Time and Space Resolved Measurements from Rocket Engines.

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Abstract

ECAPS has recently developed a new satellite propellant called HPGP (High Performance Green Propulsion). This propellant is less toxic and more efficient than the hydrazine commonly used nowadays for satellite propulsion. Thrusters using this new propellant have recently been developed by ECAPS and one newton versions have been successfully tested during the PRISMA mission in 2011. To attain high reliability before real condition tests, thrusters are fired several times in a vacuum chamber. Under these conditions, it is very difficult to measure the thruster temperature with conventional contact methods such as thermocouples. Thus, a non-contact temperature measurement system consisting in an Infra Red camera was investigated to obtain the spacial temperature distribution over the thruster during firing. This master thesis analyses the implementation of this method. First, a series of emissivity measurements were performed on a sample of the thruster’s material at different temperatures and surface states. Then some measurements were done on the thruster on real test conditions, i.e in a vacuum chamber while firing. Using the previously calculated emissivity of the material, we were able to compute the real temperature distribution based on the IR camera output.
Acknowledgements

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Nomenclature

\( \epsilon \) Emissivity [-]
\( \lambda \) Wavelength [m]
\( \phi \) Viewing Angle [°]
\( \nabla T \) Gradient of temperature [K.m\(^{-1}\)]
\( q \) Heat flux [W.m\(^{-2}\)]
\( k_B \) Boltzmann’s constant [1.381.10\(^{-23}\).J.K\(^{-1}\)]
\( k_T \) Thermal conductivity [W.m\(^{-1}.K^{-1}\)]
\( h \) Planck’s constant [6.6.10\(^{-34}\).J.s]
\( T_m \) Melting temperature [K]
\( c \) Speed of light in vacuum [3.10\(^8\).m.s\(^{-1}\)]
\( M \) Total radiant power of an object [W.m\(^{-2}\)]
\( \alpha \) Absorption coefficient [-]
\( \rho \) Reflection coefficient [-]
\( \tau \) Transmission coefficient [-]
\( \phi_{object} \) Radiation emitted by an object [W.m\(^{-2}\)]
## Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tr>
<td>SSC</td>
<td>Swedish Space Corporation</td>
</tr>
<tr>
<td>FOI</td>
<td>Swedish Defence Research Agency</td>
</tr>
<tr>
<td>HPGP</td>
<td>High Performance Green Propellant</td>
</tr>
<tr>
<td>IR</td>
<td>InfraRed</td>
</tr>
<tr>
<td>SW</td>
<td>Short Wave IR spectrum</td>
</tr>
<tr>
<td>MW</td>
<td>Middle Wave IR spectrum</td>
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<tr>
<td>LW</td>
<td>Long Wave IR spectrum</td>
</tr>
<tr>
<td>ZnSe</td>
<td>Zinc Selenid</td>
</tr>
<tr>
<td>MLI</td>
<td>Multi Layer Insulator</td>
</tr>
<tr>
<td>TZM</td>
<td>Titanium Zirconium Molybdenum alloy</td>
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1 Introduction

1.1 Problem description

The current method of measuring HPGP rocket engines temperature manufactured by ECAPS AB, is the use of a pyrometer, and some thermocouples of different types (mostly R/S and K). Thermocouples are used to monitor the internal temperature of the thruster at some strategic points, like the combustion chamber and the preheating system. The pyrometer is used to monitor the external temperature of the engine. But a pyrometer gives the temperature only over a really small area. This implies that a large number of measurements are to be carried out in order to obtain temperature information for the whole engine and to be able to detect errors in the engine’s structure. This is not practical and to further complicate matters the surface of the engine will deteriorate over time. Solving this problem using an IR camera instead of a pyrometer was therefore investigated. Both these systems measure the amount of radiation from an object in the infrared spectrum. But the IR camera offers the possibility to obtain a thermal picture of the whole thruster.

1.2 Objective

The objective for this master thesis work was to perform accurate measurements of rocket engine temperature with a commercial IR camera FLIR SC620 available at ECAPS. The temperature measurements were done during firing of the thruster in a vacuum chamber. The IR pictures taken by the IR camera had to show the correct temperature distribution. One of the main problems that had to be overcome during this thesis was the strong dependency of the emissivity over different parameters such as wavelength, temperature and surface state of the object. Emissivity is a key parameter to correctly derive the temperature from an IR picture, therefore its knowledge is of paramount importance.

1.3 Wavelength dependency of emissivity

It is important to understand well the definition of the emissivity to be aware of the wavelength dependency of $\epsilon$. The emissivity of an object is the ratio of the amount of emissions actually emitted by the object to that emitted by a blackbody at the same temperature. Because all real objects are selective emitters, they radiate differently at different wavelengths.

It can be seen from Figure 1.1 that the emissivity of a selective emitter depends on the wavelength, sometimes strongly. Figure 1.2 shows the emissivities of some real materials.

One must be very careful when using emissivities found in tables, because they are usually given for a wavelength range that does not correspond to the one needed. The same problem applies for our project, if emissivity measurements are needed, they must be done at the exact same spectral range as the IR camera used, i.e from 7.5 to 13 $\mu$m. The emissivity can be in some cases considered as independent of the wavelength. For example when measurements are performed over a very narrow wavelength band, as in a two-color pyrometer, or if the behavior of the material is close to that of a gray body over the given wavelength band.
1.4 Temperature and oxidation dependency of the emissivity

This is one of the main difficulties that had to be overcome in our project. The thruster endures extremely high temperatures during firing, and therefore the emissivity of the material varies a lot during a test. This is particularly true for metals, for which the emissivity is very low, around 0.2, at room temperature, and can become high at high temperature, see Figure 1.3.

Oxidation processes occur at high temperature, and the oxide often has a different behavior than the metal. This become even worse with alloys, were different oxides behave differently. Figure 1.4 shows the emissivity as a function of the temperature for different aluminum alloys at $\lambda = 3\mu m$.

If the behavior of the different alloys is almost similar at low temperature, this is completely different after 700K where there can be some non negligible differences between two alloys of the same metal, for example Al-5083 and Al-7005. This can be problematic when one need data on a rare alloys like the one used on ECAPS’ thruster. It is extremely inaccurate to rely on the data of a different alloy, even one with an almost similar composition.
1.5 Surface state and geometry

The surface state of the object, independently of the level of oxidation, also plays an important role in the way the object emits thermal radiations. A well polished metal always has an emissivity inferior compare to the same roughened metal. Figure 1.5 illustrates that with the use of a so called Leslie cube, a cube that can be filled with hot water and whose 4 vertical sides are different.
Blackbodies behave like perfect isotropic emitters, that is, for any surface emitting radiation, the quantity of emitted radiation is independent of the direction into which it is emitted. Unfortunately, real objects are Lambertian radiators, the amount of thermal radiations they emit is different depending on the viewing angle. As the emissivity is the ratio of real emitted radiations over blackbody radiations, so is the emissivity. The behavior of conductor and non-conductor material is different, see Figure 1.6. But usually, the emissivity can be considered constant between normal incidence, $\phi = 90^\circ$ and $\phi = 45^\circ$.

![Figure 1.6: Schematic illustration of radiance for a blackbody and a Lambertian radiator.](image)

### 1.6 Implementation of the solution

The software used for analyzing the thermal image at SSC, ThermaCam Researcher pro, does not allow the user to set different emissivity values at different locations on the picture. This is a problem because the temperature as well as the emissivity vary a lot along the thruster. Therefore, a way of adjusting the emissivity along the thruster has to be investigated in order to the IR picture to show the correct temperature of the thruster. A small program written in Matlab has been investigated, it changed the material emissivity depending on its temperature on the picture. Unfortunately, the program cannot acquire IR Camera data in real time, so has to be run afterwards.
2 Background

2.1 Heat transfer

All the different aspects of heat transfer will be considered during this master thesis, even if radiation will be the more important one. A short overview of those phenomena is therefore necessary.

2.1.1 Conduction

Conduction refers to the heat flow in a solid or fluid which is at rest and presents a temperature difference. The law of conduction was found by Fourier and is called the Fourier’s law:

\[ \vec{q} = -k \cdot \nabla T \]  

Equation 2.1 is the general Fourier’s law in 3 dimensions, where \( q \) (\( \text{W/m}^2 \)) is the heat flux and \( k \) (\( \text{W/\text{mK}} \)) is the thermal conductivity, characteristic of the material.

It can be seen from eq 2.1 that the heat flux is directed from the hotter part of the object to the colder part. This can be explained in a microscopic point of view. The temperature is a measurement of the atomic excitation of the material (proportional to \( k_B T \)), the hotter, the more kinetic energy. The atoms with the more kinetic energy will collide with the less energetic atoms and transfer some of their energy, leading to a thermal equilibrium.

![Figure 2.1: Heat conduction through gas separating two walls](image)

This is the mode of heat transfer that occurs in the thruster material during firing, but as its geometry is very complex, and the heating is not evenly distributed in the inside, it is very complicated to calculate. The reason we were asked to perform temperature measurements with the IR Camera is to overcome this specific problem.
2.1.2 Convection

Convection refers to the heat flow between a solid and a fluid in motion. The general equation for convection transfer is:

\[ q = h \cdot (T_{\text{body}} - T_{\text{gas}}) \] (2.2)

In equation 2.2, \( q \) (\( W \text{m}^{-2} \)) is the heat flux and \( h \) (\( W \text{m}^{-2} \text{K}^{-1} \)) the heat transfer coefficient. Here again the heat flux is directed from the hotter object to the colder one. Convection can be used to heat an object or to cool it. The determination of \( h \) is a fairly difficult task, as a great number of parameters come into play, as the surface of the solid, its roughness, geometry and the nature of the fluid (gas or liquid). The order of magnitude for natural convection in gases is \( 5 \text{ Wm}^{-2} \text{K}^{-1} \), and can reach up to \( 1000 \text{ Wm}^{-2} \text{K}^{-1} \) for forced convection in a liquid.

For our project, the convection will not play a big role because the majority of the tests had been run in a vacuum, so it eliminate the natural convection with air. Of course the convection between the exhaust gases and the internal part of the thruster is still present. But this is a way to complicated process for us, and we will only consider it as a heat source for the thruster.

2.2 Thermal radiation

2.2.1 BlackBody

In physics, visible light, ultraviolet radiation and IR radiation can be described as Electromagnetic waves (for some properties of IR radiation, e.g. in detectors, a different point of view with the radiation acting like a particle is adopted, but for most applications, the wave description is more useful). Waves are periodic disturbances that keep their shapes while progressing in space as a function of time. The spatial periodicity is called wavelength, \( \lambda \) (given in meters, micrometers, nanometers etc.), the time periodicity is called period of oscillation, \( T \) (in seconds), and its reciprocal is the frequency, \( f = 1/T \) (hertz). Both are connected via the speed of propagation \( c \) of the wave by Eq. 2.3:

\[ \lambda = c \cdot T \] (2.3)

Figure 2.2 show an overview of the Electromagnetic spectrum. The IR spectral range goes from 780 mm to 1 mm.

Figure 2.2: Overview of the Electromagnetic spectrum
Every object at any given temperature above 0K emits radiation. An ideal emitter is called a blackbody, no object can emit more energy. For real bodies, an additional material property, the emissivity $\epsilon$, comes into play. The total radiant power that a blackbody emits per unit area at a given temperature and for a certain wavelength, is the spectral emittance given by Planck’s law, Eq. 2.4

$$M(\lambda, T) = \frac{2\pi hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda kT}} - 1}$$

(2.4)

Figure 2.3 shows the radianc of a blackbody as a function of the wavelength for different temperatures.

$$\lambda_{max} \cdot T = 2897.8 \mu m.K$$

(2.5)

Only objects with a temperature higher than 5000K emit energy in the visible spectral range, objects at room temperature emit in the IR spectral range. The total emittance is obtained by integration of the spectral emittance over wavelength, the result is called Stefan-Boltzmann law

$$M(T) = \int_{0}^{\infty} M(\lambda, T) \, d\lambda = \sigma T^4$$

(2.6)

Where $\sigma = 5.67 \times 10^{-12} \, Wm^{-2}.K^{-4}$ denotes the Stefan-Boltzmann constant. The total radiant power that can be emitted by a blackbody only depends on its temperature.

2.2.2 Emissivity

The BlackBody is an idealization of a perfect emitter and no real object can emit the same amount of radiation at a given temperature. The real emission of radiation from any object can, however, be easily calculated by multiplying the blackbody radiation with a quantity that describes the influence of the object under study, the emissivity $\epsilon$. The emissivity of an object is the ratio of the amount of radiation actually emit to that emitted by a blackbody at the same temperature. Therefore, $0 \leq \epsilon \leq 1$. Unfortunately, the emissivity of a real object is wavelength and temperature dependent, $\epsilon(\lambda, T)$, a real object is called a selective emitter. But in some cases, emissivity can be considered constant over wavelength, this
is the gray body approximation. Figure 2.4 shows the spectral emissivities of a BlackBody, a gray body and a selective emitter for a given temperature.

![Figure 2.4: Spectral emissivities of a blackbody, a gray body and a selective emitter](image)

The energy conservation principle requires that any radiation incident to any object is either reflected, absorbed or transmitted through the object. That leads us to equation 2.7 where $\rho$, $t$ and $\alpha$ respectively denote the fraction of reflected, transmitted and absorbed radiation.

$$1 = \alpha(\lambda, T) + t(\lambda, T) + \rho(\lambda, T) \quad (2.7)$$

Kirchoff’s law state that the amount of radiation absorbed by an object is equal to the amount of radiation that is emitted by this object, that is usually written in the form $\alpha = \epsilon$. Using Kirchoff’s law, equation 2.7 can be rewritten as follow:

$$1 = \epsilon(\lambda, T) + t(\lambda, T) + \rho(\lambda, T) \quad (2.8)$$

In most cases, one will consider IR opaque objects, for which $t=0$. Therefore, the emissivity is directly related to the reflectivity of the material.

$$\epsilon(\lambda, T) = 1 - \rho(\lambda, T) \quad (2.9)$$

For example highly reflective metals in the IR range (as in the visible range) have very low emissivity value, usually $\epsilon \leq 0.2$. That can lead to some problems when dealing with IR measurements because metal reflect more radiation that they emit.

## 2.3 Remote temperature sensing

### 2.3.1 Basics of thermography

Thermography is a science that focuses on imaging and studying radiation emitted by objects. As the quantity of thermal radiation emitted by an object increase with temperature, see eq. 2.4, thermal imaging systems are often used as non contact thermometers. An infrared camera basically works on the same principle as numerical camera. The infrared detector acts as a transducer, which converts radiation into electrical signals. This electrical signal is then converted into an image.

As the IR spectral range is width, it is divided in 3 regions, the ShortWave (SW) from 0.9 to 1.7 $\mu m$, Mid-Wave (MW) from 3 to 5 $\mu m$ and Long-Wave region (LW) from 7 to 14 $\mu m$. Different detectors are
used for these different regions. The choice of the IR region depends on various parameters including the temperature range of the measurement and the object’s surroundings.

To perform accurate measurements with an IR device, several parameters must be taken into account. To simplify, we will only consider opaque gray body object in the following figure 2.5.

The object himself emits a radiation $\phi_{object}$ which can be written $\phi_{object} = \epsilon \phi_{bb_{object}}$ considering the definition of $\epsilon$. When passing through the atmosphere, part of this radiation is absorbed due to several processes, the part of the radiation reaching the IR device is proportional to the transmittance of the atmosphere, leading to a received radiation of $\tau \epsilon \phi_{bb_{object}}$. Another part that must be taken into account is the ambient radiations reflected by the object. This is particularly true for metallic object with high reflectivity or small emissivity. The part of the ambient radiations that reach the IR device is $\tau (1 - \epsilon) \phi_{amb}$. Finally, the atmosphere itself emits some radiations that reach the camera $(1 - \tau) \phi_{atm}$. This part is usually very small and can be neglected when the object is close to the IR device. The total amount of radiations that reach it is then:

$$\phi_{det} = \tau \epsilon \phi_{bb_{object}}(T_{obj}) + \tau (1 - \epsilon) \phi_{amb}(T_{amb}) + (1 - \tau) \phi_{atm}(T_{atm}) \quad (2.10)$$

It can be seen from Eq. 2.10, that in order to perform accurate measurements, the following parameters are very important:

- The object emissivity $\epsilon$
- The ambient temperature $T_{amb}$
- The atmosphere temperature $T_{atm}$
- The atmosphere transmittance $\tau$
2.3.2 IR camera

An infrared camera is a device used to convert an infrared radiation into a picture or a movie. A color scale is added to the picture to show the intensity of the incoming radiation or the temperature distribution. The colors can be chosen to maximize contrast for each particular case. The following picture 2.6 is an example of an IR picture.

![Figure 2.6: A picture of me taken by an IR camera](image)

The core of an infrared camera is the infrared detector which converts radiation into electrical signals. The quality of this conversion determines the performance of the imaging system to a great extent. Infrared detectors can be separated into two groups: photon detectors and thermal detectors.

In photon (or quantum) detectors, absorption of photons from the infrared radiation leads to changes of concentration or mobility of the free charge carriers in the detector element.

Thermal detectors can be treated as two-step converters. First, the incident radiation is absorbed to change the temperature of a material. Second, the electrical output of the thermal sensor is produced by a respective change in some physical property of a material (e.g., temperature-dependent electrical resistance in a bolometer).[1]

Photon detectors are more accurate than thermal detectors but the detector element must be kept at very low temperature rising the price and the weight of the device. For our master thesis we used a FLIR P640 camera which used a bolometer, see figure 2.7.

![Figure 2.7: A FLIR P640 camera](image)
The knowledge of a series of values are necessary in order to achieve a good value of the temperature in the picture. Those input values are:

- The object emissivity
- The distance from the object
- The atmospheric temperature
- The reflected apparent temperature
- The relative humidity

This renders the use of an IR camera quite difficult. Some parameters as the relative humidity and the atmospheric temperature do not have a big influence on the result but a correct knowledge of the emissivity and the reflected temperature are of paramount importance to achieve precise measurement.

### 2.3.3 Pyrometer

A pyrometer is a non-contact temperature sensing device, but unlike an IR camera, it only focuses on a small portion of the object. It is typically made of several IR transparent lens with focus the IR radiation on a detector, a bolometer or a thermopile.

The pyrometer used for our experiment was a Raytek Marathon MR series, it can be used in 1 color or 2 color mode, see chapter 3.2. As the pyrometer only give the temperature of a single spot on the object, the output is not a picture but a value of the temperature. In 1 color mode, a value of the emissivity is necessary to have a good measured value of the temperature.

![Figure 2.8: A Raytek Marathon MR pyrometer](image)
2.4 Thermocouple

A thermocouple is a contact thermometer that uses the Seebeck effect to measure the temperature of the object. The temperature difference between two conductors creates a voltage that can be correlated to the temperature of the object. By varying the composition of the two conductors, different temperature ranges and precision can be obtained, see table 2.9

![Description of a thermocouple](image)

A very good precision on the measurement can be obtained with a thermocouple, but it is not suitable for all measurements. First a perfect contact between the object and the thermocouple is needed, that is a problem with the measurement of moving or vibrating objects. In some case were the object is subject to an intense magnetic field, for example in an induction heater, the presence of a thermocouple can have some bad consequences. In this kind of situation, a non contact measurement system is needed.

<table>
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<tr>
<th>Type</th>
<th>Temperature range °C (continuous)</th>
<th>Temperature range °C (short term)</th>
<th>Tolerance class one °C</th>
<th>Tolerance class two °C</th>
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<td>K</td>
<td>0 to +1100</td>
<td>-100 to +1300</td>
<td>±1.5 between -40 °C and 375 °C</td>
<td>±2.5 between -40 °C and 333 °C</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>±0.0075×T between 333 °C and 1200 °C</td>
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<td>J</td>
<td>0 to +750</td>
<td>-180 to +800</td>
<td>±1.5 between -40 °C and 375 °C</td>
<td>±2.5 between -40 °C and 333 °C</td>
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<td></td>
<td></td>
<td>±0.0075×T between 333 °C and 750 °C</td>
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</tr>
<tr>
<td>N</td>
<td>0 to +1100</td>
<td>-270 to +1300</td>
<td>±1.5 between -40 °C and 375 °C</td>
<td>±2.5 between -40 °C and 333 °C</td>
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<td>±0.0075×T between 333 °C and 756 °C</td>
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<td>R</td>
<td>0 to +1600</td>
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<td>+200 to +1700</td>
<td>0 to +1620</td>
<td>Not Available</td>
<td>±0.0025×T between 606 °C and 1700 °C</td>
</tr>
<tr>
<td>T</td>
<td>-185 to +360</td>
<td>-250 to +400</td>
<td>±1.5 between -40 °C and 125 °C</td>
<td>±1.0 between -40 °C and 133 °C</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>±0.0075×T between 133 °C and 358 °C</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>0 to +800</td>
<td>-40 to +900</td>
<td>±1.5 between -40 °C and 375 °C</td>
<td>±2.5 between -40 °C and 333 °C</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>±0.0075×T between 333 °C and 996 °C</td>
<td></td>
</tr>
</tbody>
</table>

![Different type of thermocouples](image)
3 Review of different methods used in thermography

The previous section highlights the fact that it is almost impossible to use emissivities found in tables to perform accurate IR measurements. This would lead to a big uncertainty on the value of the emissivity and thus to inaccuracies on temperature calculations. The most obvious solution to bring the project to a successful conclusion was then to measure ourselves the emissivity of the thruster material for different surface states and temperatures on the IR camera’s spectral range. To do so, we spend the first month of the master thesis work at looking for existing methods to measure object emissivity. This chapter will present a short review of emissivity measurement techniques and what are their advantages/disadvantages concerning our project.

3.1 Blackbody comparison

This method is in theory pretty simple, it consists in comparing the radiation emitted by an object with the radiation emitted by a blackbody at the exact same temperature. It is in practice not possible because a blackbody is an idealization. Instead a so called blackbody source, whose behavior is close to that of a blackbody can be used. Commercial blackbody sources have an emissivity value as high as $\epsilon = 0.99$, and are almost isotropic for a wide spectral range, figure 3.1 presents one of them.

![Figure 3.1: An example of BlackBody source.](image)

This can be really complicated to use because the temperature of the object as to be constantly monitored to adjust the temperature of the blackbody, and high precision blackbody sources are expensive. Therefore, this method is widely used to calibrate infrared camera and other IR devices, but is not suitable to measure the emissivity of materials.

A simplification of this method consists in using a piece of high emissivity coating, like tape or paint of known emissivity to play the role of the blackbody. A piece of tape is put on the object, and is assumed to have the same temperature as the object, then both the tape and object emitted radiations are measured.
Comparing both and taking into account the emissivity of the tape leads to the emissivity of the object. This method is pretty simple and is non destructive, but is impossible to use at high temperature because of the melting of the tape. High temperature paints do not have this problem, but over a wide range of temperature its emissivity may vary in an unexpected way, leading to an inaccuracy on the measure. The thermal equilibrium between the coating and the object is a rough approximation too, and is not fulfilled in the case where the object’s temperature varies rapidly.

Finally, this method is a quick and simple way of deriving the emissivity of an object whose temperature is not varying too much. But it is not a high precision method that can be use to determine the temperature of a satellite thruster while firing.

3.2 Two color pyrometer

A pyrometer is an infrared measurement instrument that works on the same way as a IR camera. It just does not give an IR picture but only the temperature of the object it is pointing at. A one-color pyrometer is of no use for deriving the emissivity of an object, because the emissivity of the object must be entered as an input parameter for the pyrometer to show the correct temperature.

A two color pyrometer on the other side can be very useful, it works as a classical one color pyrometer except that it probes the radiations emitted by an object at two different wavelengths (two "colors") instead of just one. This permit to derive the object temperature without the need of knowing the emissivity of the object.

Considering Eq. 2.10 for two different wavelengths give:

\[
\phi_{det}(\lambda_1) = \tau \epsilon_1 \phi_{bb}^{obj}(T_{obj}, \lambda_1) + (1 - \tau) \phi_{amb}(T_{amb}, \lambda_1) + (1 - \tau) \phi_{atm}(T_{atm}, \lambda_1)
\]

\[
\phi_{det}(\lambda_2) = \tau \epsilon_2 \phi_{bb}^{obj}(T_{obj}, \lambda_2) + (1 - \tau) \phi_{amb}(T_{amb}, \lambda_2) + (1 - \tau) \phi_{atm}(T_{atm}, \lambda_2)
\]

If it is assumed that the reflected part of the radiation is negligible in front of the radiate part, i.e if the emissivity of the object is high or if the temperature of the object is high in front of the ambient temperature, the latest equation can be rewritten as:

\[
\frac{\phi_{det}(\lambda_1)}{\phi_{det}(\lambda_2)} = \frac{\epsilon_1 \phi_{bb}^{obj}(T_{obj}, \lambda_1)}{\epsilon_2 \phi_{bb}^{obj}(T_{obj}, \lambda_2)}
\]

(3.3)

Now let’s consider Planck’s law, Eq. 2.4. Writing \( c_1 = 2\pi hc^2 \) and \( c_2 = \frac{hc}{k} \) and assuming \( e^{c_2 T_{obj}} - 1 = e^{c_2 T_{obj}} \), which is valid until high value of the temperature, leads to:

\[
\frac{\phi_{det}(\lambda_1)}{\phi_{det}(\lambda_2)} = \frac{\epsilon_1 \lambda_1^{-5} e^{c_2 T_{obj}}}{\epsilon_2 \lambda_2^{-5} e^{c_2 T_{obj}}}
\]

(3.4)

The object’s temperature can then easily be derived

\[
T_{obj} = \frac{c_2 (\frac{1}{\lambda_1} - \frac{1}{\lambda_2})}{\ln(\frac{\phi_{det}(\lambda_1) \epsilon_1}{\phi_{det}(\lambda_2) \epsilon_2})}
\]

(3.5)

For a pyrometer operating at two very closed wavelengths, the emissivity can be considered as being the same for the two wavelengths giving \( \frac{\epsilon_2}{\epsilon_1} = 1 \), the object’s temperature can then be determined without the knowledge of the emissivity.

But this method also has counterparts, because the two wavelengths must be closed from each other, the
amount of radiation reaching the camera must be important in order for the ratio not to be too small. This is usually the case for temperature higher than 500 °C, a commercial two color pyrometer commonly ranges from 500°C to 2000°C. That high temperature requirement is also important when considering objects with low emissivity. But he non-consideration of the ambient temperature reflection can lead to big inaccuracies when dealing with low emissivity material surrounded by hot gases. Typically a two color pyrometer is not suitable for measuring the temperatures of metals strips during production.

Part of this problems can be solved by using more wavelengths or bands of wavelengths, this is called multi-spectral pyrometry. But then, the assumption that the emissivity is the same for the different wavelengths does not stand anymore and a model of how $\epsilon$ varies with the wavelength must be used. Different model exists, but the result are not always very accurate. Furthermore, experiments are pretty complicated to set up, so multi-spectral pyrometry was not deeply investigate during our literature review.

Two-color and multi-spectral pyrometers can be used to find the emissivity of an object. By using a pyrometer and an other IR device like an infrared camera for example. Focusing both devices on the object and adjusting the value of the object’s emissivity in the IR camera in order to read the same temperature as the one given by the pyrometer leads to the emissivity of the object.

The problem is that a pyrometer only focuses on a really small area, if the object’s surface state is constant, then the emissivity can be considered as been constant over it. But the thruster we used had completely different surface states from one side to the other, and thus a pyrometer was not suitable for what we needed.

3.3 Active Pyrometry

The active pyrometry is another method used to measure the temperature of an object without previous knowledge of the emissivity. It uses the reflection of an IR source on an object to measure the reflectance of the object $\rho = 1 - \epsilon$.

When an object is illuminated with a IR source of known temperature, the measured radiation is:

$$\phi_{det,ill} = \rho_{object}\phi_{source}(T_{source}) + \rho_{object}\phi_{ob ject}(T_{object}) + \phi_{amb}(T_{amb})$$  \hspace{1cm} (3.6)

Without the source, the measured radiation is:

$$\phi_{det} = \rho_{object}\phi_{ob ject}(T_{object}) + \phi_{amb}(T_{amb})$$  \hspace{1cm} (3.7)

Combining equations 3.6 and 3.7 gives the following expression.

$$\rho_{object} = \frac{\phi_{det,ill} - \phi_{det}}{\phi_{source}}$$  \hspace{1cm} (3.8)

Then the reflectance is known, and so is the emissivity, the temperature of the object can be derived.

The major problem in this method is the determination of $\phi_{source}$. The geometry of the object and the angle of incidence of the source have a big influence on how the IR radiation are reflected by the object. The best is to measure $\phi_{source}$ as the reflection of the source radiation on a reference material of very high reflectance and with the same geometry as the object that need to be measured.

The source must of course emit in the same wavelength band as the detector, and it must be powerful enough to produce a high difference in the measured radiations.

This method can also be used with several wavelengths band for an improvement of the accuracy, it is called multi-band active pyrometry. But this method requires source and detectors of several wavelengths and thus is complicated to set up.
4 Test method

After an intensive literature review on the subject of infrared thermography and emissivity measurement, we found a lot of different ways to achieve a proper temperature measurement of an object with unknown emissivity, as described in previous chapters. But unfortunately all those methods require a lot of expensive apparatus that we did not have at ECAPS. So we decided to keep things simple and try to measure the emissivity of our metal (which is not available in the literature) and then used the emissivity value on the IR camera to obtain an accurate thermographic picture.

4.1 Suggested Solution

It must be noticed that the emissivity is temperature dependent. Whereas this does not really make any difference close to room temperature, it must be taken into account when dealing with a rocket thruster. It has therefore been decided that the best way was to measure the emissivity at different temperatures to obtain the emissivity as a function of the temperature $\epsilon(T)$. The surface condition is also an important parameter, so the tests where performed with different sample’s surface states.

4.1.1 Emissivity calculation

Temperature dependence

There is no general law that describes the behavior of the emissivity as a function of the temperature. Therefore an analytic function was investigated to describe the behavior of the thruster material. Using eq 2.10, it can be shown that the true emissivity of the object is given by:

$$\epsilon_{\text{true}} = \frac{\phi(T_{\text{cam}}) - \phi(T_{\text{refl}})}{\phi(T_{\text{true}}) - \phi(T_{\text{refl}})} \cdot \epsilon_{\text{cam}} \quad (4.1)$$

where:

$$\phi(T) = \int_{7.5\mu m}^{13\mu m} M(\lambda, T) d\lambda \quad (4.2)$$

Here $7.5\mu m$ et $13\mu m$ are the lower and upper values of the detection’s spectrum of the IR camera.

Equation 4.1 means that knowing the real temperature of the sample and the temperature shown by the camera, it is possible to derive the real emissivity of the sample. That can be done at several temperatures.

Surface state dependence

The measurements are carried out on materials with differing surface conditions. This is done in order to visualize the radiative properties of surfaces with degraded finishes. The surfaces tested will vary according to the variations they might experience. This means that a completely new surface is tested as well as more or less oxidized surfaces.
4.1.2 Computations

The data from the IR camera are saved and each frame is exported from the accompanied software ThermaCAM Researcher Professional to Matlab as a $640 \times 480$ matrix. This matrix contains temperature information for each single pixel in the thermal image. This also enables the possibility to export and alter system parameters such as the emissivity setting of the camera. This was usually set to $\epsilon_{\text{cam}} = 1$ in order to simplify equation 4.1 further.

A program was written in Matlab to post process the data. A routine was written that detects the geometry of the sample then detects the place where the tip of the thermocouple is located, and computes the radiated power using Planck’s law. It also extracts the necessary information from the vector containing object parameters. The reflected temperature is also inserted into Planck’s law in order to calculate the radiated power from the surrounding reflected by the sample. The true radiated power is calculated using the temperature from the thermocouple. Lastly, equation 4.1 is used to calculate the true emissivity of the object. All computations were done using Matlab.

4.1.3 Material used

During all our experiments, we used the previously cited FLIR P640 infrared camera, Raytek marathon MR, a couple of K types thermocouples, a vacuum chamber, some cartridge heaters and an home made heater which will be describe in next chapter.

4.2 Experiment set-up

As the material used in the thruster is pretty expensive and difficult to machine, we did our first test on a stainless steel sample. This offers the advantage of being able to compare the measured values of the emissivity to the ones available on the literature.

4.2.1 Stainless steel sample experiments on air

The main reason of this experiment was to validate our method on a sample of known emissivity. The sample was a piece of 2 millimeter thick stainless steel with varying surface states. In one side was glued two 100 W cartridge heaters and three K types thermocouples. The temperature varies largely on the sample due to convection and can not be considered as constant all over the plate, that’s why thee thermocouple were used. The other side was polished or oxidized depending of the measurement and was facing the IR camera. To achieve a very good thermal contact between the heaters, the thermocouples and the sample, a thermal cement capable to glue until up to 700 °C was used. The IR camera was set to the correct values, except for the still unknown emissivity which was set to 0.9.
The reflected apparent temperature was measured using a method given in the FLIR camera handbook. A piece of crumbled aluminum foil is put on the sample, then the temperature is measured with the camera set to $\epsilon = 1$ with all the other settings at the correct values, see picture 4.2. To minimize reflection from the surrounding, the sample and the camera were put down in an opaque box.

The temperature reached with this experimental set up was around 400 °C. This was pretty low but enough to improve the Matlab code and validate the method. As on this experiment the heating took place in air, an oxidation process occurred. So the plate had to be polished after each test. This was a problem as the polishing is not completely the same each time, the surface state was varying. The next step implied the use of a vacuum chamber, that was generously lent by the Department of Space and Plasma Physics of KTH.
4.3 Tests on the vacuum chamber

In order to achieve a vacuum-like surrounding, and decrease convections effects during measurements, a vacuum chamber was used. The chamber is shown in picture 4.3 and is borrowed from the Department of Space and Plasma Physics at KTH. The vacuum chamber is fitted with a TRIVAC prevacuum pump and a Alcatel CFV100 turbo pump which allow for the pressure to be lowered to less than $4 \times 10^{-5}$ Torr (0.005 Pascals).

![Figure 4.3: The vacuum chamber](image)

As common $SiO_2$ glass are opaque to infrared light, a special IR transparent window made of Zinc Selenid glass was fitted on one side of the vacuum chamber. The ZnSe glass is shown in picture 4.4.

![Figure 4.4: Zinc Selenid glass](image)
Zinc Selenid (ZnSe) is a material widely used for infrared measurement because of its high transmittance between 1 and 15 µm, see Figure 4.5. ZnSe glasses usually come with an anti reflective coating due to their high reflective index, around 2.4. The melting point of ZnSe is 1500 °C, it is a material very hard and thus difficult to manufacture and to polish. It is therefore very expensive. The glass we used during our experiment was a 10mm thick, 20mm in diameter ZnSe glass, with a broad band anti reflective coating in each side.

![Figure 4.5: Transmittance versus wavelength of ZnSe](image)

The stainless steel sample was held in the middle of the chamber. The two cartridge heaters were powered by two separated power supplies by means of a feed trough. Different voltages were applied in order to reach different temperatures, the maximum temperature reached was 800 °C. A lots of tests were performed to improve the experimental set up. It was found that it was necessary to coat the inner part of the vacuum chamber with a high absorbance material in order to minimized the reflection on the sample. That was done using a black MLI paper. The size of the sample was also an obstacle to reach high temperature. It was chosen to use a smaller TZM sample to run the next experiment.
4.4 Test on the TZM sample

4.4.1 The TZM sample

TZM (Titanium Zirconium Molybdenum) alloy is the main material used when constructing the ECAPS thruster. It mainly consists of Molybdenum (Mo), but with small quantities of Titanium (Ti) as well as Zirconium (Zr). The typical composition is Mo 99.4%, Ti 0.5% and Zr 0.08%.

The basic physical properties of TZM are:

- Melting point, $T_m$: 2600°C
- Density, $\rho$: 10g/cm$^3$
- Thermal conductivity, $k_T$: 118W/(m.K)

TZM alloy is widely used throughout the aerospace industry due to the possibility of very high operating temperatures, low thermal expansions, corrosion resistance and relatively low cost compared to other high temperature alloys, for example Niobium or Rhenium. The total hemispherical emissivity of Niobium and pure Molybdenum, which TZM consists of 99.4%, are shown as a function of temperature in Figure 4.6, depicted as red, and Niobium as green. Since the total hemispherical emissivity is calculated according to "in all directions and over all wavelengths", the experimentally obtained values are not to be directly compared to the ones presented below without caution. The TZM alloy is commonly described as having emissivity "around 0.1", or regarded as a "low emissivity" alloy.

Figure 4.6: Total hemispherical emissivity of Molybdenum (red) and niobium (green) as a function of temperature
The sample was a circle with a thickness of 5mm and a diameter of 20mm. A hole was drilled in the sample in order to put the thermocouple, see picture 4.7.

![Figure 4.7: TZM sample](image)

### 4.4.2 The heating system

The heating system consists of tungsten filaments inserted into a pellet of boron nitride, a material with excellent thermal conductivity and poor electrical conductivity. Physical properties of boron nitride:

- Melting point, $T_m$: 3000°C
- Thermal conductivity, $k_T$: 200W/(m.K)
- Volume resistivity, >$10^{14}$ ohm.cm

The tungsten filaments are taken from 50W halogen bulbs, which when in use reach temperatures of several thousands of Kelvin. Given a good enough thermal connection with the boron nitride, a substantial amount of that heat is transferred conductively to the boron nitride and the sample. The sample is placed in a small cavity on the boron nitride, both in order to reduce movement and to ensure good thermal contact, the sample is held in the cavity with a thin pure tungsten wire. This can be seen in picture 4.8.

![Figure 4.8: Sample and heating system](image)
The heating system is held by a small piece of ceramic in order to prevent the inner part of the vacuum chamber to reach too high temperatures. This setup allows the sample to reach temperatures close to 1000°C in vacuum surrounding only since a tungsten filament disintegrates in a matter of seconds if used in atmospheric conditions. The maximum power input needed for the heating system was 100W in order to reach the maximum temperature, i.e 50W on each filament powered by two separated generators.

![Thermogram of the TZM sample at ambient temperature on the vacuum chamber](image)

Figure 4.9: Thermogram of the TZM sample at ambient temperature on the vacuum chamber

A picture taken during one measurement is presented in picture 4.9. The sample is the small circular, glowing portion in the center of the figure. The contact heater made from boron nitride is the circular area around the sample. In this picture the heating system is turned off, and yet the sample appears to have a higher temperature compared to the boron nitride. This is actually due to the reflections of the camera in the sample. This shows the high reflectivity and thus the low emissivity of TZM. At higher temperature, reflections have less influences and so the TZM sample appears at lower temperature, due to its lower emissivity.

### 4.4.3 Test plan

It is of paramount importance to have repeatability in the experiments in order to obtain accurate results for the emissivity. Several tests were performed on the same conditions for different surface states. The first test was done using a polished surface. The surface condition was then deteriorated throughout the experiments to obtain a highly oxidized surface for the last measurement. The surface state was changed by heating the sample and allowing it to cool in atmospheric conditions between two tests. The power input of the heating system was increased stepwise and the temperature is allowed to stabilize at each level in order to avoid measurement errors. The temperature shown by the thermocouple is then assumed to be the same as the temperature of the sample. The input power was increased until a sufficiently high temperature is reached, or the maximum temperature possible for the heater configuration.

It would have been better not to move the camera neither the sample between each tests. But the tungsten filaments had the unfortunate tendency to break, so we had to change them very often, moving therefore...
the sample and the camera.

The following table shows the different experiments that had been done on the TZM sample:

<table>
<thead>
<tr>
<th>Experiment number</th>
<th>Temperature span</th>
<th>surface state °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>350-955</td>
<td>unoxidized</td>
</tr>
<tr>
<td>2</td>
<td>350-894</td>
<td>unoxidized</td>
</tr>
<tr>
<td>3</td>
<td>281-772</td>
<td>unoxidized</td>
</tr>
<tr>
<td>4</td>
<td>294-923</td>
<td>Cooling in air from 300 °C</td>
</tr>
<tr>
<td>5</td>
<td>297-806</td>
<td>Additional cooling from 300°C</td>
</tr>
<tr>
<td>6</td>
<td>271-836</td>
<td>Additional cooling from 400°C</td>
</tr>
<tr>
<td>7</td>
<td>369-637</td>
<td>No further oxidation</td>
</tr>
<tr>
<td>8</td>
<td>344-874</td>
<td>No further oxidation</td>
</tr>
<tr>
<td>9</td>
<td>331-763</td>
<td>Additional cooling from 800°C</td>
</tr>
</tbody>
</table>
5 Results

5.1 Stainless steel

The results when measuring the emissivity as a function of the temperature of a polished stainless steel plate are presented in Figure 5.1. It should be noticed that since this sample was only used as a trial piece, no extra attention was given to the surface state of the sample before each test. This implies that the results presented are not to be compared to tabular values of the emissivity without extra caution.

![Emissivity of Stainless steel](image)

Figure 5.1: Emissivity of a stainless steel plate as a function of temperature. The first measurement is in red and the second in black.

The first test (red dots), was performed on a freshly polished stainless steel plate. The tendancy is an increase of the emissivity with the temperature, that is a normal behavior for a conductive material as a metal. The low emissivity is also consistent with the value that can be found on the literature, between 0,1 and 0,2.

The plate was also polished for the second test (black dots), as one can see, the result are pretty much the same. The only difference is that the emissivity increases less with the temperature. This can be due to a difference in the polishing process, or a different viewing angle from the camera. In any case the difference is small, and the two curves show a clear tendency. That leads us to confirm our method of experimentation, with all the possible errors that can arise from it.
5.2 TZM sample

The results of the measurements carried out on TZM are presented in the following chapter. Due to various problems encountered while using an unsheathed R-type thermocouple together with TZM a more conventional K-type probe was used. TZM is not tested in atmospheric conditions due to the alloy being prone to heavily oxidize if subjected to high temperatures.

5.2.1 Unoxidized TZM

The three first measurements are presented in Figure 5.2. They were carried out on an unoxidized sample, see picture 4.7. After each test, the sample was allowed to cool to room temperature in vacuum in order not to alterate its surface condition.

![Figure 5.2: Results of emissivity measurements on an unoxidized TZM sample](image)

Theoretically, the three curve should be perfectly matched. One can see here that the difference is more important at low temperature. At low temperature, the quantity of radiations reflected by a low emissivity object is proportionally high compare to the radiated ones. This is why it is very complicated to have good precisions IR measurements on low emissivity object. The potential source of errors are investigated more in details on the next chapter, but it is likely that the fact that we had to change the tungsten filament after almost every test leads us to small variations of the experiment conditions.

The blue line is the average of the three measurement. It is increasing with temperature and is pretty smooth, which is the good tendency for metal. The emissivity goes from 0.65 at 250°C to 0.9 at 950 °C. This is a small absolute variation but a high relative variation, almost 50%. Therefore it is very inaccurate to consider the emissivity as constant over the temperature, even on a small temperature range.
5.2.2 Slightly oxidized TZM

In order to alter the radiative properties of the surface of the sample, it was oxidized. Since the heater setup used does not allow for heating in atmospheric conditions, the sample was heated to a predetermined temperature and then allowed to cool until room temperature. During the cooling, air is allowed to enter the chamber, i.e. the heating system is turned off and the chamber is opened. The sample was not polished between each test.

The results are presented in Figure 5.3:

![Figure 5.3: Results of emissivity measurements on an oxidized TZM sample](image)

What was expected here was an increase of the emissivity with an increase of the oxidation. The mean value of the emissivity has slightly increased compared to the one of the unoxidized sample. But no clear conclusion can be drawn from Figure 5.3. One can clearly see that increase of the oxidation state does not come with an increase of the emissivity. That was investigated and it was found that the oxidation temperature of TZM is around 600 °C. Therefore a cooling in air of TZM at 400 °C was not enough to create an oxidation layer on the sample. That is consistent with the fact that the sample showed the exact same surface condition to the naked eye.
5.2.3 highly oxidized TZM

The same process was used but this time the sample was cooled in air from 800°C, i.e. above its oxidation temperature. The oxidation layer was then clearly visible, see Figure 5.5.

Figure 5.4: Unoxidised sample.

Figure 5.5: Sample after cooling in air at 800°C.

Figure 5.6 shows the result of the emissivity measurement on the highly oxidized sample:

Figure 5.6: Results of emissivity measurements on an highly oxidized TZM sample.
Figure 5.7 show the curves of highly and slightly oxidized sample on the same graph:

![Graph showing emissivity of slightly and heavily oxidized TZM](image)

**Figure 5.7: Emissivity of slightly and heavily oxidized TZM**

In Figure 5.7 the difference is obvious, a real oxidation occurred. The emissivity of the highly oxidized sample is more than two times greater than for the slightly oxidized sample. Even if this state of oxidation is never reached by the thruster in space vacuum condition, it is good to have a clear overview of the different oxidation state of TZM. One can see here that the emissivity of the highly oxidate sample is less subject to increase with the temperature, this is very often the case for metal oxide like alumine.
5.2.4 Results summary

On the following Figure 5.8 are presented the average emissivity curve for the three different surface condition tested.

![Figure 5.8: Summary of the results](image)

Whereas no clear conclusion can be drawn for the emissivity difference between unoxidized and slightly oxidized TZM, it appears that an oxidation at high temperature have a big effect on the emissivity of the sample. The three curves have the particularity of increasing with temperature, except for the red curve which tend to decrease after 800 °C. We do not have any explanation for that, it may be due to error in the experimentation process. In any case it is important to notice that temperature actually has a big impact on the emissivity of an object, therefore considering it as constant can lead to big inaccuracies during IR measurements.
5.3 Comparison with reference data

No direct value of the emissivity of TZM was found on the literature. The closest was the total hemispherical emissivity of Molybdenum. A comparison is shown in Figure 5.9. A comparison is not to be done directly without caution since the reference contains the complete wavelength spectrum unlike the experimental data. This only includes wavelengths from 7.5 to 13.5 \( \mu m \), the wavelength spectrum of the IR camera. Additions of other metals in TZM (Titanium and Zirconium) might also have an effect on the radiative properties of the alloy. This came without information regarding the surface state of the molybdenum, which can differ from the sample we used.

Figure 5.9: Comparison between the experimentally obtained values of the emissivity of unoxidized TZM in red, and the total hemispherical emissivity of Molybdenum in black
5.4 Accuracy

The repeatability of the measurement system is crucial in order to obtain correct information. The standard deviation was used to show the consistency of the experiments carried out. In this chapter the standard deviation for stainless steel was not investigated because it was only used as a preliminary test material. Due to a lack of time, only one test was carried out on the highly oxidized sample, thus any standard deviation calculation was impossible.

5.4.1 Standard deviation in emissivity

In Figure 5.10 the standard deviation from the average value of the emissivity is shown. The desired behavior of the deviation is for it to be as low as possible for all temperatures since this means that the data points obtained coincide or are very close together, thus a high accuracy is obtained.

As expected the standard deviation is maximum at low temperature, where reflections on the sample have the most influence. The standard deviation stays below 5 % after 500 °C, that leads us to the conclusion that the value of the emissivity after 500 °C are pretty consistent. Further tests have to be run below 500 °C to be sure to eliminate all the perturbations due to unwanted reflections.
5.4.2 Standard deviation in temperature

As standard deviation in term of emissivity is not very easy to analyze, the standard deviation in temperature was calculating using Planck’s law, the result is presented in Figure 5.11.

![Figure 5.11: Standard deviation of slightly oxidized and unoxidized TZM](image)

The tendency is the same as for the standard deviation of emissivity. The only difference here is that the value of the standard deviation is more important due to Planck’s law in \( T^4 \). The error is pretty high and can lead to important errors in temperature if the results we obtained are used without caution. In next section the potential experimental errors are investigated to explain such inaccuracies in our results.
5.5 Investigation of the source of errors

It must first hold that to have accurate measurement with a low emissivity object is a very complicated task and that it causes a lots of problem in the industry, for example in steel or aluminum factories. Different expensive materials have been tested and they all shown some limitations. Different potential source of errors were found, but it was impossible to say which one was predominant for each test.

- Reflections from the surrounding at low temperatures.
- Changing of the experimental condition, especially viewing angle, distance from the sample to the camera, and focusing of the camera.
- Changing of the sample surface state.
- Precision of the sample detection by the Matlab routine.
- Precision of the temperature reading due to the variation of the contact between the thermocouple and the sample.

Finally, the temperature reached with the home made heater is lower as expected, with two tungsten filament running at a temperature of more than 2000°C, we expected a higher sample temperature. Were were limited here by the fact that it was impossible to find something to fill the space between the boron nitride and the filament, the best thermal cement we found was only capable of enduring a temperature of 1000 °C, i.e way lower than the temperature of the tungsten filament.
6 Conclusion

The results obtained while measuring the emissivity clearly show that the emissivity is increasing with the temperature. This is true for all materials tested, which is in line with the expected results and corresponds well to the typical behavior for metals. The order of magnitude of the values also correspond well with values obtained from other experiments. It also fits well to tabular values found through online investigations. The TZM data also fit reasonably well with data found for the total hemispherical emissivity of Molybdenum, the main component of TZM (99.4% Molybdenum).

The surface condition was the major problem that had to be handle during this master thesis. We had no way of characterizing with precision the surface state of the samples. But it is clear that it has a big impact on the emissivity of the metal. Further test have to be done to clearly show the impact of subtle difference of polishing on the sample and different oxidation states below 500°C.

The standard deviation was used to characterize the accuracy of the measures and the repeatability of the results. It showed pretty good results at high temperature but not so good ones at low temperature. It was found that reflection from the surrounding at low temperature was of paramount importance and had to be handle with an extreme precision. It was unfortunately not possible for us to be that precise in the experimental setup, so the results at low temperature have to be used with caution.

Finally, this master thesis was a very formative experience. It is difficult to realize all the problems that have to be handle when creating an experiment. You sometimes have to find creative solutions to overcome a problem, as we did with the heater. But once you have done it is very gratifying, and you feel proud of yourself.
Bibliography


