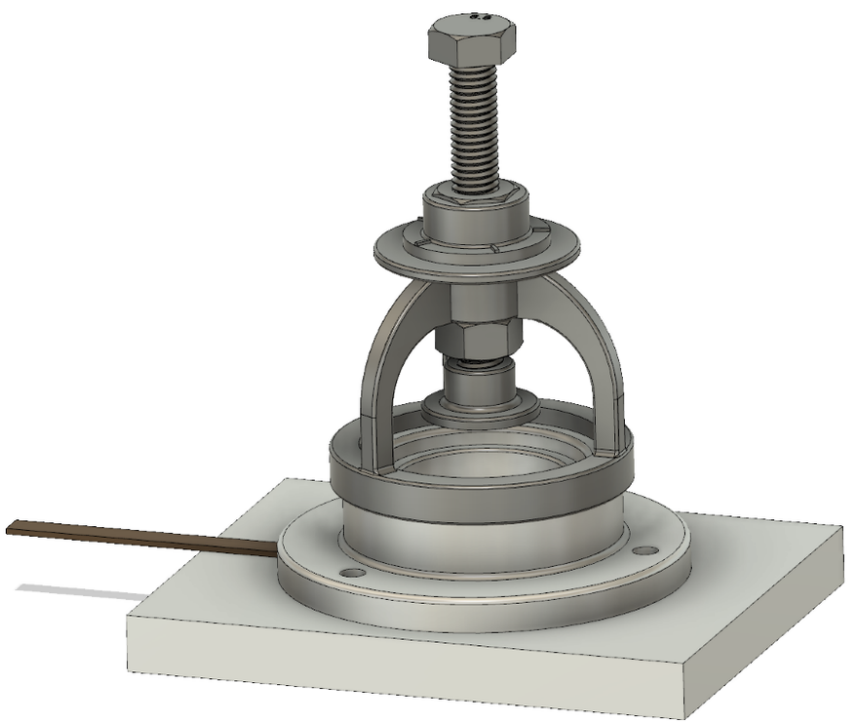

Figure 13. 3D model of the test fixture configuration.

Unlike the area on the top of the filter, the area on the bottom of the filter, between the filter and the sensor, should not be open. On an earlier test setup the distance between the filter and the sensor was open and left the sensor susceptible to infrared radiation from the surroundings. In the new test fixture this is fixed by using a 3D-printed plastic chamber around the sensor and the filter.

The test fixture was originally planned to be made of aluminum, but after the prototype for the test fixture was 3D-printed, it was decided that the PLA-plastic of the 3D print would be the material of the final test chamber. 3D-printed PLA-plastics thermal insulation properties are good enough for the low-heat and low-voltage tests.

The test chamber, filter frames and the LED configuration all help to keep the system aligned throughout the testing. Keeping the alignment of the filter, LEDs and the sensor similar in all tests is essential, as differences in the alignment of the system lead to differences in the position of the surfaces. Some alignments could weaken the infrared radiation and therefore the output voltage, causing differences in the test conditions. The tube-like shape of the test chamber makes sure that the tests are easily repeatable and major differences in LED and filter alignment can be prevented.

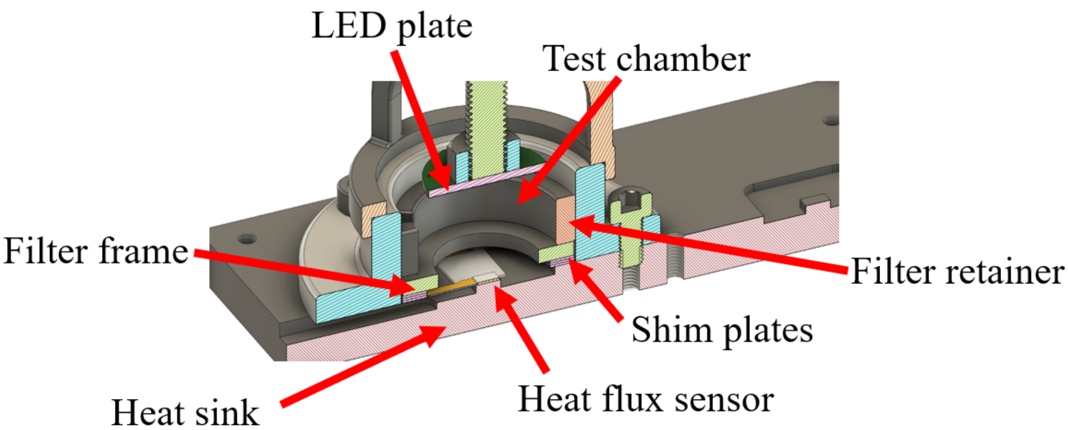

Figure 14. The bottom part of the test fixture with parts of it labeled. The LED plate has the LEDs on it, the filter frame holds the filter and the filter retainer is used to keep the filter frame in place. The heat flux sensor in on the bottom of the fixture and is placed on top of the heat sink. Shim plates are used to change the distance between the heat flux sensor and the filter. Test chamber refers to the space inside the test fixture.

A filter frame, pictured in Fig. 15, is used to keep the alignment of the filter the same between tests. The filter frames are 3D-printed pieces of PLA plastic that have a filter-sized hole in the middle. The filters were placed in the middle of the frame. The filter frame allows different sized filters to be used in the same fixture, given that their diameter is smaller than that of the test chamber. This resolved the question of how the same setup could be used for testing different sized filters interchangeably, which was one of the biggest challenges in the design of the setup. The filter frame also makes the implementation of the PT100 temperature sensor easier as the sensor wires can be passed through the filter frame. This can be seen in Fig. 15.

The filter-sensor distance could be changed by adding shim plates in between the test chamber filter plate catchers and the filter plate. The shim plates are pictured in pink in Fig. 14, between the green filter frame and the heat sink on the bottom of the test fixture. The shim plate thickness determines the smallest possible amount of difference in the filter-sensor distance. The thinnest shim plate used in this research was 100 micrometers thick.

A filter retainer was used on top of the filter frame to make sure the filter frame stays on the bottom of the test chamber and right on top of the shim plates. The retainer is a round 3D printed piece that can be seen in Fig. 14 in orange, inside the test chamber. It is slightly bigger in circumference than the test chamber and has an opening on one side. This opening allows the retainer to bend and be placed in the test chamber. Because of the opening and the retainer being slightly bigger than the chamber, the retainer keeps a tension on the test chamber walls and stays in place. By putting the retainer in top of the filter frame, the alignment of the filter frame can be secured in place.

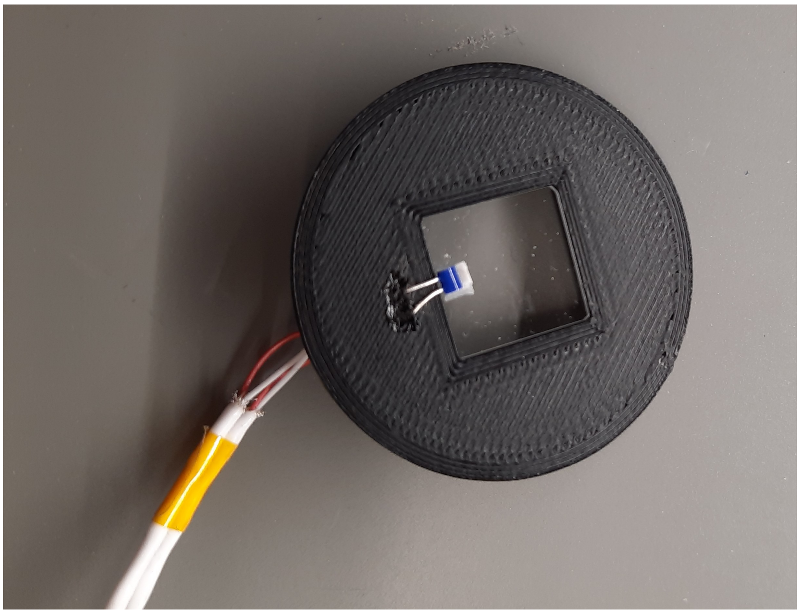

Figure 15. A filter and the filter frame for JGS1 Fused Silica filter. The blue device is a PT100 temperature sensor.

The LED alignment on the bottom of the LED plate needed some extra caution before the final tests. There were 3 different types of LEDs that emitted different wavelengths, 1.65 μm, 3.6 μm and 4.3 μm. There were 5 of each type of LED and 15 LEDs in total. The LED plate configuration can be seen in Fig. 16. The 1.65 μm LEDs were situated in the middle of the plate and the 3.6 μm and 4.3 μm LEDs in rows on different sides of the plate.

It was suspected that the unsymmetric LED placings on the plate might result in some LEDs getting a better field of view on to the filter and the heat flux sensor and therefore causing a bigger signal. It was also suspected that the LEDs might work differently in different LED plate rotations, meaning that rotating the LED plate would also have an impact on the heat flux sensor signal. Because of these suspicions, extensive practical tests were made. In these tests, the heat flux sensor signal was measured every 10° of the angular rotation of the LED plate. The angular scale used in the tests can be seen in Fig. 17. This test was repeated with all three LED wavelengths and as a result the optimal angles for all LED wavelengths were found. The plate angle was then adjusted for each LED according to these results. For future test setup configurations, it might be a better idea to have separate LED plates and holders for each LED wavelength so that all LEDs can be in the middle of their own plate.

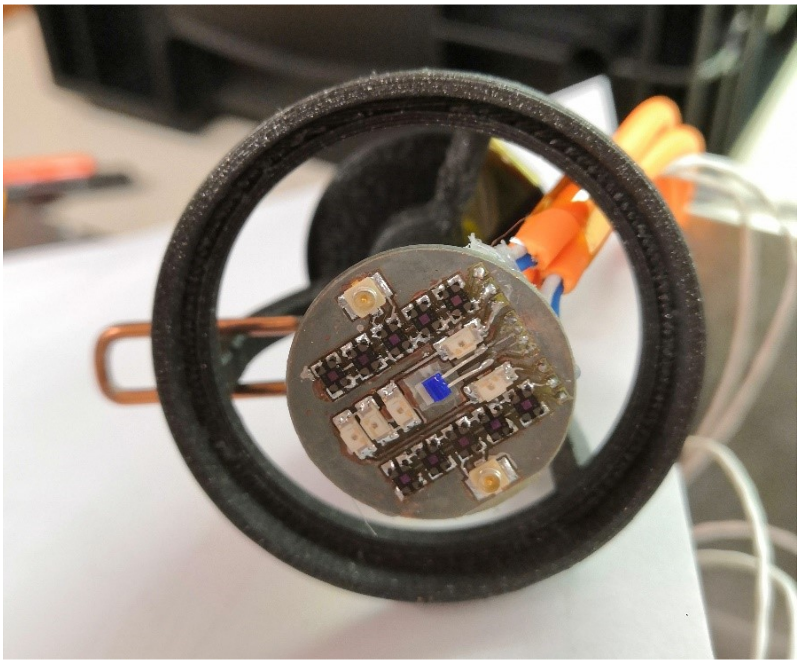

Figure 16. LED plate from the bottom. The LEDs are in rows.

Even with the optimal angles of the LED plate, there was still some differences on the signal the LEDs produced on the heat flux sensor. This was because the LEDs were of different models and had different powers of irradiation. The 1.65 μm and 4.3 μm LEDs

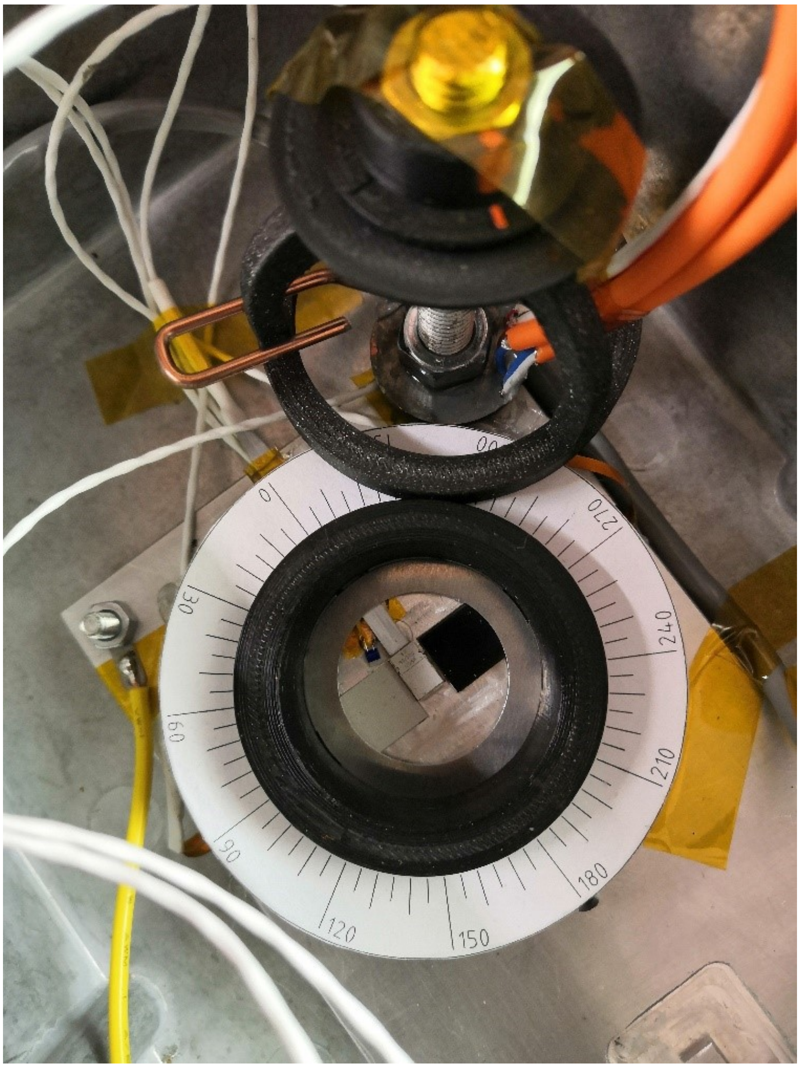

Figure 17. Sensors at the bottom of the test chamber and the scale for LED plate angular rotation around the chamber.

outperformed the 3.6 μm LED by producing much clearer and larger signals on the heat flux sensor. The differences could also be due to some differences in the reflection on the surface of the heat flux sensor between different wavelength radiation.

The height of the LED plate was also experimented to map out the difference it makes on the heat flux sensor output signal. This experiment was also to determine an optimal height of the LEDs and to make sure that the differences in the heat flux sensor signal between different LED wavelengths noted in the earlier LED plate rotation tests were not due to the filter window not being in the LED field of view. This could be a possibility because in the LED angular rotation tests, the LEDs were very close to the filter and some of them quite close to the edge of the filter and the filter frame. This is another potential problem of the LED plate design.

After experimenting on different LED heights, it was concluded that the LED plate being closer to the filter-sensor system caused a higher signal on the sensor. A height of 3 mm from the filter, when the filter is in contact with the heat flux sensor, was determined to be a good height for the final experiments. This allows for a 1 mm increase in the filter height without drastically changing the setup. The heat flux sensor signal level was also satisfactory on this LED height.

The possible variables that could cause differences in the setup were tested before the final experiment. These included the rotation angle of the LED plate and the filter frame. Different LED pulse lengths and the time intervals waited between the tests were also experimented. Optimal values for these variables were found and chosen for the final tests.

Two different filters were used in order to determine the transferability of the results. Transferability of results means that the results are general to the setup type, and can be repeated with other filters. In other words, the results are not dependent on the exact filter type, and can be generalized to other filter-sensor systems too. The first filter used in the experiment was a SiO_2 filter. It is a silica composite developed in Aalto University in research of the near-infrared reflection of silica-silicon composites [2]. The composite is made of micro-silica powder and it transmits electromagnetic radiation according to Fig. 18. The filter is 3 mm thick with a diameter of 2 cm and it has a translucent white look to the eye. The filter is pictured in Fig. 19 inside the filter frame with the filter temperature sensor attached to the other side of the filter. The wiring of the temperature sensor through the filter frame can also be seen in this picture.

The second filter used in the experiment was a fused silica filter named JGS1. JGS1 was a square shaped, completely transparent filter, pictured earlier in Fig. 15. The size of this filter was 12 mm by 12 mm and the thickness was 1 mm. The filter was produced by Shijiazhuang Tangsinuo Optoelectronic Technology Company. The transmittance spectra of this filter can be seen in Fig. 20, and from it can be concluded that from the different wavelength options the JGS1 filter transmits 1.65 μm radiation best, and mostly blocks 3.6 μm and 4.3 μm radiations.

The heat flux sensors used in this experiment were the gSkin-XM and gSkin-XP sensors by Greenteg. The gSkin-XM sensor was the smaller sensor, that was placed on the very center of the test chamber. The gSkin-XM sensor was the main interest of the study. The additional sensor, gSkin-XP, was placed on the side of the test chamber and was partially covered by the filter frame. The size of the sensing area on the gSkin-XM sensor 4.4 mm

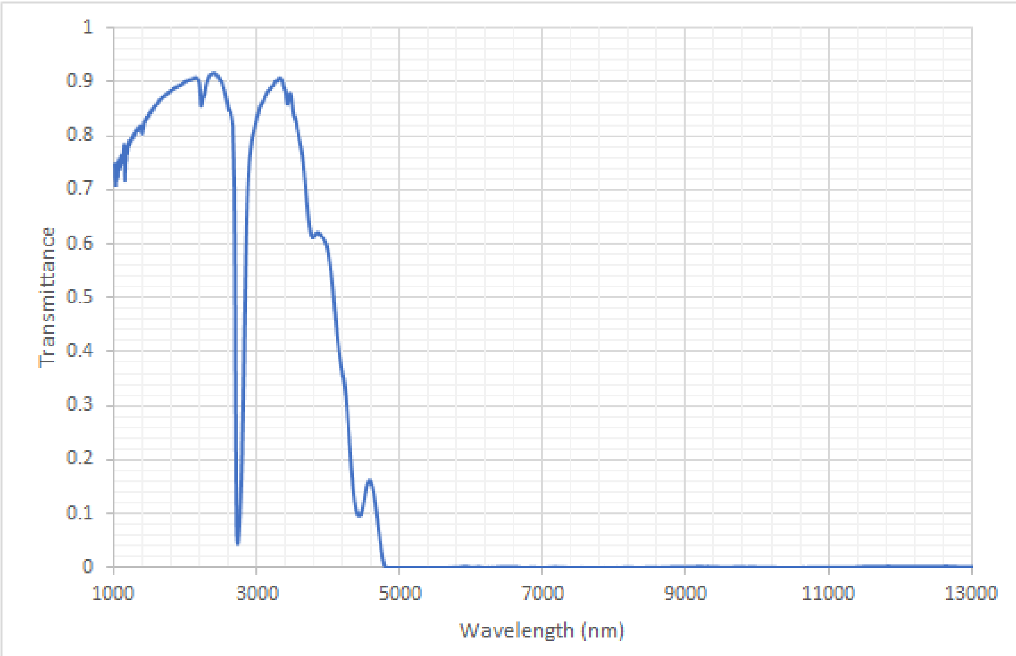

Figure 18. Transmittance spectrum of the Aalto SiO_2 filter.

x 4 mm and on the bigger gSkin-XP 10 mm x 10 mm. The sensing area of both sensors was made of anodized aluminum.

The thermal interface material used in this experiment was a thermal gap filler produced by T Global called H486-150-0.5. The thermal conductance of the material was 3.2 W/m*K and it was chosen as the thermal interface material for the tests because it was the best value of thermal conductance of the materials available. The material was 0.5 mm thick and had a thermal adhesive on one side, which made its implementation on the test system very easy. In the thermal interface material tests the adhesive side of the material was put on the Aalto SiO_2 filter. This can be seen in Fig. 20.

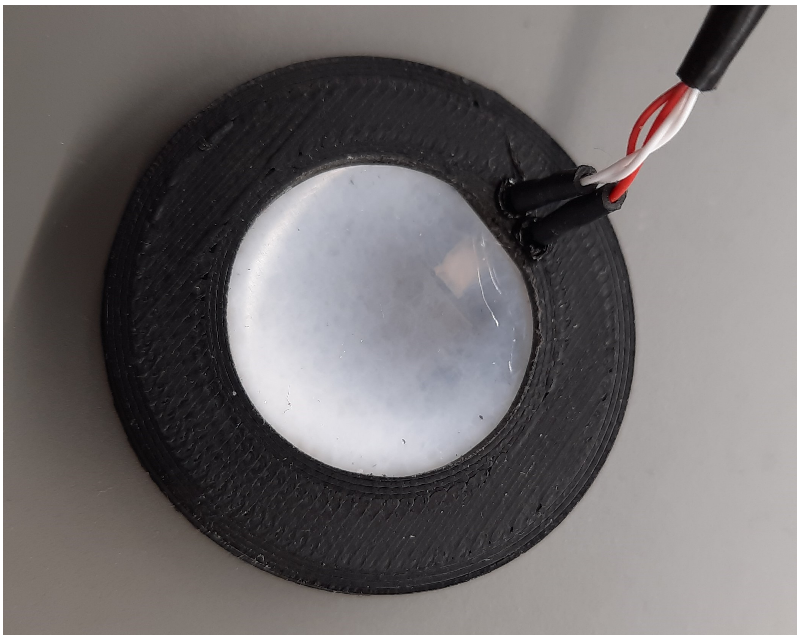

Figure 19. Aalto SiO_2 filter pictured inside the filter frame. The PT100 temperature sensor can be seen faintly on the other side of the filter.

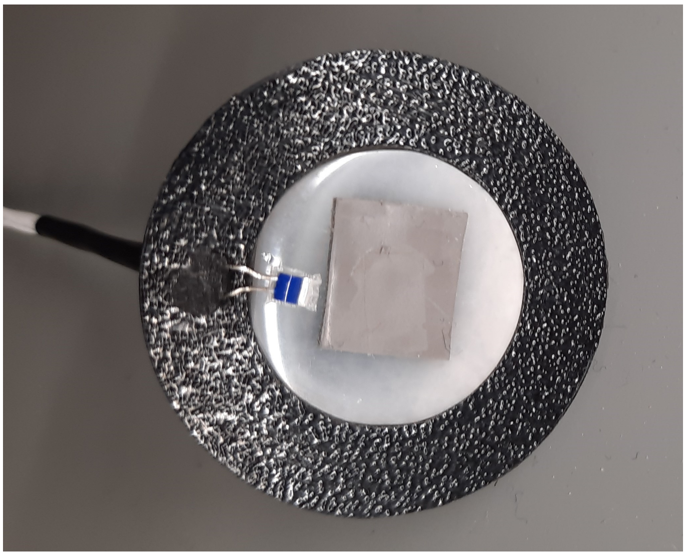

Figure 21. Thermal interface material on the bottom side of the Aalto SiO_2 filter. This side was put facing the sensor.

In addition to the heat flux sensor and current measurement channels, temperature measurement channels were also an essential part of the experiment. The temperature sensors were PT100 sensors that were referenced to as follows: source, which was on the LED plate; filter, which was located on the bottom side of the filter and can be seen in Fig. 15;

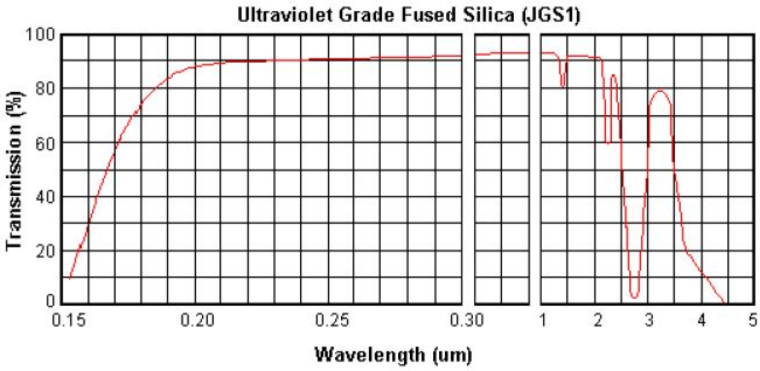

Figure 20. Transmittance spectrum of the fused silica JGS1 filter. Between the LED wavelengths, the transmittance is highest on the 1.65 μm region where it is at around 90 % and lower in the 3.6 μm and 4.3 μm regions.

base, which was located on the heat sink plate next to the heat flux sensors; enclosure, which was located inside the test box but outside of the test chamber; and environment, which measured the temperature in the room outside the test box. The temperature measurement placements are pictured in Fig. 22.

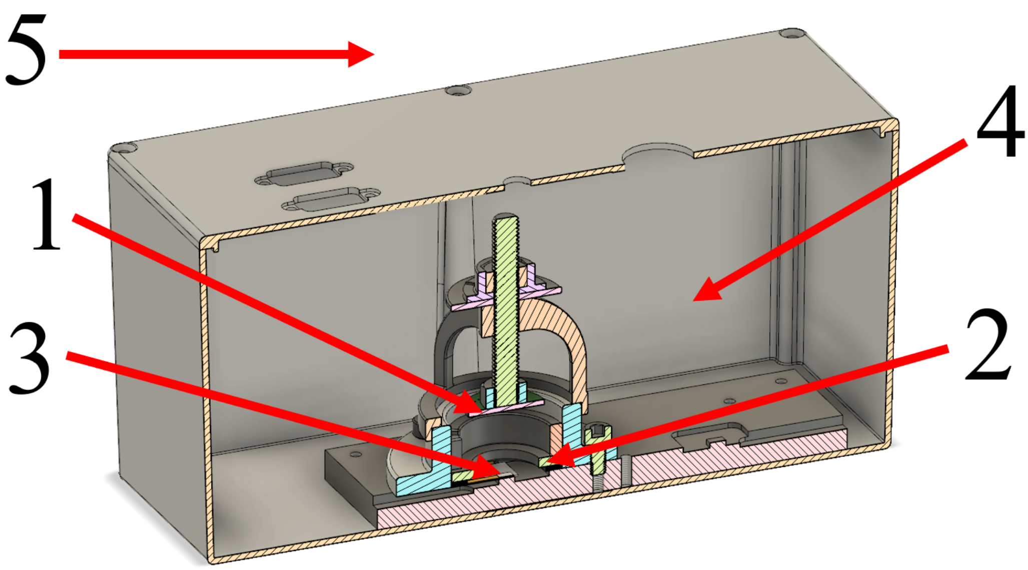

Figure 22. PT100 temperature placements in the test setup: 1. Source, 2. Filter, 3. Base, 4. Enclosure and 5. Environment.

4.2 Experiment outline

The experiment outline is explained in Fig. 23.

Test number	Filter	Distance between filter and sensor	Medium
1	No filter	-	Air
2	No filter, Aalto SiO_2 filter frame	-	Air
3	Aalto SiO_2 filter	0 mm	Air
4	Aalto SiO_2 filter	0.1 mm	Air
5	Aalto SiO_2 filter	0.2 mm	Air
6	Aalto SiO_2 filter	0.3 mm	Air
7	Aalto SiO_2 filter	0.4 mm	Air
8	Aalto SiO_2 filter	0.5 mm	Air
9	Aalto SiO_2 filter	0.6 mm	Air
10	Aalto SiO_2 filter	0.7 mm	Air
11	Aalto SiO_2 filter	0.8 mm	Air
12	Aalto SiO_2 filter	0.9 mm	Air
13	Aalto SiO_2 filter	1 mm	Air
14	No filter, JGS1 filter frame	-	Air
15	JGS1 filter	0 mm	Air
16	JGS1 filter	0.1 mm	Air
17	JGS1 filter	0.2 mm	Air
18	JGS1 filter	0.3 mm	Air
19	JGS1 filter	0.4 mm	Air
20	JGS1 filter	0.5 mm	Air
21	JGS1 filter	0.6 mm	Air
22	JGS1 filter	0.7 mm	Air
23	JGS1 filter	0.8 mm	Air
24	JGS1 filter	0.9 mm	Air
25	JGS1 filter	1 mm	Air
26	Aluminium sheet on a filter frame	3 mm	Air
27	Soot covered aluminium sheet on a filter frame	3 mm	Air
28	Soot covered aluminium sheet without a filter frame	0 mm	Air
29	Aalto SiO_2 filter	0.5 mm	Thermal interface material

Figure 23. Numbered tests done in the experiment

The baseline of the heat flux sensor signal was first determined without any filters or filter frames in test 1. Tests number 2 and later 14 determined the impact the different empty filter frames had on the signal. In tests 3 to 13, the Aalto SiO_2 filter was raised by 0.1 mm between every test, the 0 mm meaning that the filter was on the sensor and 1 mm meaning that there was a 1 mm gap between the filter and the sensor. The same was repeated to the JGS1 filter in tests 15 to 25. These tests were done to determine the impact of changing the filter-sensor distance on the heat flux sensor function.

In test 26, the filter was replaced with a piece of an aluminum sheet. In tests 27 and 28 the aluminum sheet was held next to a candle to get a layer of soot on it. The idea behind these measurements was to make sure that the infrared signal from the LEDs was not a false positive by creating a measurement where all of the IR radiation was reflected. In a way, this was the antithesis of the first test.

Lastly, the impact of a thermal interface material was tried out in test 29. In this measurement, the 0.5 mm thermal gap filler was put between the Aalto SiO_2 filter and the heat flux sensor.

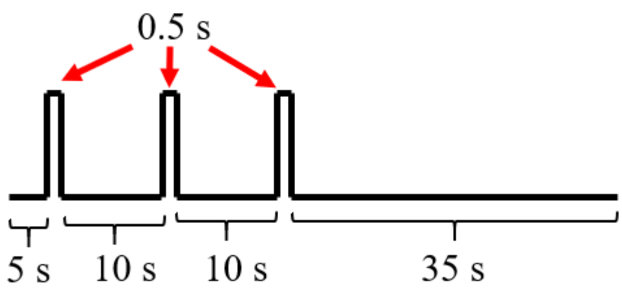

Figure 24. The LED signal consisted of three 0.5 second pulses, separated by 10 seconds.

The infrared excitation was provided with LEDs of three different wavelengths: 1.65 μm, 3.6 μm and 4.3 μm, and in each test the LED plate was rotated in the optimal angle for each LED. The current going to each LED type was measured and monitored. The height of the LED plate was 3 mm from the filter. The LED signal was made of three 0.5-second-long pulses with 10 seconds in between. In the measurement period there was a 5 second time before the first LED pulse and a 35 second waiting period after the third pulse. This was to ensure that some of the cooling down of the system could also be visible in the heat flux sensor output voltage. A graph of the LED signal can be seen in Fig. 24

5 RESULTS AND DISCUSSION

The tests were overall successful and provided a lot of new information about how the different filters work with the heat flux sensor. It is planned that the data acquired in the tests will be accessible in an open data service like the research data storage service IDA.

One of the main findings in the results was how differently the infrared radiation affected the heat flux sensor signal compared to conductive and convective heat transfer. It is beneficial to notice the difference between them before reading the results. Firstly, the heat flux sensor signal caused by radiation and the signal caused by other types of heat transfer, conductance or convection, can be easily told apart by their shapes. The radiative heat transfer causes a sharp spike on the sensor signal because it's heating effect on the sensor is instantaneous and does not have a delay. The heat flux sensor signal with the infrared spikes can be seen in blue Fig. 25. In contrast to this, the heating effect caused by convection and conduction causes a softer signal, that rises slowly compared to the signal caused by radiation. Convection and conduction are slower forms of heat transfer that cause a more gradual change in temperature, the magnitude of which is comparable to the magnitude of the source temperature. This slower heating up of the sensor is picture in red in Fig. 25, where it is caused by the test system warming up slowly. The infrared spikes are not present in this signal because the filter filtered them out.

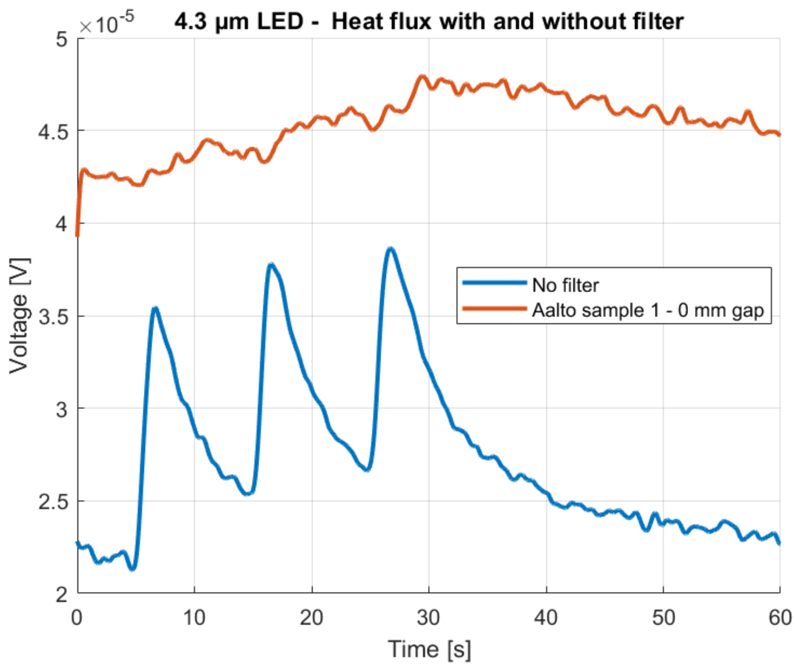

Figure 25. Heat flux sensor signal from 4.3 μm LED, in blue without any filter between the source and the sensor, and in red with the Aalto SiO_2 filter on top of the sensor. The Aalto SiO_2 filter blocked majority of the infrared radiation that could have reached the sensor.

The differences between different heat transfer type signals are beneficial in analyzing the results because they help identifying the different heat transfer methods and therefore the different effects those heat transfer types have. Even though the signal shape is a good indicator of whether there is radiative heat transfer, it should not be taken as an absolute measure of it, because the heat flux sensor is not designed for signaling different types of heat transfer. It could also be suspected that some infrared radiation still passes through the filter even when the heat flux sensor does not signal it, because the heat flux sensor is inherently not designed to sense infrared radiation, even though the effects of it can be seen in the sensor signal.

All three different effects the filter material can have on infrared radiation can be seen in the heat flux sensor output voltage. Reflection from the filter material causes the output voltage to stay the same. Absorption on the filter material causes the output voltage to rise slowly, because absorbed heat is dissipated on to the sensor as conductive or convective heat. The radiated heat can be seen as the rapid spikes on the sensor output voltage.

Another thing to note before looking through the results is that the baseline of the heat flux sensor, in other words the level of the heat flux before the infrared source signal, is quite different in all the measurements. The difference in baseline can be seen well in Fig. 26. This is likely because of slight temperature changes in the system due to changing the LED plate rotation. The differences in initial baseline did not affect the amplitude of the heat flux sensor signal and can therefore be ignored. In some of the results, the measurement plots have been normalized on the same level, so it is easier to spot similarities and differences in them.

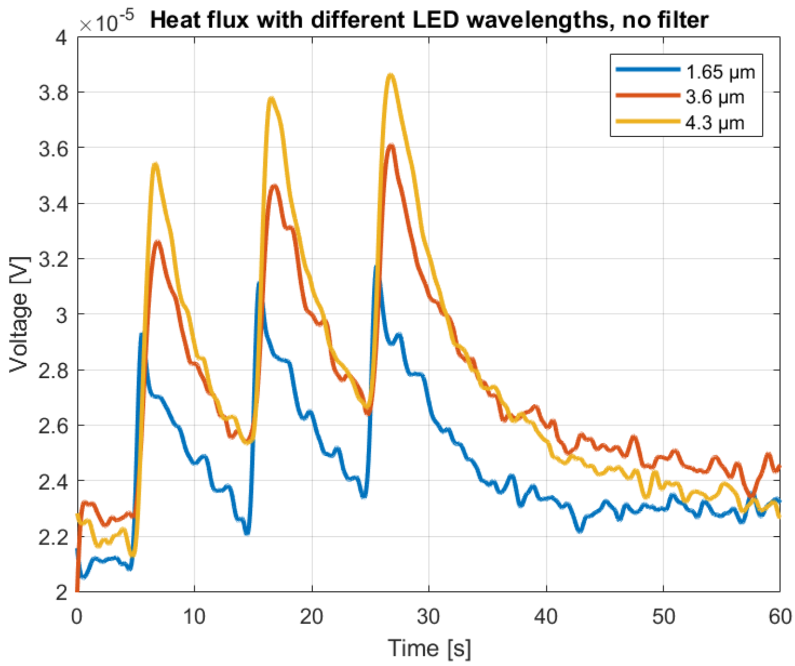

Figure 26. Heat flux sensor signal with all different LEDs and without any filters. All LEDs caused an infrared peak on the sensor when there were no filters in the way.

All three different wavelength LEDs caused a visible infrared radiation peak on the heat flux sensor when no filter was used. This can be seen in Fig. 26. Both the Aalto SiO_2 filter and the JGS1 filter transmitted the 1.65 μm wavelength radiation but filtered out the 3.6 μm and 4.3 μm wavelengths.

In the results, it was demonstrated clearly that the tested filters have all selective properties and can transmit infrared radiation of a wanted wavelength. It was also found that the filter did attenuate the radiation, causing the filtered infrared radiation to be more muted compared to the comparable test without a filter. It was also found that the filter frame worked well and did not block the radiation from the LEDs, even though it did absorb some heat from the radiation and handling of the filter, causing it to raise the temperature of the test chamber slowly. This was noticed in the very first tests and could be eliminated by leaving some time between handling the test chamber and the measurements.

5.1 Results with different filter-sensor distances

The heat flux signal caused by the 1.65 μm LED when the Aalto SiO_2 filter is on top of the sensor is pictured in Fig. 27. The heat flux signal with the same filter but with a 1 mm gap between the filter and the sensor is pictured in Fig. 28. It can be seen from these results that the air gap between the sensor and the filter did not make a big difference in the amplitude of the sensor signal. On the other hand, there is a slight difference on how the baseline of the heat flux sensor signal settles after each infrared pulse. In the measurement with the air gap, seen in Fig. 28, the heat flux signal comes back to the original baseline level after each LED pulse. When there is no gap between the sensor and the filter, the heat flux signal does not come back to the original baseline level and the baseline gradually rises throughout the measurement.

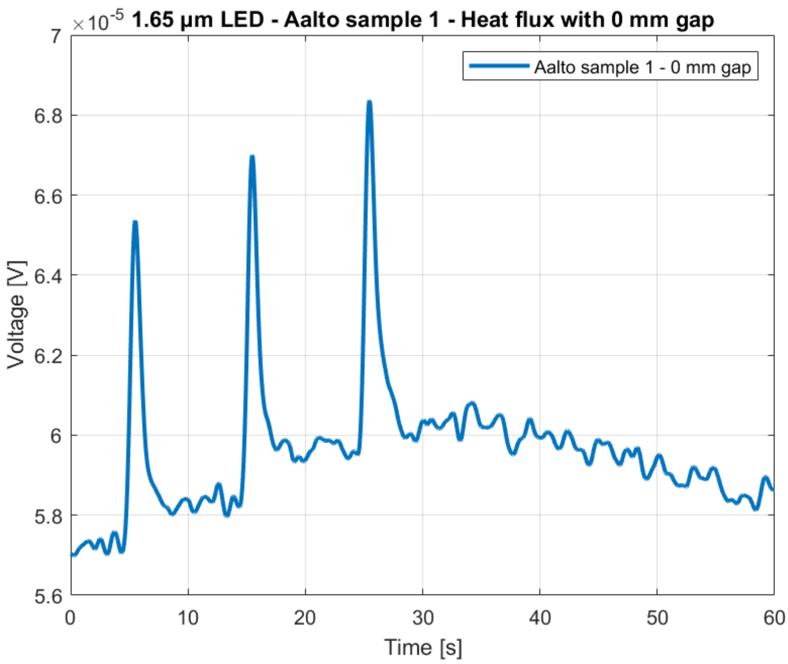

Figure 27. Heat flux sensor signal with the Aalto SiO_2 filter on top of the sensor. The infrared peaks are visible, and the baseline of the filter rises during the measurement.

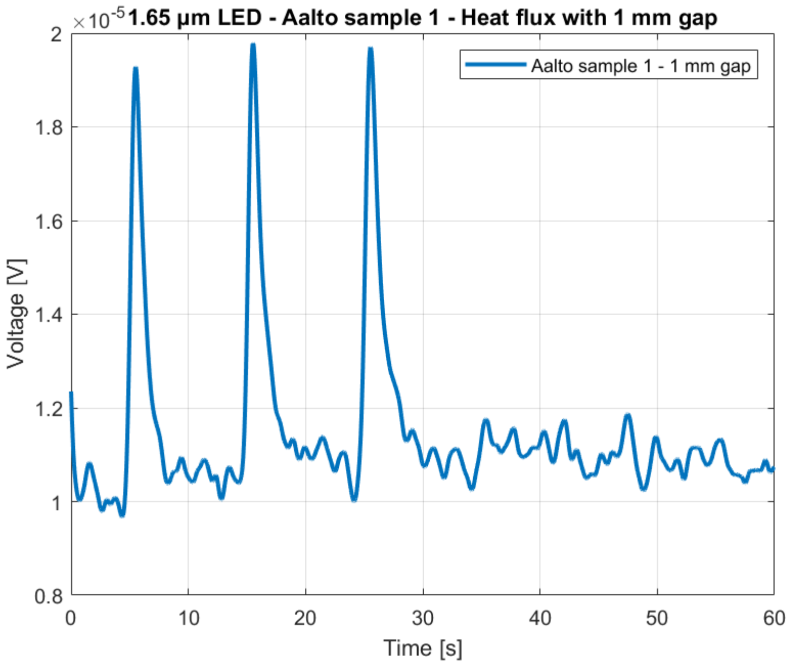

Figure 28. Heat flux sensor signal with the Aalto SiO_2 filter, now with a 1 mm gap between the filter and the sensor. Infrared peaks are visible but the baseline of the signal does not rise.

The JGS1 filter did not cause baseline rise in the same way that the Aalto SiO_2 filter did. The heat flux signal with the JGS1 filter straight on top of the filter can be seen in Fig. 29. The infrared amplitudes are distinct and the baseline is somewhere in between a stable and a rising one, but the rising is not very significant. The air gap between the filter and the sensor did not significantly change the heat flux signal.

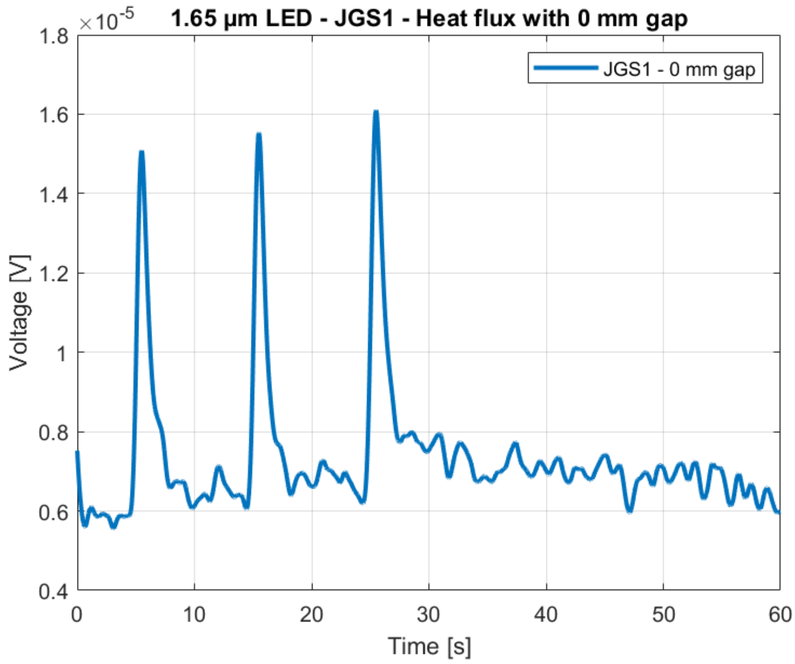

Figure 29. Heat flux sensor signal with the fused silica JGS1 filter, with the filter on top of the sensor without an air gap. No major baseline rise was found between the infrared signals.

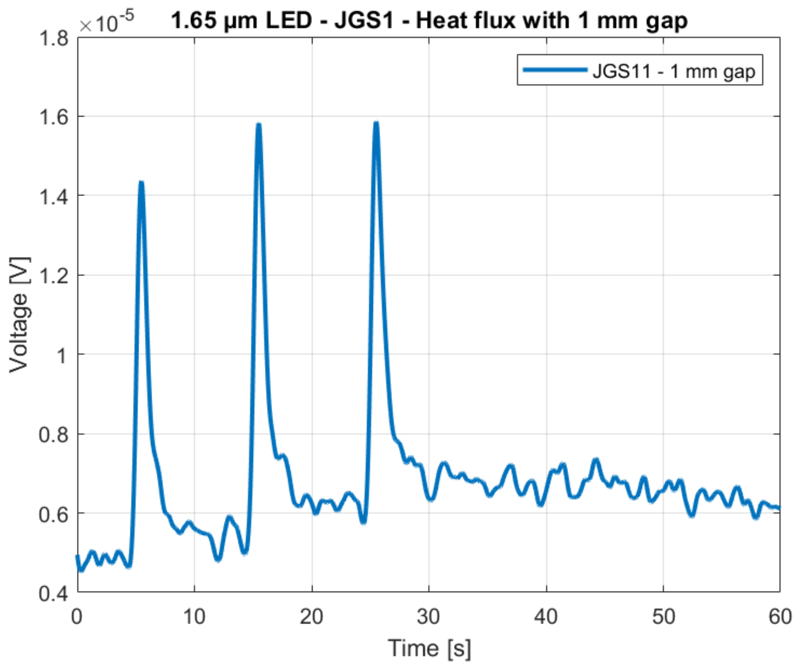

Figure 30. Heat flux sensor signal with the fused silica JGS1 filter, with a 1 mm air gap between the filter and the sensor. The baseline did not rise significantly between the infrared signals.

The baseline rise of the sensor signal, pictured in Fig. 27 can be the result of many things. It was noted through Fig. 27 to Fig. 28 that as the filter and the sensor had an air gap between them, the baseline did not rise. As the filter and the sensor were closer to each other, the baseline rose between the infrared pulses. Most of the differences in the baseline rising happened in the very first measurements when the filter was very close to the sensor, while the measurements from 0.5 mm to 1 mm looked all very similar. Because of that, the later measurements were done with either 0 mm gap or 0.5 mm gap

The difference in the results between the Aalto SiO_2 and JGS1 tests is most likely because of different optical properties of the filters. The Aalto SiO_2 filter absorbed more of the radiation whereas the JGS1 filter reflected it. The Aalto SiO_2 filter was also thicker in size than the JGS1 filter, which could mean that it could absorb more heat.

The results from these heat flux sensor measurements would suggest a temperature rise in the filter as the cause of the baseline rise of the sensor. First, no significant filter temperature rise could be found. This might be because of a poor contact between the filter and the PT100 sensor or that the LED power was not big enough to cause the expected temperature rise on the filter. New complementary tests were done to further investigate the filter temperature. In these new tests the PT100 temperature sensor was re-applied to the filter with glue instead of thermal tape, which was used in earlier tests. This alteration allowed the temperature sensor to have a better contact to the filter and the temperature differences could be sensed.

The temperature of the Aalto SiO_2 filter was tested with two different filter-sensor distances: 0 mm and 0.5 mm. Both distances were tested with all three LED wavelengths and the setup was similar to the original tests with the difference that the LED power settings were set from 10 V and 300 mA to 16 V and 1 A. This way the LEDs were “brighter” and emitted more infrared radiation, making the unwanted thermal effects, like the filter temperature rise, more noticeable.

In these results, the filter temperature rise was more noticeable, and the hypothesis of the baseline rise of the heat flux sensor signal being due to the filter temperature rise got more confirmation. There was not a noticeable difference in between the gapped and gapless filter temperatures, but a significant difference in between the temperatures when a wavelength that caused an infrared spike on the sensor was used, in compared to when a wavelength that did not cause a spike was used. The first option can be seen in Fig. 31 and Fig. 32, where the Aalto SiO_2 filter was used with a 1.65 μm LED. The infrared spikes the LED caused can be seen in Fig. 31. There is also some heat flux baseline rise. The temperature measurement can be seen in Fig. 32. The signal contains a lot of noise, and the signal-to-noise ratio is bad. No significant temperature rise can be seen.

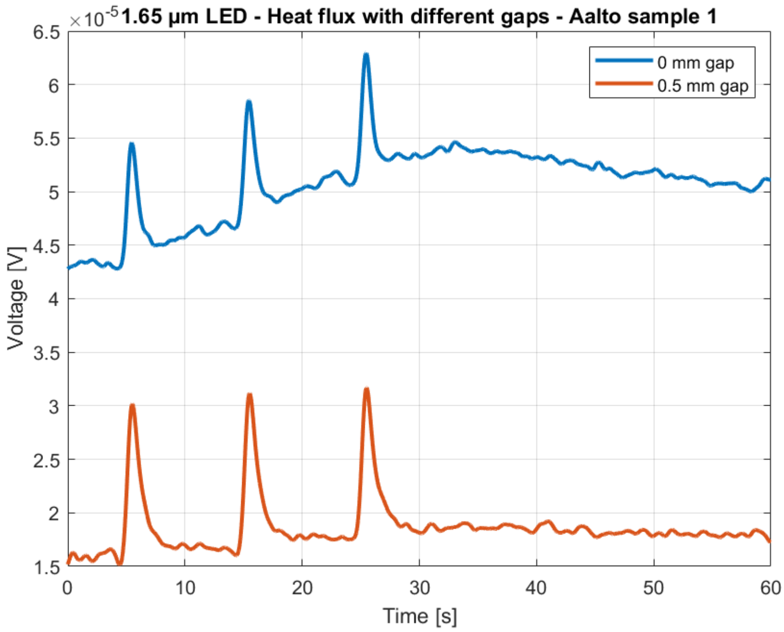

Figure 31. Heat flux sensor output voltage when a higher power was used on the 1.65 μm LEDs. In blue there is no gap between the filter and the sensor, and in red there is half a millimeter gap. The gapless integration caused the baseline of the heat flux sensor to rise, whereas it stayed stable in the integration where there was a small gap. This is most likely because of the filter absorbing heat and heating up the sensor.

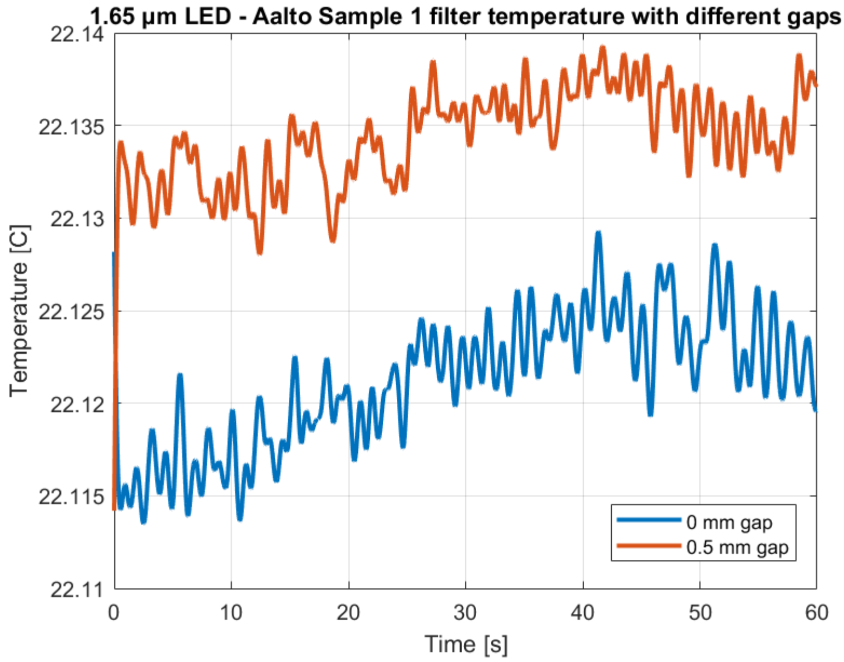

Figure 32. Filter temperature measurements when the filter transmits the infrared radiation, blue is when there is no gap between the filter and the sensor and red is when there is a 0.5 mm gap. There was no significant temperature rise when the infrared radiation transmitted through the filter.

The heat flux sensor output voltage with 3.6 μm LEDs is pictured in Fig. 33. In this case, no infrared spikes are noticeable. The heat flux signal rises in both cases, whether there is a gap or not, but it is notably larger when there is no gap and the filter is on top of the sensor. The Aalto SiO_2 filter temperatures are pictured in Fig. 34, in this case when the 3.6 μm LED is used. The filter temperature can be seen rising throughout the measurement as the LEDs make infrared pulses and heat up the filter until about the 35 second mark, after which the temperature of the filter tapers down.

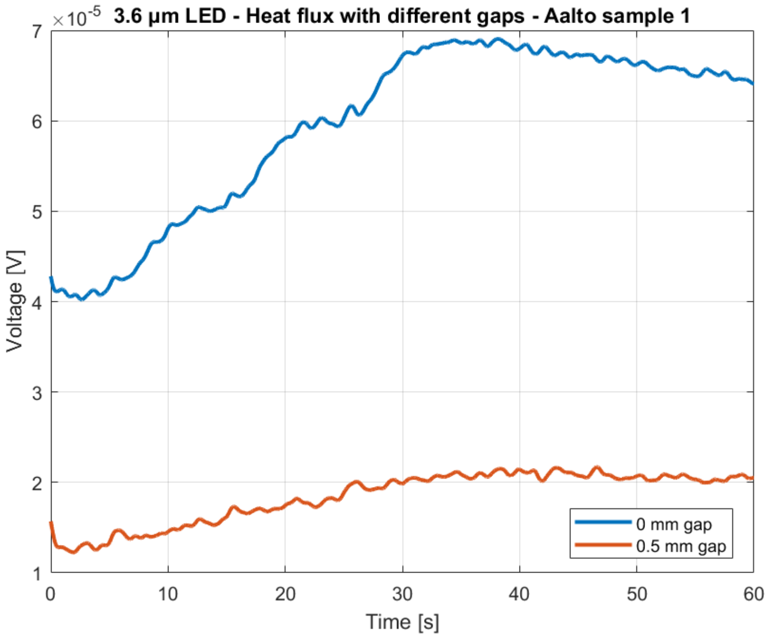

Figure 33. Heat flux sensor output voltage when a higher power was used on the 3.6 μm LEDs. In blue there is no gap between the filter and the sensor and in red there is half a millimeter gap. There was some temperature rise in the system because of the LED pulses, but no infrared spikes were visible.

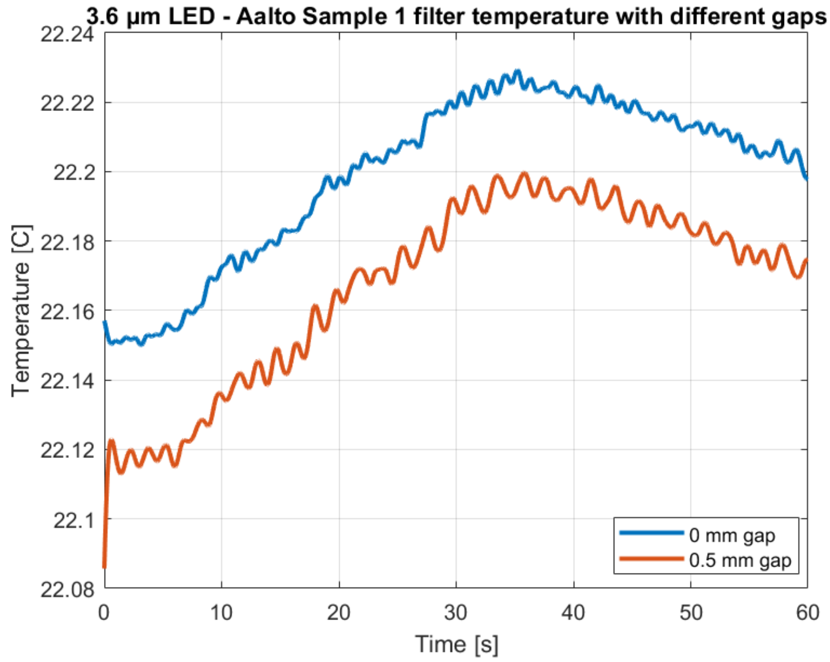

Figure 34. Filter temperature measurements when the filter does not transmit the infrared radiation. Blue is when there is no gap between the filter and the sensor and red is when there is a 0.5 mm gap. The temperature of the filter rose when the infrared radiation peaks were not visible in on the heat flux sensor, most likely because the filter blocked them partly by absorption, which then showed up as filter temperature rise.

With the Aalto SiO_2 filter, there is a big difference in the filter temperature when the radiation can be seen on the heat flux sensor and not. When the radiation spikes were visible in the heat flux sensor output voltage, the filter temperature did not rise and therefore it could be concluded that the filter did not absorb much of the infrared radiation. Alternatively, when the radiation spikes were not visible on the heat flux sensor signal, the filter temperature rose, meaning that the filter absorbed some of the radiation. In these tests there was no significant difference in the temperature measurement between the filter that was placed closer to the sensor and the one with an air gap between the filter and the sensor.

At first, it might seem that the filter temperature rise should be seen as a soft peak in the heat flux sensor output voltage after the infrared emission peak. This is because the filter releases the heat slowly, so it would be intuitive that the heat flux sensor output would also have that soft peak shape, similar to a temperature measurement of a material that has been subjected to a short infrared pulse. This intuitive conclusion is not correct in reality, as the heat flux sensor senses the derivative of temperature, and therefore can in theory have a downward sloping “tail” even when the filter is still emitting some absorbed heat. This way, even when the filter has some temperature rise and emits or conducts that to the heat flux sensor, it does not necessarily show up on the signal, as the heat flux sensor only senses the difference in the temperature between the filter or the air gap between the filter and the sensor, and the heat sink underneath the sensor. The “tail” that shows up in the heat flux sensor output voltage after the initial infrared pulse can be a combination of the LED and LED plate post-pulse heat, filter or other system temperature rise or partially the result of a slow sensor.

More measurements were made, this time with a 5.5 μm longpass filter. The function of this filter was to filter out all infrared radiation that had wavelength smaller than 5.5 μm. The filter temperature was measured with a Keysight multimeter, which had a better signal-to-noise ratio than the data acquisition tool used in the earlier measurements. The Keysight multimeter was not in sync with the other measurements, so the time signature of the measurement is not comparable to other measurements. Conclusive Keysight data about the JGS1 and Aalto SiO_2 filters is unfortunately not available as the 1.65 μm test setup LEDs blew out during the later tests when the LED power was increased over the suggested amount.

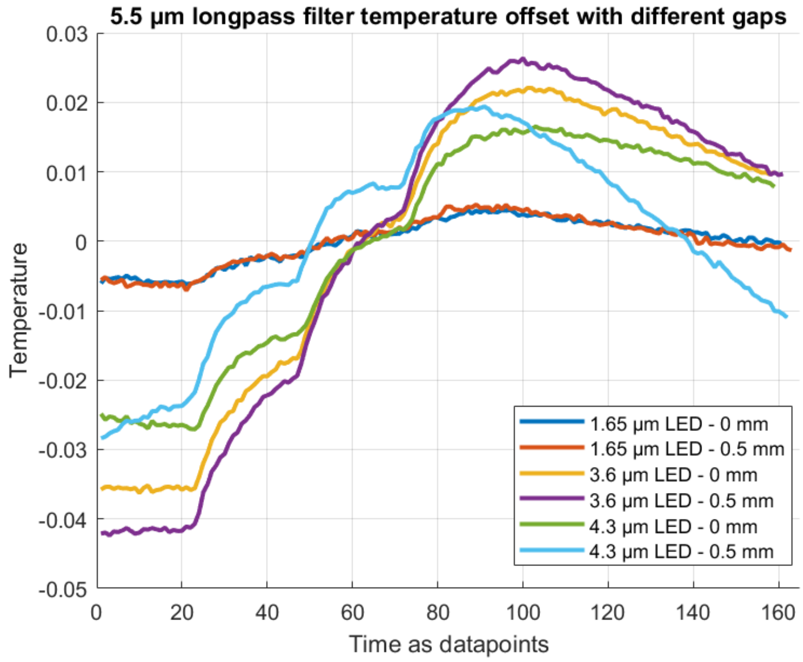

Figure 35. The offset values of all different measurements used with 5.5 μm longpass filter. The temperature of this filter rose as it transmitted radiation and stayed stable as it blocked radiation. The axes of this measurement are not comparable, as the Keysight multimeter did not sync the measurements with time and the temperature values are offset values and are the difference between the actual value and the datasets mean.

The different filter temperature measurements are plotted in Fig. 35. In this case, there is a significant difference in the measurements of the 1.65 μm LEDs and the other LEDs. The 1.65 μm LEDs heated up the filter but in a very mild manner compared to the 3.6 μm and 4.3 μm LEDs. This is most likely because the filter filters out the 1.65 μm radiation most effectively but might also be because the 1.65 μm LEDs were used in a much bigger power than they were originally intended to, which might have resulted in some of them breaking.

From the data that is usable and not affected by the LED mishap, it can be concluded that the 5.5 μm long pass filter heats up when it transmits radiation. The filter was supposed to transmit only radiation with a wavelength bigger than 5.5 μm but it ended up passing 4.3 μm and some 3.6 μm radiation too. This most likely happens because the LEDs emit radiation in Bell curve-like variety of wavelengths around the reported wavelength, some of which goes over the 5.5 μm limit. This results in even the slightly off-wavelength LEDs to show up through the filter.

The difference between the 4.3 μm radiation with the filter straight on the filter and with a 0.5 mm gap can be seen more easily in Fig. 36. The gapless system in pictured in blue, and shows how the temperature of the filter rises in pulses, matching to the LED signal pulses. The red graph shows the same for the system with the 0.5 mm gap between the filter and the sensor. The temperature of the filter that has a gap between it and the sensor becomes steady between the pulses in contrast to the temperature of the filter and sensor without a gap, the temperature of which keeps on rising in between the pulses. The filter with the air gap also lowers its temperature quicker after the last LED pulse compared to the case where the filter in right on top of the sensor.

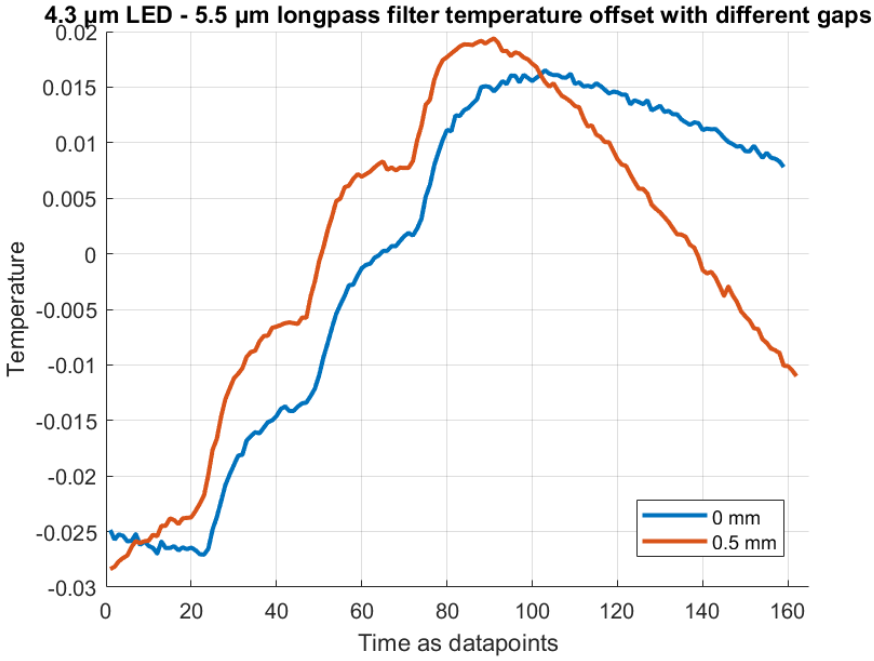

Figure 36. 4.3 μm LED through the 5.5 μm longpass filter, without a gap in blue and with a 0.5 mm gap in red. The filter in the integration with the gap cools down faster than in the integration without the gap. Similarly to Fig. 35, the axes of this graph are not comparable.

In these tests with the 5.5 μm long pass filter, pictured in Fig. 36, it can be concluded that the gap between the filter and the sensor makes the filter cool down more rapidly after the infrared radiation has been cut off. This means that the gap between the filter and the sensor does not necessarily make a difference in how the filter heats up, but on the way it cools down. A sensor attached on the filter without any gap leads to the filter taking longer to cool down.

The temperature rise of the filters is mostly dependent on the optical properties of the filter. Filters transmit the wanted radiation and what happens with the unwanted radiation is dependent on the filter. The filter can either reflect the unwanted radiation away off the surface of the filter or scatter it inside the filter material, which leads to absorption of the radiation to the material. The Aalto SiO_2 filter absorbed the infrared radiation and heated up when the LEDs did not show up on the heat flux sensor – this could be used as an example of an absorbing filter.

5.2 Results using the thermal interface material

The heat flux sensor output signal with Aalto SiO_2 filter and a 0.5 mm thermal interface material between the filter and sensor is pictured in Fig. 37. In this figure it is very clear that in addition to the radiation spikes, there is a lot of conduction heat transfer through the thermal interface material that shows up as a gradual rise in the heat flux. Using a thermal interface material made the baseline of the sensor signal rise even more than the filter close to the sensor. In addition to this, the heat flux amplitude of the thermal interface material version was smaller than in the air gap version. This phenomenon is very distinct especially when comparing it to Fig. 38, which portrays the heat flux signal of a sensor with the same filter and the same gap distance, but with air instead of thermal interface material as the gap medium.

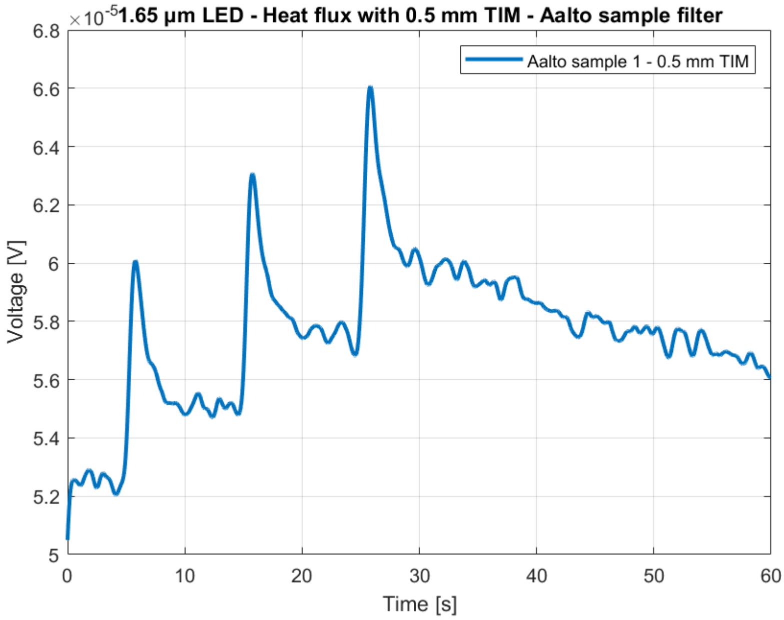

Figure 37. Heat flux sensor signal when the gap between the sensor and the Aalto SiO_2 filter was filled with a 0.5 mm thick thermal interface material. The thermal interface material causes the signal baseline to rise. The infrared spikes are also smaller than in the version without the material.

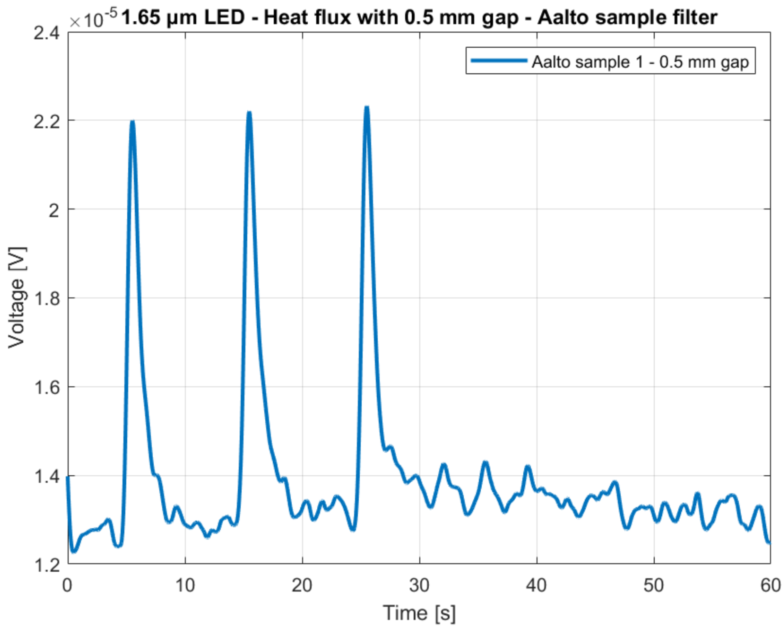

Figure 38. Heat flux sensor signal with Aalto SiO_2 filter, with an air gap of 0.5 mm, comparable to the 0.5 mm thermal interface material. The infrared spikes are big and distinct while the baseline of the signal is stable.

One possibility for the reason behind the heat flux sensor baseline differences could be the air gap acting as a type of insulation in between the filter and the sensor. This is seen in the tests with the thermal interface material, pictured in Fig. 37 and Fig. 38 where the heat flux sensor output voltage can be compared in cases with and without the material in between the filter and the sensor. A conducting material between them causes the heat flux sensor baseline to rise more than it would by just having the filter directly on the sensor. Air is a good opposite material to the thermal interface material as the two materials serve very different thermal functions: air is a good insulator and a bad conductor, the thermal interface material is designed to conduct heat and is therefore not insulating the filter and the sensor from each other at all. The thermal interface material still surprisingly showed signs of transmitting radiative heat while also conducting it, seen in Fig. 37 as the infrared peaks.

5.3 Discussion about the test setup

The test setup worked well for these types of tests. In the context of this filter-sensor integration research, the test setup used in this thesis was named “Test setup 1”, with the premise that it is only the first version of the setup and that it could be used as a model for future test setups. There were many properties of the test setup that could be subjects of future improvements.

One of the biggest problems during the testing was found to be the LED plate and the LED placements on the plate. The LEDs were all put on the same plate and later it was found that the angular rotation of the plate affected the intensity the emitted radiation on the heat flux sensor. This was described in Chapter 4. Having to rotate the LED plate between every measurement slowed down the test process and allowed more space for human error, as the rotation had to be remembered every time. Small differences between the rotations were possible even with the help of the LED plate turn scale, which was pictured in Fig. 17. In an improved version of this test setup all different LED wavelengths would have their own LED plate. This way the LED plate could be changed between different wavelength measurements, but the LEDs could all be arranged identically.

Another problem in the test setup came up with changing the filter. Because of the filter temperature sensors wiring coming from in between the LED plate and the sensor, the filter had to be put in place through an opening between the LED plate and the plate holder. This could be made easier by just making a small slit in the holder circumference, which would allow an easier filter change.

In future versions a different type of filter frame material could be used. The PLA plastic was an easy and functional choice, but a more thermally conducting material could help decrease the time needed to cool down between filter and shim-plate handling. A more conducting filter frame could also change the functionality of the selectively absorbing type of filters by increasing heat transfer out of the filter to the filter frame.

Another improvement for future setups would be using the same type of LEDs for each wavelength. Because the LED used for 1.65 μm was a different product than the ones used for 3.6 μm and 4.3 μm, the LEDs had different spectrums and fields of view, which eventually cause differences in the way they perform in the system. Using LEDs of the same product line would help standardize the test setup.

The last possible upgrade to the test setup would be the addition of a LED emission chopper. This chopper would be located underneath the LED plate, between the LEDs and the filter. The idea of the chopper would be to suppress and eliminate the effect of the post-pulse LED heat. The chopper could be a rotating piece of insulating material that stops the LED emission from reaching the filter manually by being in the way of the LEDs. This could help with "cleaning" the LED pulse, by making the end of the pulse more abrupt. The addition of a chopper would require more space in between the LED plate and the filter and this would then require more powerful LEDs.

6 CONCLUSIONS

The integration of the filter should always be done with consideration of the application of the system and the optical properties of the filter. One of the biggest problems with using the heat flux sensor for sensoring infrared radiation is that it cannot differentiate between different types of heat transfer. Therefore, it can show unwanted filter temperature rise in a similar way as it does the wanted infrared radiation. The difference between radiated and conducted heat is visible in the shape of the signal. In a fire detection application, the system could have an additional “signal filter”, that would filter out the heat flux signal caused by conducted heat transfer, identifiable by its slow rise.

This study can be concluded by answering all of the research questions introduced in the first chapter. The first research question was *“How does the filter work?”* The filter works by transmitting the infrared radiation of wanted wavelengths while either reflecting or absorbing unwanted wavelengths. Scattering can be a part of either the reflection or absorption.

The second research question was *“How can the heat from the filter transfer to the heat flux sensor?”* The heat transfers by a combination of three different heat transfer types: radiation, conduction, and convection. Radiation and conduction are the most important types of heat transfer for this configuration. For conductive heat transfer to happen there needs to be a conductive material in between the filter and the sensor. A conductive material might absorb some of the heat as it transfers it. Radiative heat transfer is the most desirable type of heat transfer between the filter and the sensor as it is instantaneous and causes a sharp signal on the sensor. Radiative heat transfer is also less dependent on the material between the filter and the sensor than conductive heat transfer.

The third research question *“How do different surface interfaces affect the heat transfer?”* can also be answered through the test results. The effects of the different surface interfaces on the filter-sensor system are based on the thermal and optical properties of the material. With every addition of a surface interface there is an increased chance of reflection, scattering and absorption in the system, but which effects are the most prominent is dependent on the material. Air between the filter and the sensor insulates them, decreases the conduction and convection between them and therefore increases the fraction of the heat flux signal that is caused by radiative heat transfer. A thermally conductive material instead attenuates the infrared radiation and increases the part of the heat flux signal that consists of conductive heat transfer.

“What would be a good test setup to test the heat transfer between the filter and the sensor?” The test setup designed in this thesis was a good setup that allowed the testing of many variables. A good test setup is easy to use, insulated from its surroundings and allows for precise changes in the variables. Some improvements to the current test setup could include: LED standardization, trying out a different filter frame material, making the changing of the filter and the LED wavelength easier and adding a chopper underneath the LEDs to suppress the effects of the post-pulse heat of the LED plate.

The research question *“How should the filter and the sensor be connected?”* was quite well researched in this thesis as the test measurements addressed different types of filter-sensor attachment. The filter and sensor should be attached to each other with a small air gap, around 1 mm, in between them. The air gap works as a small insulator that controls the conducted heat from the filter, which is a byproduct of the filter warming, from raising the heat flux sensor output signal baseline. Putting the filter on the sensor without any air gap is an “okay” way to attach the filter, although it causes the baseline of the heat flux sensor to rise slightly. The baseline rise in this case should not be detrimental to the function of the heat flux sensor. The addition of a thermally conductive material, a thermal interface material, between the filter and the sensor on the other hand is not a good way to attach the filter to the sensor. A conductive material between the filter and the sensor causes a slow and pronounced baseline rise on the filter and can also decrease the size of the infrared signal amplitude.

The last research question was *“Does the filter and the sensor attachment affect the selectivity of the filter?”* The answer to this question is no, the selectivity of the filter is neither compromised nor improved by changing the type of attachment between the filter and the sensor. Some attachment types, such as using the conductive thermal interface material between the filter and the sensor, did worsen the overall function of the filter by making the heat transfer between the filter and the sensor less effective, but did not negatively impact the selectivity of the filter.

Overall, the conclusion of this research is that even though the heat flux sensor is not necessarily designed to sense infrared radiation, it is possible to use it for this application. An infrared filter can be integrated on the sensor to make this system usable for selective infrared detection.

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Appendix 1. Measurements of the test setup

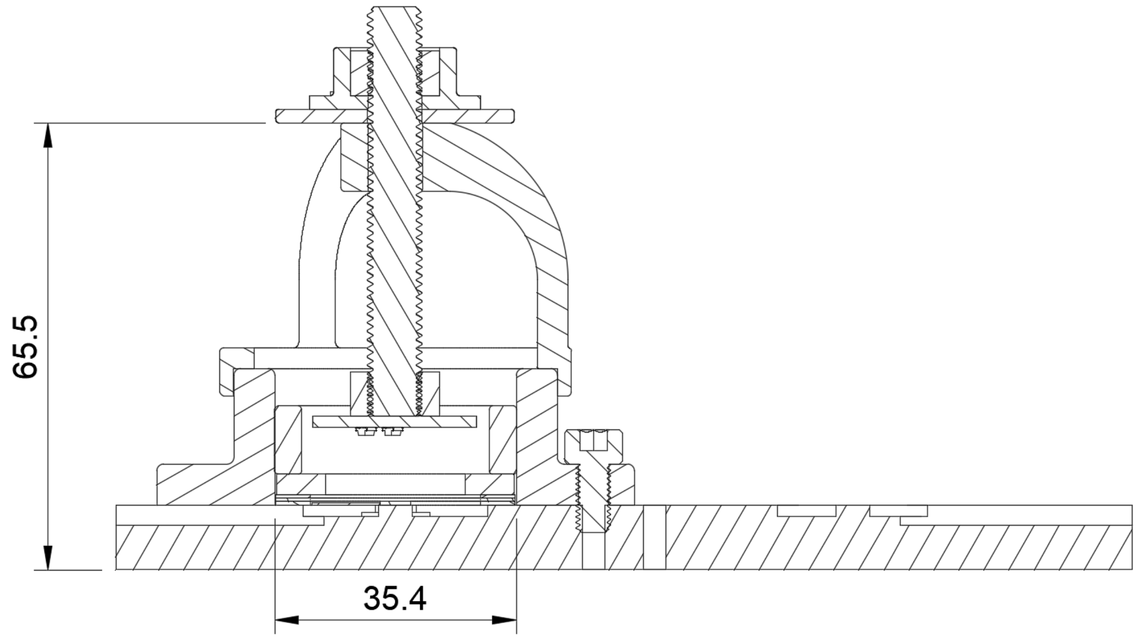

Figure A1.1. Measurements of the test setup in mm. Picture is a cross-section view of the CAD model of the setup.

Appendix 2. Input and output channels of the test setup

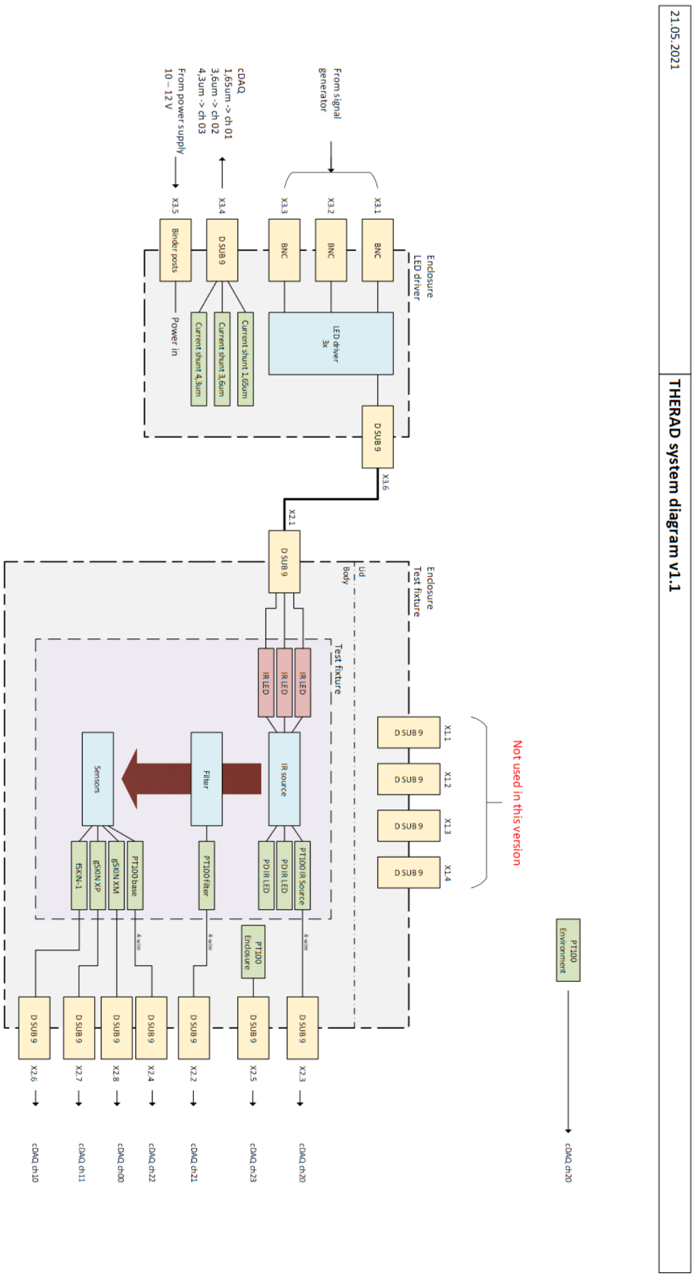

Figure A2.1. Diagram of the test setup construction with all of the input and output channels.