ME301 project 2024 GROUP 04

✉ **Email addresses:**
[1]fatumah.doukoure@epfl.ch
[2]giuliano.zennaro@epfl.ch
[3]salome.lavine@epfl.ch
[4]stanislas.vanhoudenhoven@epfl.ch

Sciper numbers:
[1]340969
[2]344437
[3]311643
[4]315323

DOUKOURE, Fatumah Binta Sakho[1]
ZENNARO, Giuliano[2]
LAVINE, Salomé[3]
VAN HOUDENHOVEN, Stanislas[4]

Abstract An investigation was made into the burning of candles in a closed environment. The key parameter to be investigated was the placement of the candles within this space, specifically the height and its effect on the burn time. A Plexiglas box was made to allow direct visual observation of the candles burning, while ensuring a hermetically sealed environment. Three candles were placed within this box at three different heights and lit. Each experiment lasted 75 seconds, enough to extinguish each candle due to a lack of O_2.

Three measurements were performed: temperature, dimensions of the flames and CO_2 concentrations. The temperature was measured with a temperature sensor board, and the dimensions of the flames were determined from images captured by a DSLR camera. For the CO_2 concentration, an innovative system using colorimetry was attempted. This was done by using a pH indicator solution and using a color sensor to quantify its reaction to CO_2. Unfortunately, this proved to be challenging, as the change in color was small, and the sensitivity of the color sensor was not sufficient.

The results of the experiment highlighted the effect of relative height on the candles in the closed environment.

Introduction

The motivation of the experiment was to get a better understanding of the mechanisms at play in a closed environment with burning candles. Temperature induces pressure changes and thus movement of molecules, whilst the burning of the candles produces CO_2, by product of O_2 consumption, in large enough quantities to extinguish the candles. Previous literature suggests CO_2 concentration varies as a function of height, and we hoped to confirm this as well as map temperature and said concentration within the closed environment as a function of height.

During this course, our group chose to have at least two challenging and not "plug and play" measurements. This led to the use of a camera and color sensor.

Challenges appeared along the way, notably with the implementation of the color sensor and experiment protocol. The results provide insights into phenomena locally affecting each candle wick, and draw a better picture of the interactions between the candles.

Further research is necessary to enable CO_2 concentration measurements within the closed environment.

Experimental set-up and measurement systems

Candle and environment setup

Experiment set up

In order to control our environment, we produced a box of dimensions: 200x230x110mm (HxLxW) out of plexiglass available at the DLL (fig: 1). The total volume contained within is: 5060 cm^3. All faces except the one from which pictures were taken were covered by cardboard in order to mitigate the effect of secondary light sources.

Figure 1. Box setup with candles and without cardboard

Candles

To minimise height loss from the burning of the candles, a model with large diameter relative to height and wick size was chosen. Their nominal diameter is 50mm, and our three candle heights (height at start of testing and end of testing) as well as wick sizes are as follows:

Candle 1	Candle 2	Candle 3
Wick: 6.4x2mm (HxW)	Wick: 6.6x2mm (HxW)	Wick: 5.2x2mm (HxW)
Height: 135mm/133mm	Height: 100mm/97mm	Height: 80mm/72mm

Colorimetric Co_2 sensor

Motivation

In the closed environment, the candles go out due to the decreasing concentration of O_2 in the environment, and thus the increasing CO_2 concentration. The goal of this measurement is to monitor the evolution of CO_2 in the environment using a *Color Sensor*.

Color sensor

We use the TCS3200 color sensor for this measurement.
The sensing element of the TCS3200 color sensor is an array of photodiodes. These photodiodes are arranged in a 8x8 grid, making a total of 64 photodiodes. Each photodiode in the array is covered with either a red, green, blue, or clear (no filter) filter, with 16 photodiodes for each color. The photodiodes generate electrical currents proportional to the intensity of the light of their respective colors falling on them.
The signal conditioning is performed by an integrated circuit that converts the photodiode currents into frequency signals.
The output signal is a square wave whose frequency is proportional to the intensity of the detected color. This signal can be interfaced with micro controllers or other digital electronics for further processing and presentation.
Sensor protocol

1. Create a cover , which ensures consistent distance between the sensor and the sample and the same luminosity while tracking the desired data.
2. Calibrate the sensor: using the calibration code and the RGB calibration sheet. For each color, keep the lowest and highest frequency values.
3. Update the color sensor code, with the value collected before. Read the data collected.

We designed a cover to limit outer interference's to our sensor, and to make sure we always put the object to measure at the same distance of the sensor, around 4cm. The data we collect consists of an RGB code. Due to the fact that this sensor is really sensitive to its environment, the RGB codes we collect are *relative* to one another. They make sense in our configuration, but are susceptible to vary a lot in others.

Method

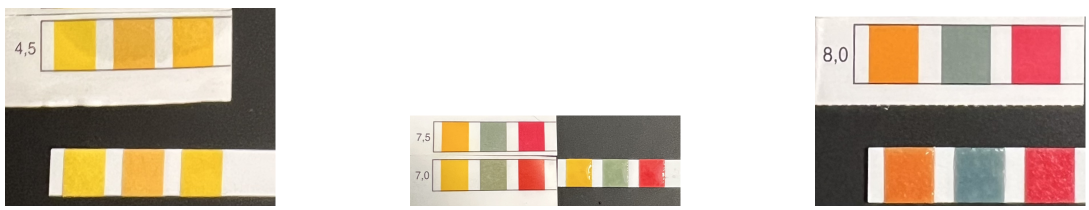
Color-changing solutions
We intended to monitor the CO_2 concentration of the environment by using a solution which reacts to the level of carbon dioxyde.
With the help of chemistry labs at EPFL, for whom we are thankful for their help and time, we tried multiple solutions:

1. Hydrogen carbonate:
   This solution was supposed to change color (from red/purple to yellow) as the pH becomes more acidic, due to the CO_2 disolving in it. Therefore, with the color sensor we could connect the evolution of the solution to the increasing concentration of CO_2 [2].
2. Lime water:
   It is a saturated aqueous solution of calcium hydroxide ($Ca(OH)_2$). When it reacts with CO_2, the initially clear solution becomes opaque as insoluble calcium precipitates in it. The idea was to observe a colored piece of paper through the translucent solution during the experience to highlight the evolution of CO_2.

Each of those measurements appeared to be impossible due to diverse reasons. Firstly, they both did not react enough in our environment in order to produce measurable changes, even though it is sure that the CO_2 concentration has increased.This might be due to the fact that there is not enough air movement in the closed environment for the gas to properly react with either solution. Secondly, when there were some visible changes, the colour sensor could not detect them. After some experimentation with the sensor, we can assume that the solutions were too translucent to reflect enough color change to the photo-diodes. In fact, as stated earlier, any change of texture, reflection, or exterior luminosity impacts the reading of this sensor.

Final measurements

Therefore, we decided to measure the pH paper's color change once dipped in acid, basic and neutral solutions. After following the sensor protocol , we collected five times the color received by the sensor, for each solution and for the three colors on the pH paper (fig 2). The conclusion of this measurement and the sensor's accuracy, will be discussed in the results paragraph.



(a) acid solution, pH=4,5 **(b)** neutral solution, pH=7 **(c)** basic solution, pH=8

Figure 2. pH paper and its referenced scale after experimentation for the 3 solutions

Another challenge that appeared with this measurement is that each "pixel" of the pH paper is small ($5mm^2$). We needed to find a way to isolate each pixel, without hindering the sensor detection. To do so, we used the cover we had in the beginning, with a white piece of paper and a hole of the exact size of a pixel on top.

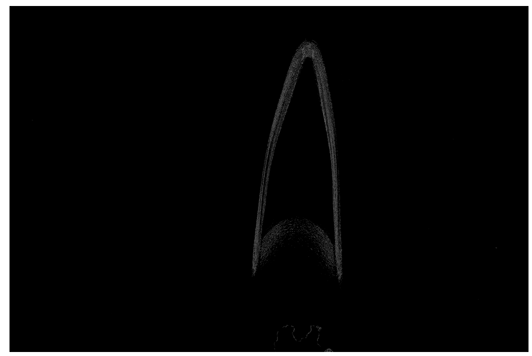
Flame dimensions

Characterisation of the flame dimensions was done by measuring the height, width and area of the flame as a function of time. Each candle was measured individually to get more resolution. To make these measurements, a DSLR camera (Nikon d7500 with a resolution of 20.9 megapixels) was set up on a tripod outside of the box. The camera was set in full manual mode to ensure consistent exposure, and an automatic interval timer was set to take one image per second. This then gave a total of 75 images per experiment attempt. Each experiment was repeated 5 times, and 3 candle heights were tested. The sum total of photos to analyse was thus $3 \cdot 5 \cdot 75 = 1125$.

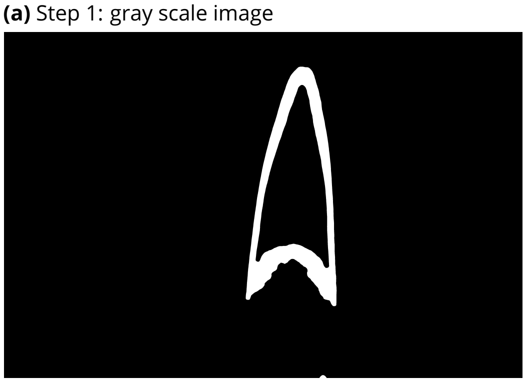
To extract the dimensions of the flames, calibration photos first had to be taken. Before each experiment attempt, a photo of a grid of known dimensions was taken. This then made it possible to calculate a conversion factor from pixels to millimeters. To ensure proper calibration, the grid was placed precisely on top of the candle wick of interest and on the focus plane. Since focusing affects the field of view, due to focus breathing, manual focus was performed and then fixed, as well as the f/stop.

The photos were then processed with the help of a Python program. The first step of the program is to convert the image to gray scale and to apply a bilateral filter to reduce noise while maintaining edges. Canny edge detection is then performed and morphological closing is applied to close the contour. The binary image is then slightly blurred, but this time with a median filter. For some images, morphological closing was not sufficient to close the contour at the bottom of the flame. Since even manually drawing a contour is somewhat arbitrary, it was chosen to force the contour to be convex for all images. This made it possible to close the bottom of the flame in a systematic manner. The complete post-processing procedure is summarised in 4 visual steps (fig: 3). In the last step, the results for 2 different methods are displayed. The contour and bounding box are displayed in blue and yellow, respectively, for the Canny edge detection method. The second method displayed in green and red uses thresholding.

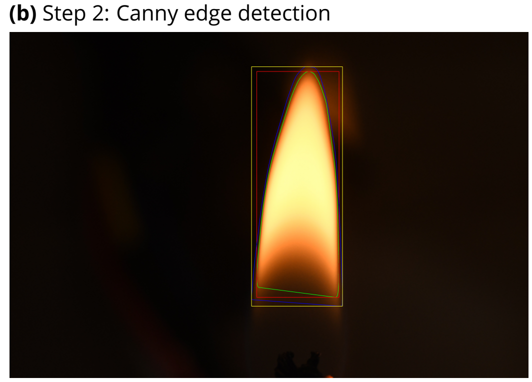
(a) Step 1: gray scale image



(b) Step 2: Canny edge detection



(c) Step 3: morphological closing



(d) Step 4 : contour and bounding box (in blue and yellow, respectively, for Canny edge detection, green and red for thresholding)

Figure 3. Steps to extract flame dimensions from image

The resulting contours were then drawn on their respective image, and the image saved. This step enabled manual verification of whether the automatic processing was correctly done. The parameters of each filter and of the Canny edge detection function were then tuned until all of the images gave satisfactory results. This procedure showed that most images were unaffected by the minute parameter changes. However, this step was necessary for some problematic images. These were images which unfortunately had a reflection on the Plexiglas, which was superimposed on the candle flame. Properly differentiating the flames from the reflections was not simple, but by fine-tuning the filter parameters, all of the images were ultimately correctly processed.

Finally, a vertical bounding box was found for each contour. The width and height of this box correspond to the respective flame width and height. For the area, a function giving the number of pixels in the closed contour was used. These dimensions were then converted to mm and mm^2 with the previously calculated scale factors. All the dimensions were then saved in a file for future use.

Temperature measurements

Motivation

Since our candles die out when O_2 concentration is too low (locally), we wanted to get a better understanding of how varied the temperature could be within the relatively small confines of our box. High temperatures induce lower air density, and pressure varies accordingly. This is one of the factors at play "mixing" the air.

Sensor

Two temperature sensors were used. An initial setup was done with the DS18B20 IC waterproof sensor. Its accuracy is +/- 0.5 degrees Celsius, however due to the size of the sensor and amount of metal, it carried too much thermal inertia and was thus replaced by the MCP9808 high accuracy temperature sensor.
The latter has a higher accuracy (of +/- 0.25 degrees Celsius), a resolution of 0.0625 degrees Celsius and temperature range from -40 to 125 degrees Celsius. The sensor uses 5v, 200µA and I2C communication protocol.

Method

Temperature evolution within our environment was measured from three fixed points. These points were such that the temperature sensor was aligned along the vertical axis of each candle (therefore straight above them). This was possible by using Velcro on the roof of the Plexiglas box and underneath the MCP9808 High Accuracy Temperature Sensor.
Our first placements had the temperature sensor on one of the walls of our box and aligned (vertically and horizontally) with each candle. This proved to be poor placement because the air at the height of the wick saw little temperature variation at a 5cm distance from said wick.

As for the experiment protocol; all three candles were lit after calibrating the camera and a cool down period for the temperature sensor. One member placed the box on the candles whilst the other held the cables aside. As soon as the box was dropped on to the candles both the images and temperature measures began. Temperature measurements were taken every 500ms for 75s. Each measure was repeated 4 times per placement. Thanks to the very low thermal inertia of our sensor and by letting two minutes pass between each set of measures, we could assure repeatability of our measurements.

An Arduino code was written for the temperature sensor and uploaded to the unit. From this point it could be executed from another Matlab program that stored the data. All graphs and data processing could then be done in Matlab.

Results

Colorimetric CO_2 sensor

In order to verify our sensors' accuracy, the first plot shows the evolution of each measure for each iteration and each pixel of the pH paper, for $pH = 8$. From what we can see, the measurements stay consistent with a small standard deviation (fig 4). The second plot(fig 5) presents the mean error with respect to the reference measurement of the color. We observe that this varies from -0.2 to 0.2, which can be tolerated. In conclusion, this sensor has many calibration steps, and can be influenced by external factors (such as variation of luminosity) but remains a reliable way to measure pH.

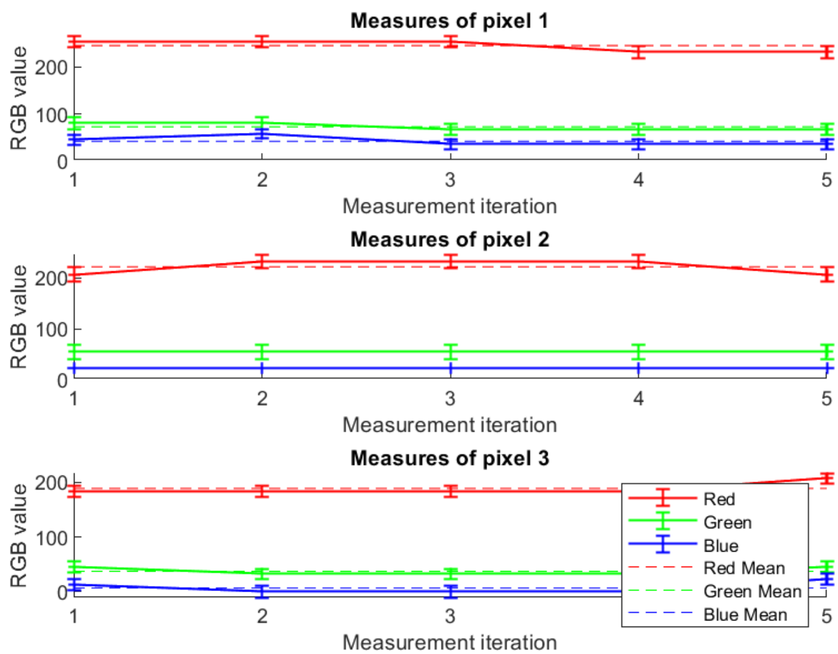


Figure 4. Analysis of the pH8 measurements

Flame dimensions

The time it takes for the candles to extinguish is greatly affected by their height in the box (fig: 6). The time ranges from 10 seconds for the tallest candle (candle 1) to over 75 seconds for the shortest one (candle 3). Furthermore, the trend of the curves is similar for each height and each dimension calculated. However, one important aspect can be highlighted: the height of the flames declines faster than the width. This fact is better exposed by plotting the aspect ratio of the flame, i.e. height divided by width (fig: 7).

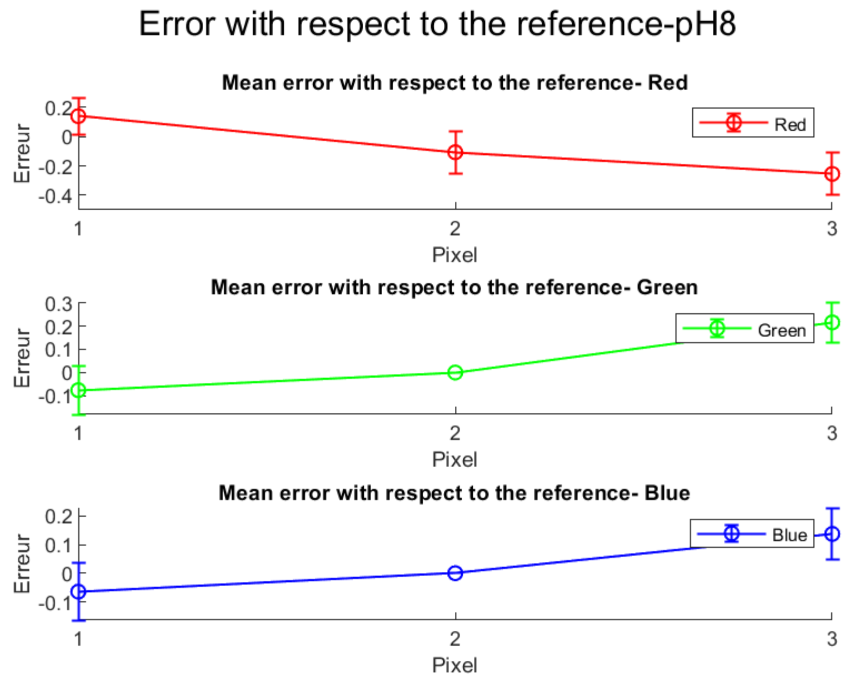


Figure 5. Error of the pH8 measurements

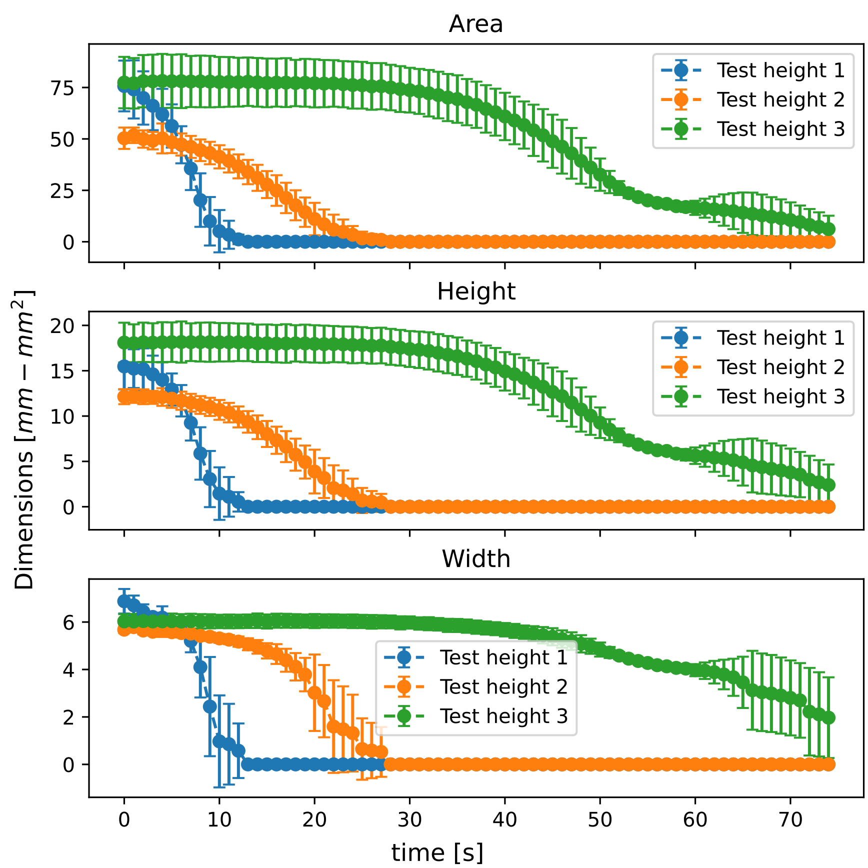


Figure 6. Dimensions of flame as a function of time for each candle height

The calculated aspect ratios show that, for each candle, they converge to 1 (fig: 7). This can be explained by the fact that the reason for the elongated nature of the flame is convection. As the flame becomes smaller, less heat is generated, and thus there is less convection. The resulting flame tends to become spherical as is the case in space, where gravity-driven buoyant convection is absent [1].

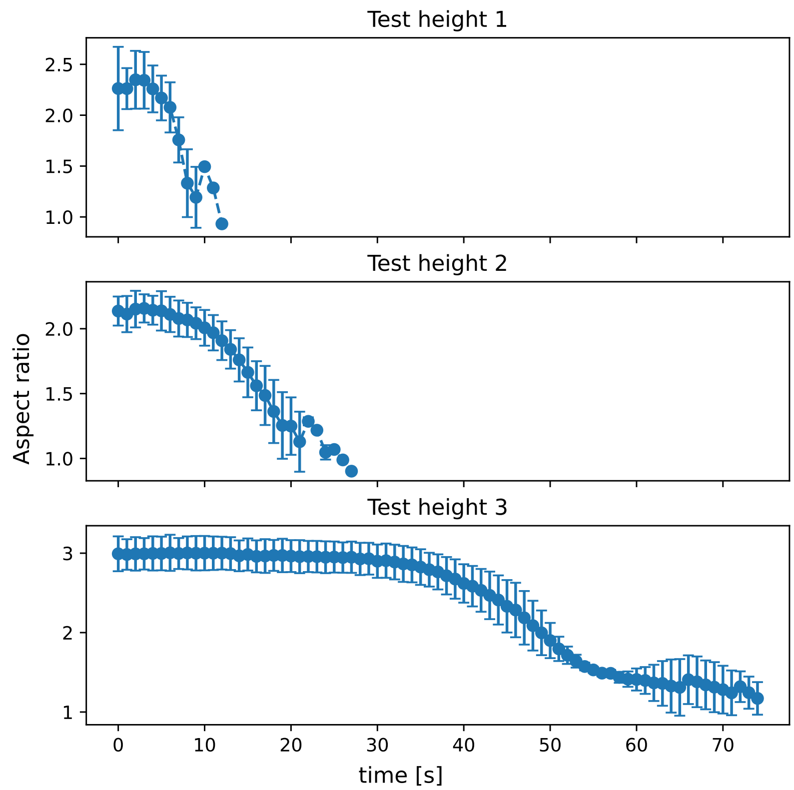


Figure 7. Flame aspect ratio as a function of time for each candle height

Temperature sensor

All data collected was treated as follows: The mean was taken from the 4 runs for each candle, then the standard deviation was calculated and finally the data was combed through to verify there were no outliers or radical values in our measurements(fig8) . The first batch of data (first four measures for candle 1) were repeated because between putting the box on the candles and avoiding unplugging the sensor cables it took some trial and error to find the best protocol. From that point, measures were taken in parallel with the camera.

There are marked temperature profile differences between the 3 candles. The tallest candle, which was closest to the sensor, reaches on average 90 degrees Celsius, 30 more than candle 2 at its peak. An interesting observation is that the temperature curves peak in order of their height: Candle 3 (shortest) peaks at the end of the experiment, Candle 2 peaks 25 seconds into the experiment and Candle 1 peaks within 15 seconds. The temperature measured for Candle 1 is also consistently above that of Candle 2, even after the flame dies. Although all measurements are taken from the same height, results showed temperature varied very locally (along the horizontal axis).

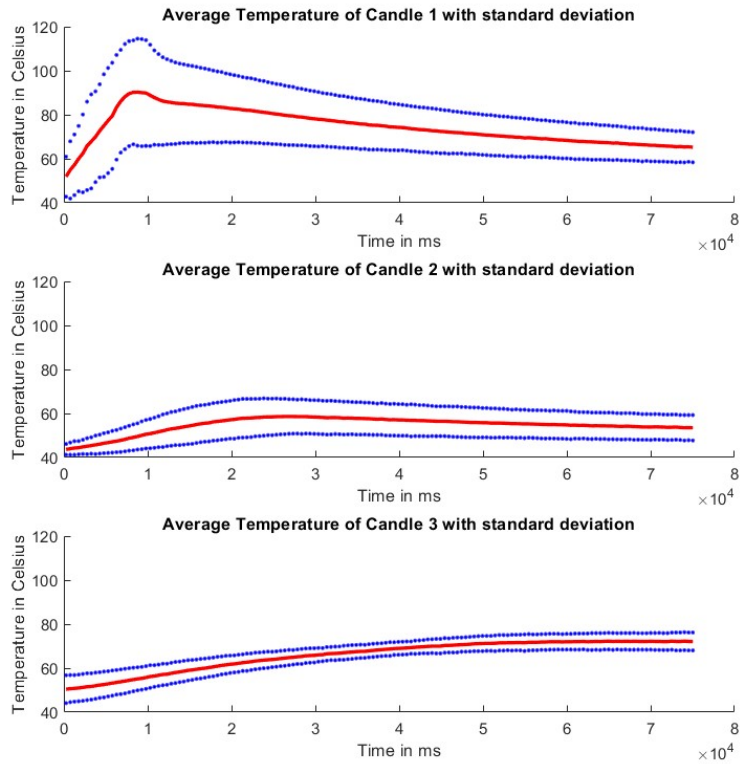


Figure 8. Temperatures for all candles in degrees Celsius as a function of time

Digital signal processing

The main digital signal processing that was made are the mean and the standard deviation on our data. In fact all of our data analysis does not demand more process (For example no frequency analysis was needed).

Limitations

Colorimetric CO_2 sensor

Although the color sensor outputs appear consistent, we notice an error when comparing the measurements to the reference value. This difference could be due to the reference value being measured on a scale provided by the pH paper manufacturer, while the pH itself is measured on the paper. Since the textures of these two surfaces are not identical, and considering the sensitivity of our sensors, it is plausible that this difference could lead to measurement variations.

Flame dimensions

Considering the lens used is a 135mm equivalent and has excellent optics, it produces little distortion (results from DXOMARK). However, since photos are taken trough the

Plexiglas box, some distortion is expected as a result. This is worsened by the fact that, as the candles burn, the heat gradients also contribute to distortion. Given the dynamic nature of the distortion and the fact that the box is placed just before starting the measurements, extrinsic distortion correction could not be performed.

A more important factor to consider is the bias produced when finding the contours of the flames. Since there is no unique way to identify the borders, the results vary significantly depending on the method used. As the bottom of the flame is particularly complicated to clearly identify, we forced the contour to be convex. A comparison between 2 methods is proposed. The first method was finally chosen. It uses Canny edge detection. The second, simply applies a threshold on the gray scale image based on pixel intensity. Comparisons of the resulting calculated dimensions reveal a bias in the order of 5% to 15% for the height and width, but can go up to 30% for the area for certain images. Both methods seem satisfactory a priori, since the resulting contour is similar to what a human would draw (fig: 3d), but it is clear that a consistent method must be chosen.

Finally, as the box is lowered above the candles, some air current is generated and the flames briefly oscillate. This introduces some error, as the width varies. This is only an issue for a couple of seconds, though, and was not systematic. By taking the average over 5 attempts, the problem can be mitigated.

From the previous paragraphs, it is clear that, although a pixel corresponds to less than one hundredth of a millimeter, the actual precision is much less. To mitigate these issues, a box made of optical grade glass could be used. Furthermore, other contour detection methods which also include colour information could be attempted.

Temperature sensor

Due to the nature of our setup, we had to light the candles before placing the box. This meant that whilst making sure the box and sensors were placed correctly the temperature sensor heated up more or less before the start of the measurements. It is most noticeable on the measurements of Candle 3 where the sensor is very close to the flame. Variance in setup time before launching the measurements was kept to a minimum and its effect filtered by taking the mean, however it is apparent from the standard deviation at the start of experiment (on Candle 1 fig:8) that this could be improved. One solution would be to have the box on vertical sliders so that once the candles are lit the only manipulation to be done is lower the box along its sliding supports.

Conclusion

The experiment sought to measure the temperature, the CO_2 concentration using a color sensor and the flames' shape. For the CO_2 concentration, we unfortunately were unable to measure it in situ, but were able to work with the color sensor, extract data, determine its accuracy, and write a protocol for its utilization. Temperature measurements proved more straightforward and with correct placement and quick setup we were able to ensure their repeatability. The flame dimension measurements helped to understand the role of convection in determining the flames' aspect ratio. Interesting considerations and simplifications had to be made to define the flames' contour.

In conclusion, we were able to observe how temperature changes along the horizontal axis correlate to the flames' profiles. We know CO_2 concentration increases (as a product of O_2 consumption) and saw that it eventually extinguished the candles, though we were unable to confirm said concentration evolution experimentally.

Author contributions

Colorimetric CO_2 sensor: Doukouré Binta and Lavine Salomé
Temperature sensor, candle and environment setup: van Houdenhoven Stanislas
Flame dimensions: Zennaro Giuliano

References

[1] *Candle Flame - 1g vs Microgravity - NASA*. en-US. URL: https://www.nasa.gov/image-article/candle-flame-1g-vs-microgravity/ (visited on 06/06/2024).

[2] Kath Crawford Kate Andrews Paul Beaumont and Davi McCaig. "Making Light of Photosynthesis". In: *SSERC* ().