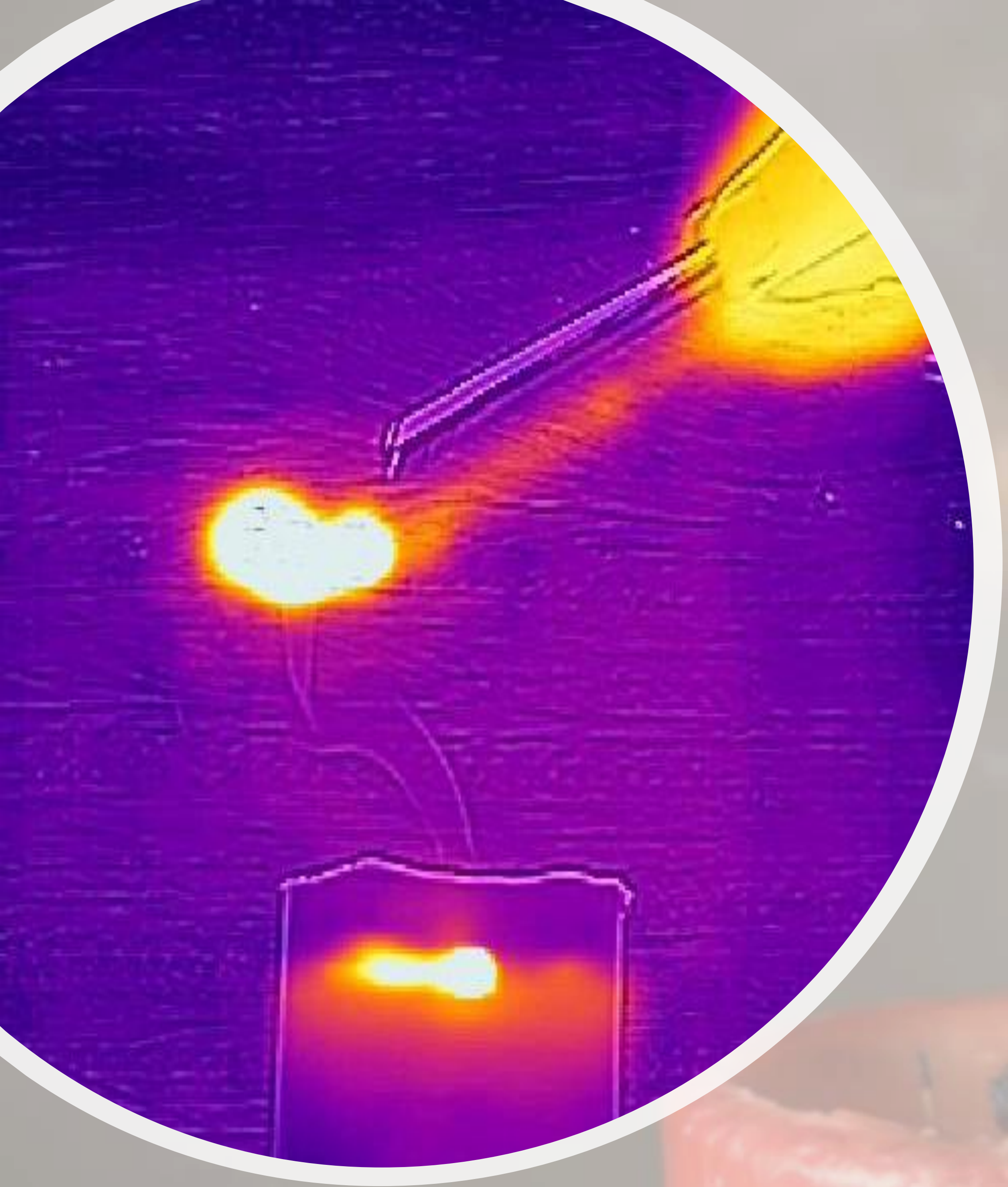

Reporter: Matheus Pessôa

Team Brazil: Andrius D., André Juan, Gustavo Saraiva, Henrique Ferreira, Lucas Maia, Lucas Tonetto, Matheus Pessôa, Ricardo Gitti

Problem 8- Candle Lighthing trick

Team Brazil

Candle Lighting Trick

- “It is possible to relight a candle that has just been blown out by lighting the smoke that is created in the process. Indeed, the smoke contains vaporized wax which is the substance that burns in the flame in the first place. **What is the maximum distance** (between the match and the candle) from which one can **relight the candle**? **Identify the important parameters** and find **how they influence this maximal distance**.”

Team Brazil

Candle Lighting Trick

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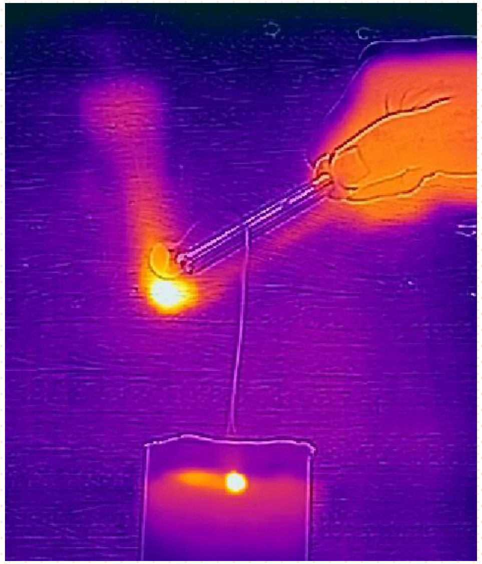
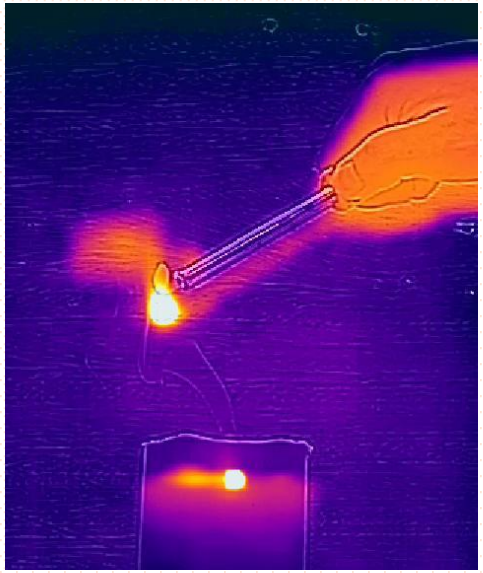
❑ Physical processes

- Smoke **diffusion** in air

- Air **convection** due temperature gradient



- External **interferences**



* Experimental images

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Candle Lighting Trick

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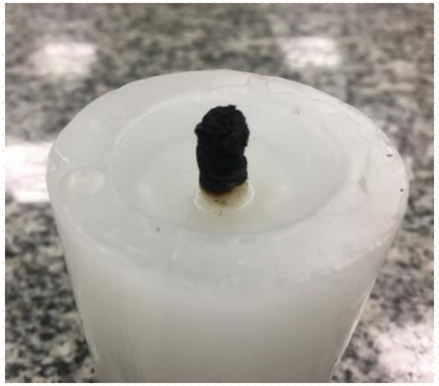
❑ Chemical compounds of candle and smoke

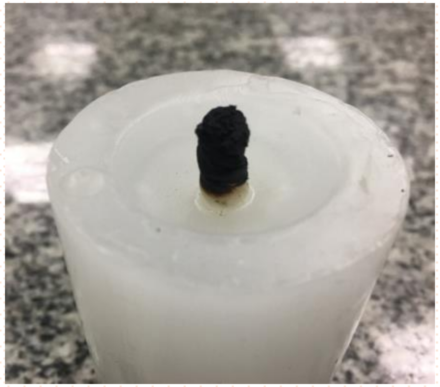


Candle

- Candle: paraffin wax and a wick

Smoke

- Contains different compounds of paraffin
  - Dynamically important to the problem

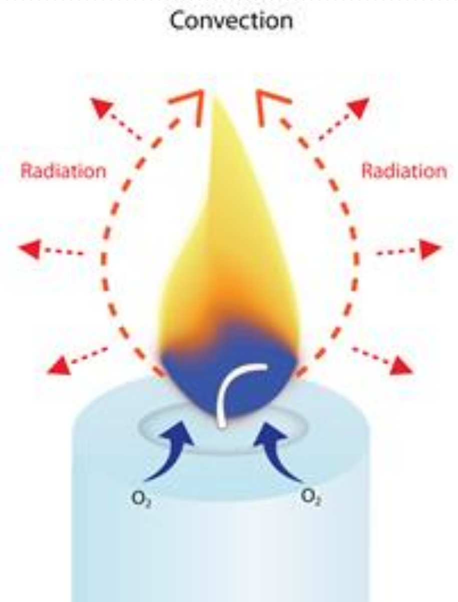


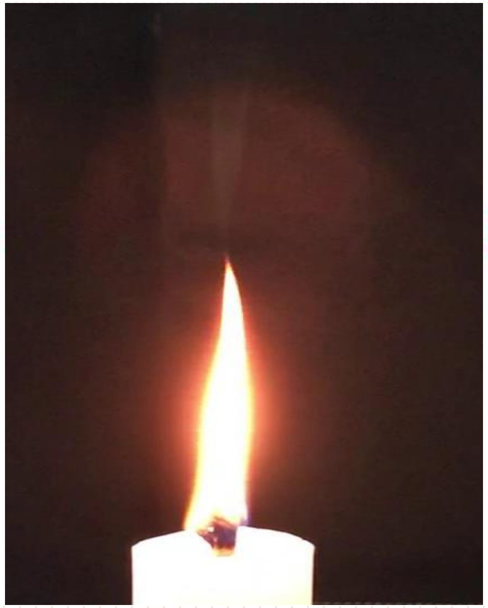
Ember

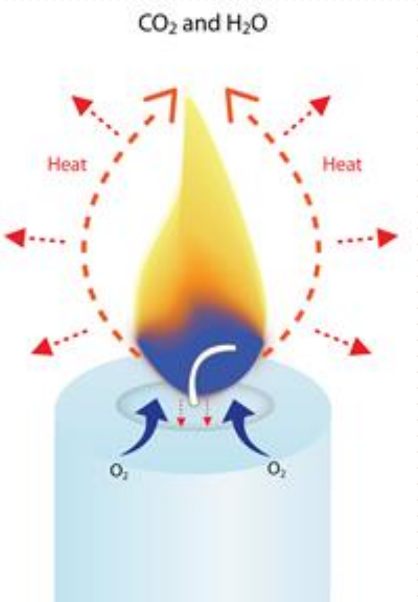
350°C~430°C

- Luminous spots keep paraffin wax melt and evaporation
  - Helps in relighting

❑ How a candle Works- Convection process



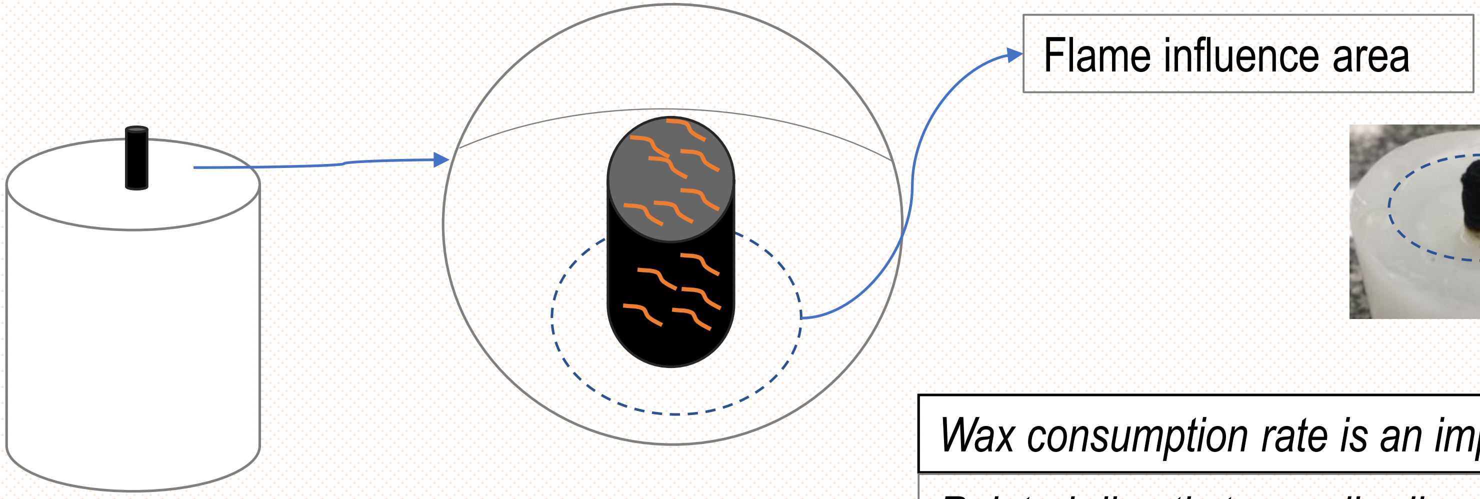


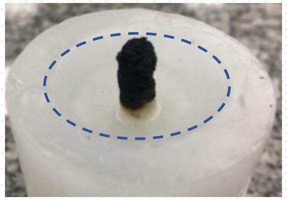


- Flame heats the air and it starts to rise.
- Cooler air rushes at the bottom to replace it.
- When cooler air is heated, it too rises up and is replaced by cooler air at the base of the flame.
- Continual cycle of upward moving air around the flame (a convection current) giving the flame its elongated or teardrop shape.

Reference [1]: http://candles.org/candle-science/

❑ Candle characteristics





Wax consumption rate is an important parameter!

Related directly to candle diameter & wick

Heat of the flame melts the wax near the wick. This liquid wax is then drawn up the wick by capillary action. The heat of the flame vaporizes the liquid wax turns it into a hot gas. Molecules are drawn up into the flame and react with oxygen from the air to create heat, light, water vapor (H_2O) and carbon dioxide (CO_2).

Reference [1]: http://candles.org/candle-science/

Conditions for relighting

Team Brazil

Candle Lighting Trick

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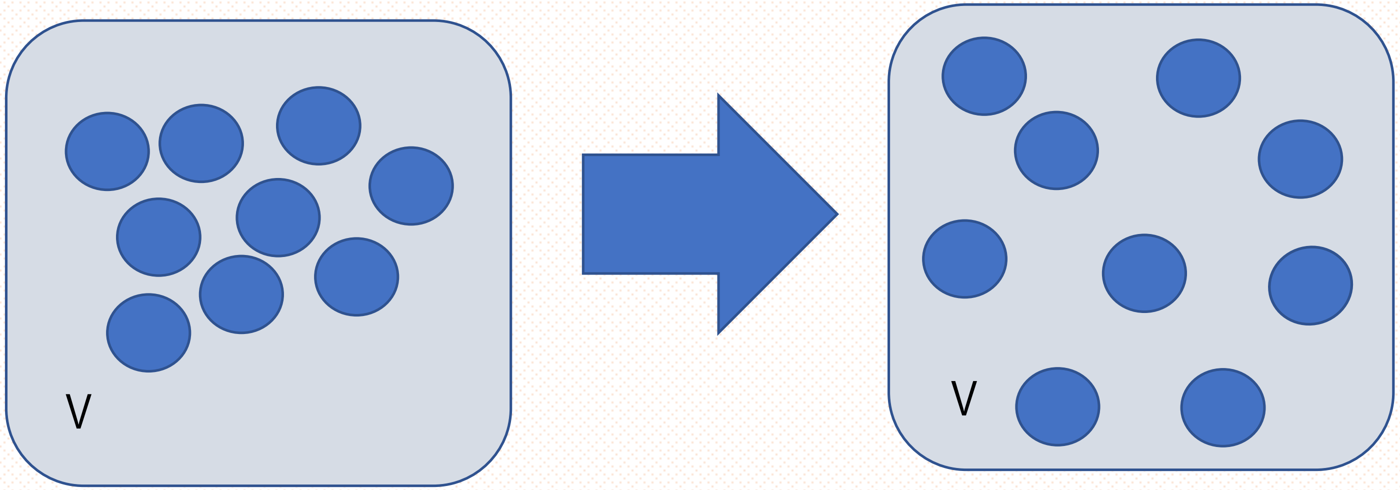
- We need a limiar value of wax to relight the candle!
- It is related to time and height, since concentration is a function of time and space
  - A value above a threshold for concentration *L* is reached in an optimal instant *t*
  - Therefore, there is a maximum height value z_{max}

❑ Physical modelling for smoke concentration

- Air density variation in function of temperature

$$\Delta\rho = -\rho_0\beta\Delta T$$

ρ is the density of the fluid in convection; ∆T is the temperature difference between two local points with their respective densities and β is the coefficient of thermal expansion, which for the air equals 3.43x10−3K−1.



Lower temperatures

Higher temperatures

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Candle Lighting Trick

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Physical modelling for smoke concentration

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Candle Lighting Trick

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- Convection process
  - Movement of air masses or particles considering different temperatures on a fluid
- The convection-diffusion process is described by

$$\frac{\partial \phi}{\partial t} = \nabla \cdot (D \nabla \phi) - \nabla (v \phi) + R$$

- Considering D>0 and R>0 constants, with $v = v_z, v_z > 0$:

$$\boxed{\frac{\partial \phi}{\partial t} = D \nabla^2 \phi - v_z \frac{\partial \phi}{\partial z} + R}$$

D = mass diffusivity coefficient
v = relative velocity field of the diffusing quantity
R =describes any sources or sinks

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Candle Lighting Trick

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❑ Physical modelling for smoke concentration

- Applying separation of variables, with

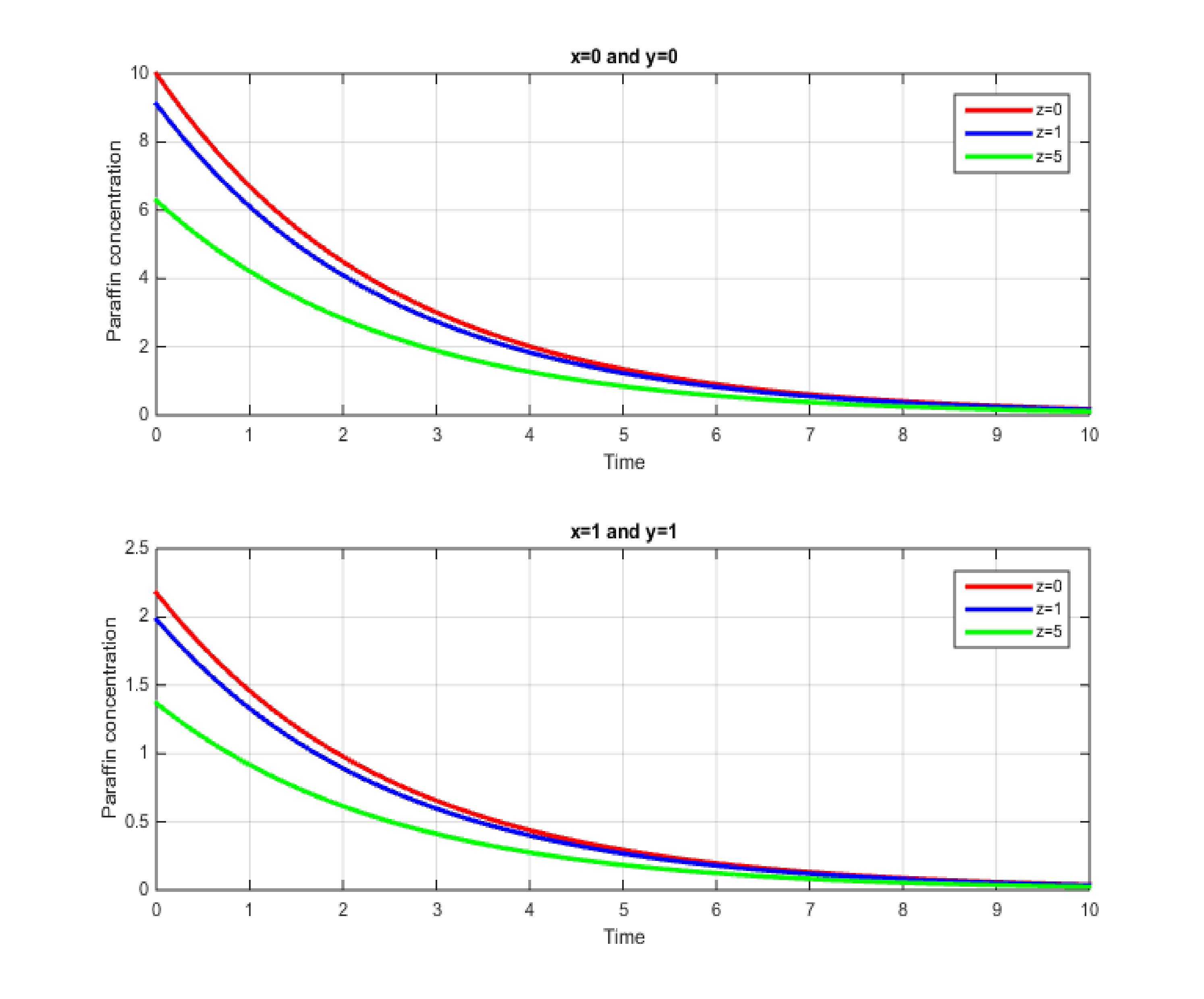
$$\phi(x,y,z,t) = \chi(x)\Upsilon(y)\zeta(z)\tau(t)$$

- We reach a solution for the behavior of concentration for each Direction and time

$$\phi(x,y,z,t) = \phi_0 \exp\left(c_1 t - \sqrt{\frac{c_3}{D}}x - \sqrt{\frac{c_2 - c_3}{D}}y\right) \exp\left(-\frac{1}{2}\left(\frac{v_z}{D} - \sqrt{\left(\frac{v_z}{D}\right)^2 - \frac{4(c_2 - c_1)}{D}}\right) z\right)$$

- This solution will be used to **simulate** the phenomenon qualitatively

Characteristic solution



- Matches qualitative expectations!
- Smoke concentration decreases with time and distance from the source in an exponential rate

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Candle Lighting Trick

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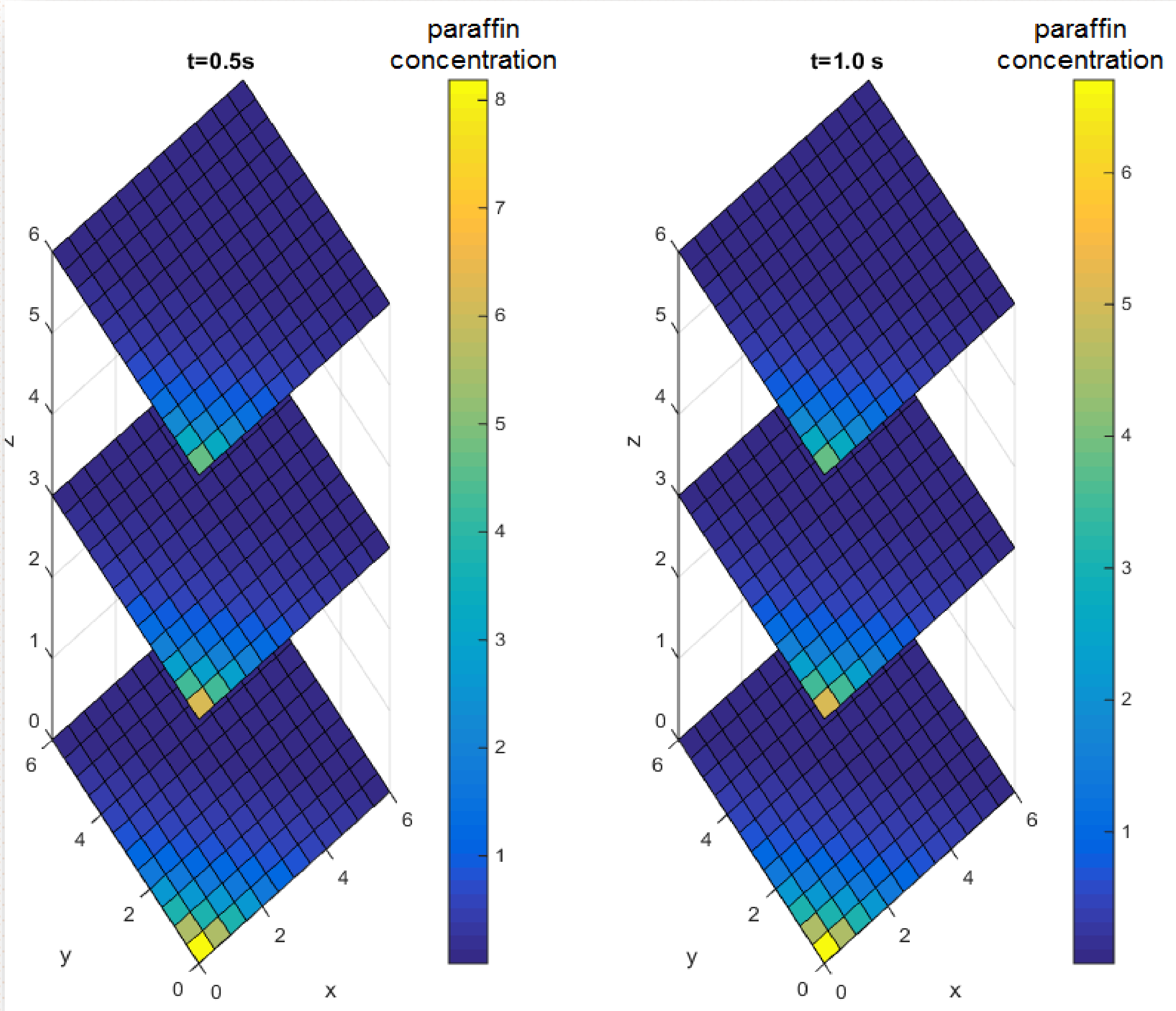
❑ Simulation for concentration in time

- Different cut planes for different heights and wax concentration in time



- Diffusion more rapidly in upward direction!
- Behavior is the same for radial directions

Plot!

$$\phi(x,y,z,t) = \phi_0 \exp\left(c_1 t - \sqrt{\frac{c_3}{D}}x - \sqrt{\frac{c_2 - c_3}{D}}y\right) \exp\left(-\frac{1}{2}\left(\frac{v_z}{D} - \sqrt{\left(\frac{v_z}{D}\right)^2 - \frac{4(c_2 - c_1)}{D}}\right)z\right)$$

❑ Methodology

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Candle Lighting Trick

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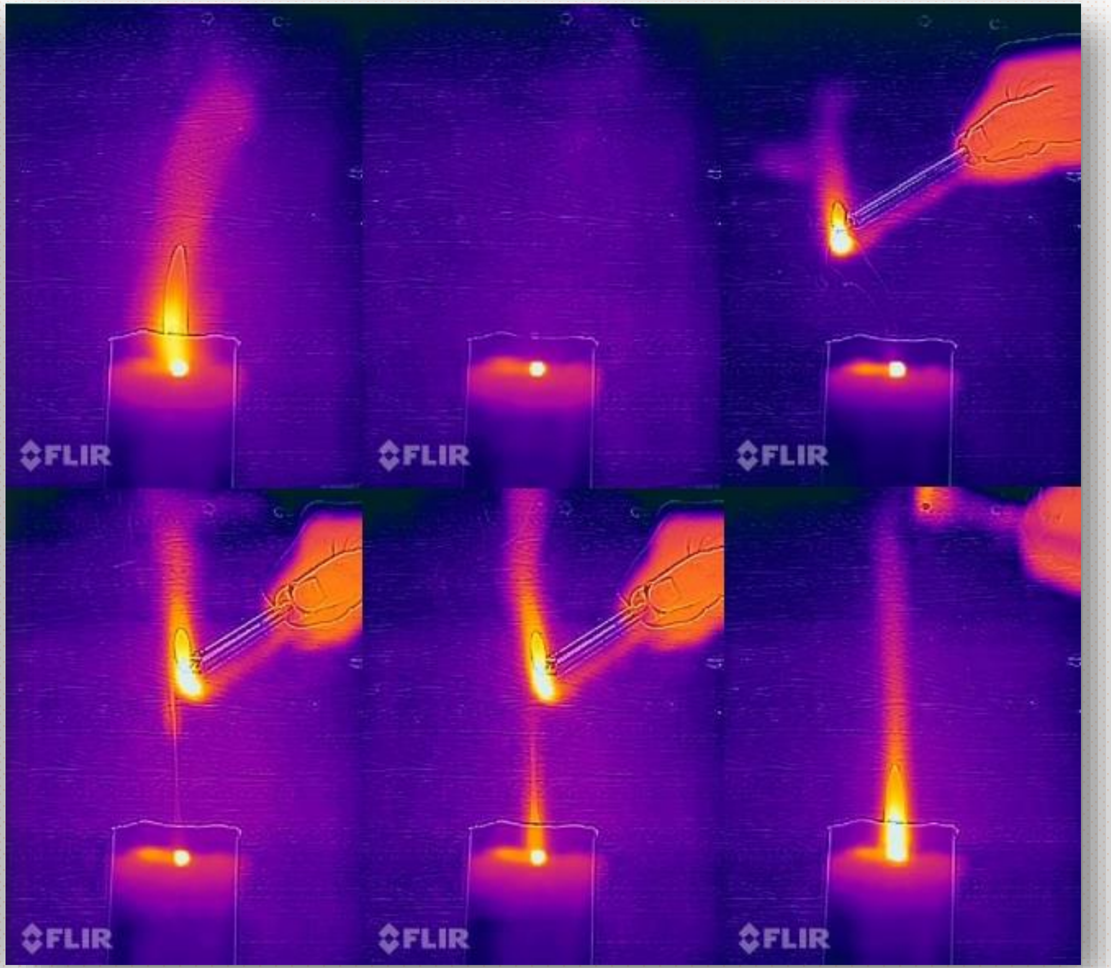
Normal footage (SONY Handycam 60 fps)*

Thermal images used with FLIR sensor



*Video analysis using the TRACKER software

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Candle Lighting Trick

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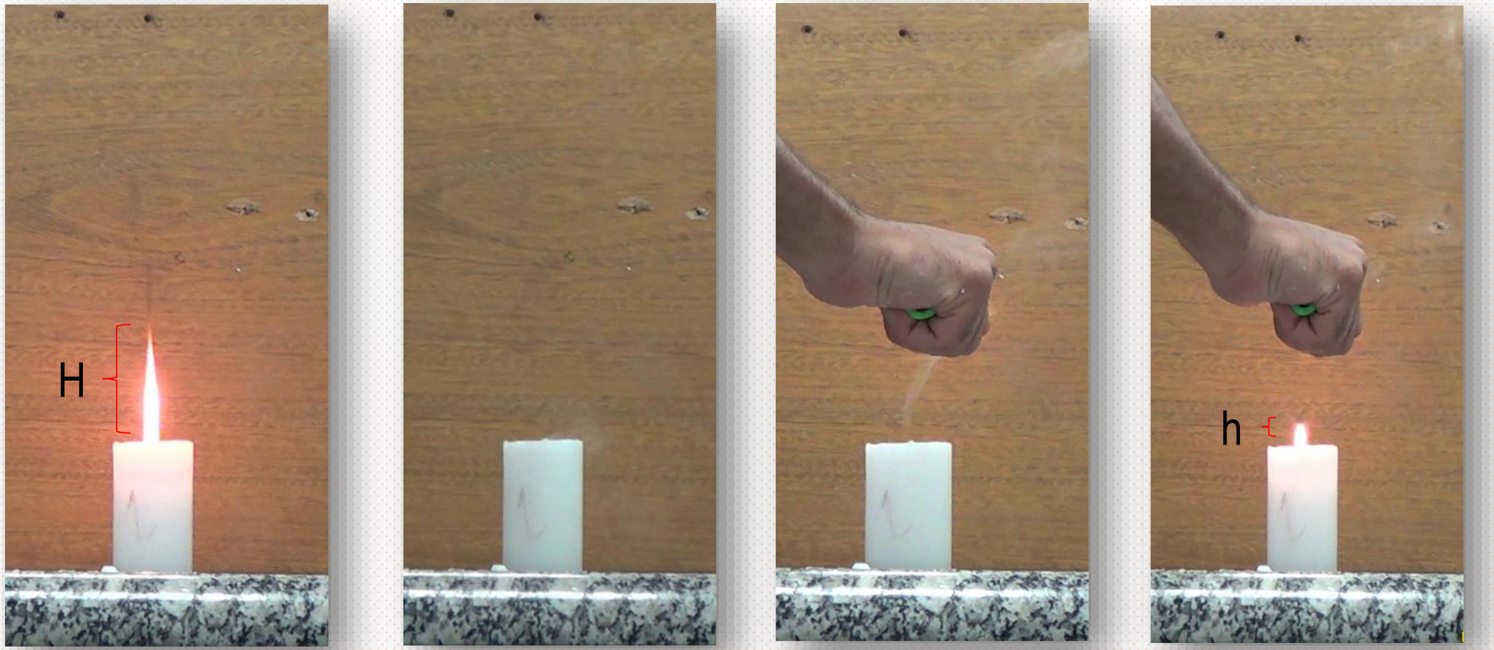
Methodology

- Obtained experimental data
  - Flame height before and after relighting
  - Time to relight the candle
  - Distance from the source

- All of these for different diameters & wick types



❑ Physical considerations

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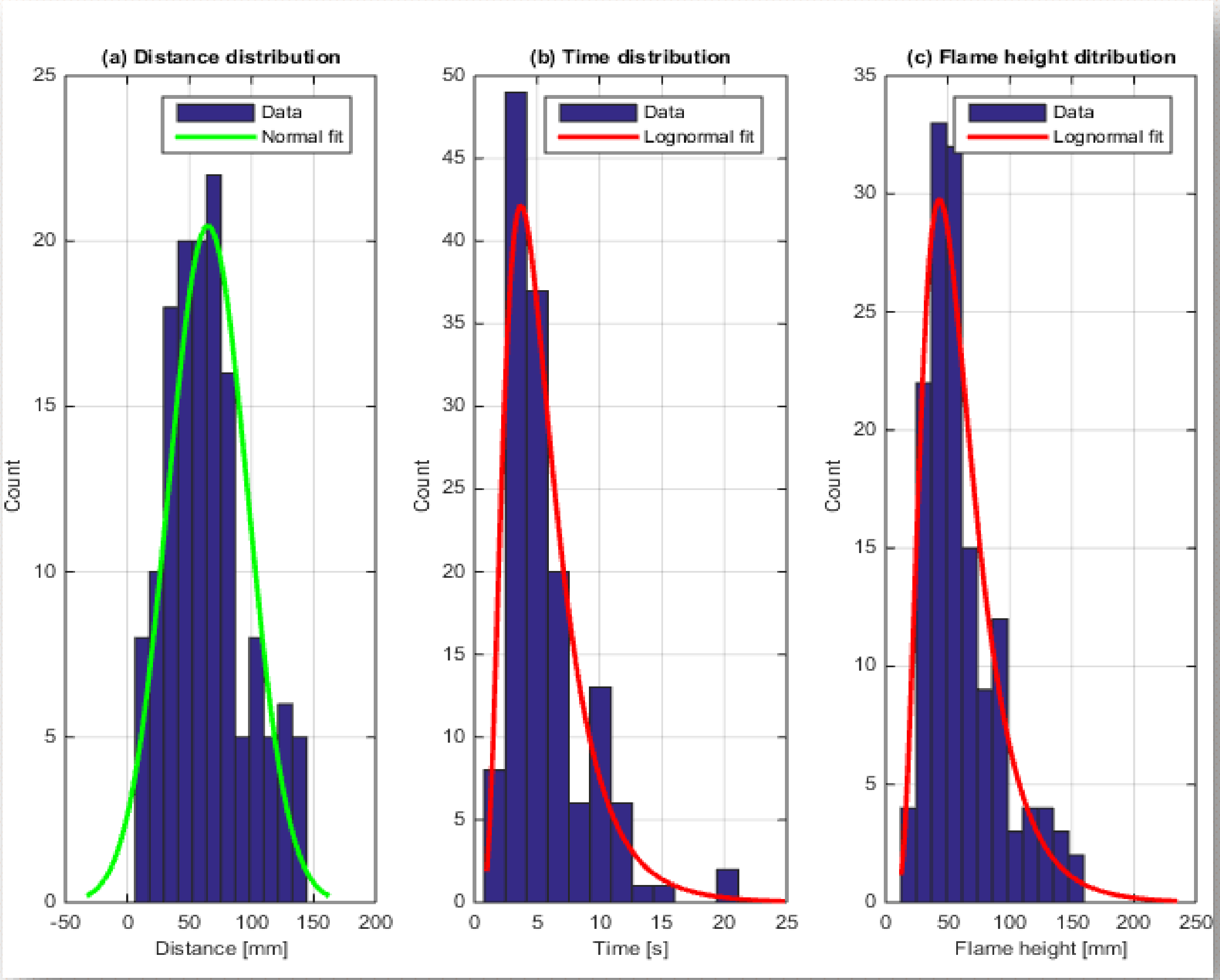
Candle Lighting Trick

- It is not possible to **perfectly isolate** the system from external interferences!
  - Experimental data will inherit fluctuations on a true value for maximum height (h)
  - This because we consider interactions between wax molecules and *external* (moving) air
  - Probabilistic approach to the problem



Distribution of all experimental results

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Candle Lighting Trick

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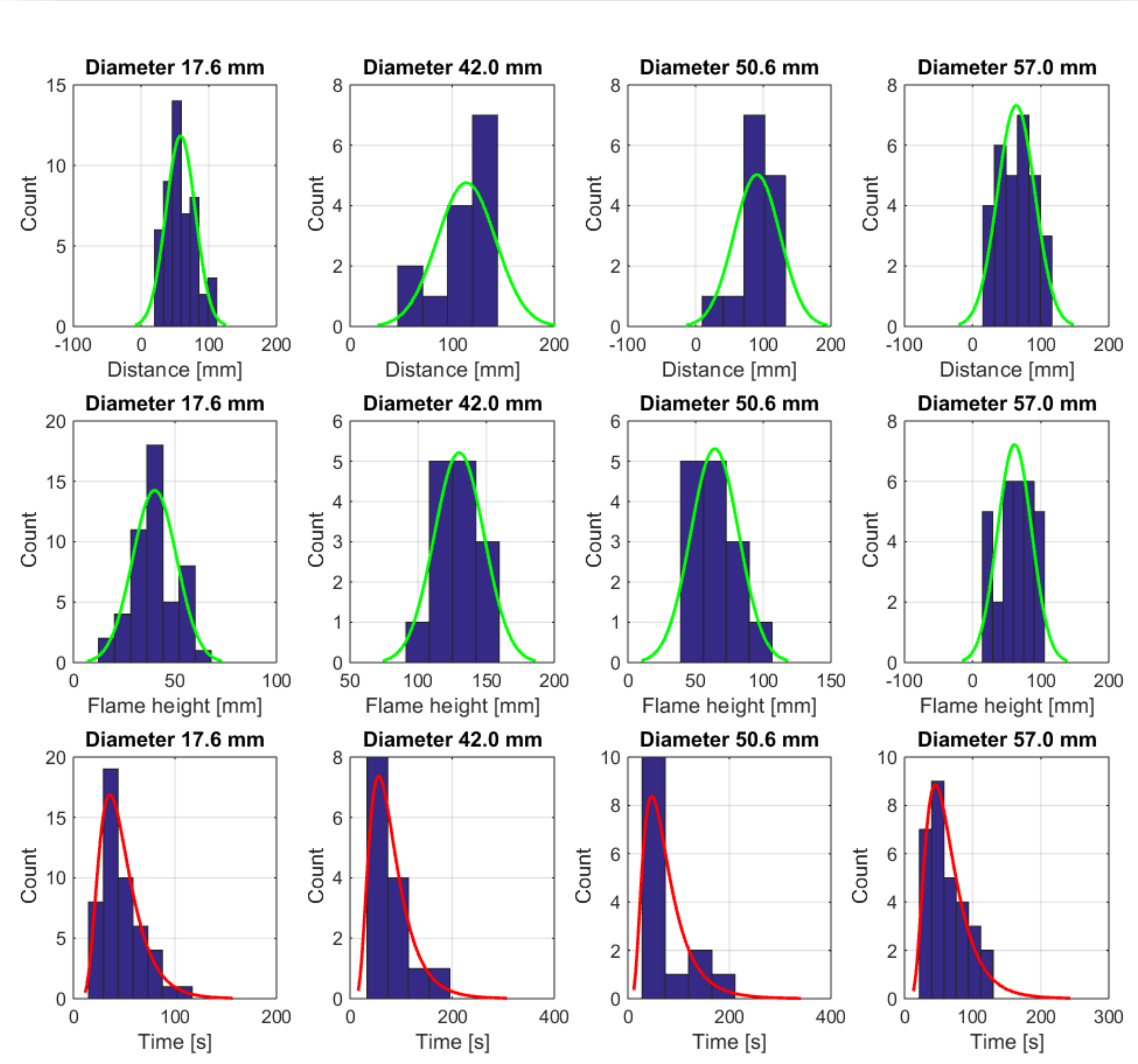
❑ What can influence the maximum height?

- Candle diameter
  - (17.5 ± 0.5)mm
  - (42.0 ± 0.5)mm
  - (50.06 ±0.5) mm
  - (57.0 ±0.5) mm

Important approximation to rule out external interferences!



Distance

Flame height

Time for relighting

Results for different candle diameters

❑ Candle diameter

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Candle Lighting Trick

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- Diameter and average distance from the source

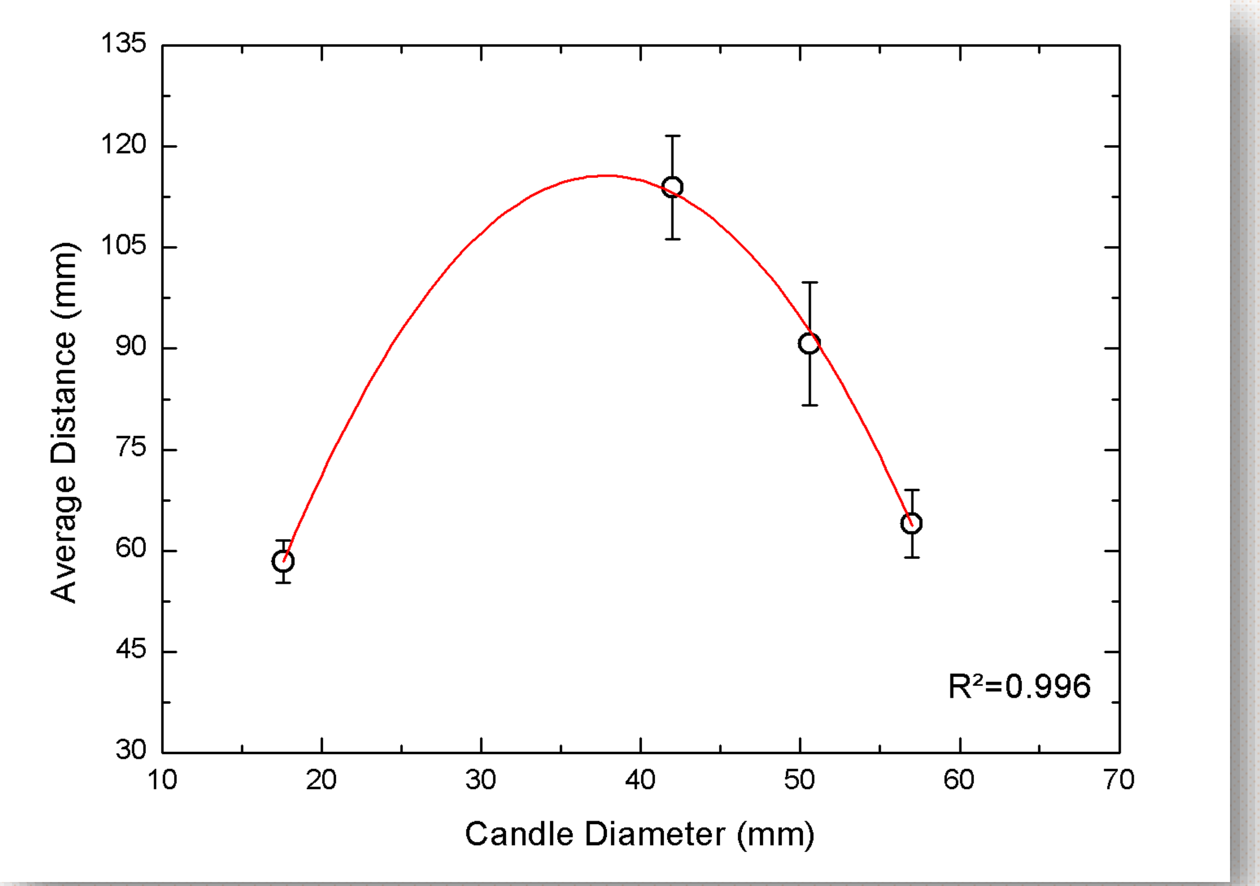
Parabolic fitting function

$$y = ax^2 + bx + c$$

$a = -(0.14 \pm 0.02)cm$

$b = (11 \pm 2)cm$

$c = -(85 \pm 22)cm$



Average behavior for distance in function of diameter

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Candle Lighting Trick

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❑ Candle diameter

- Diameter and average distance from the source

Parabolic fitting function

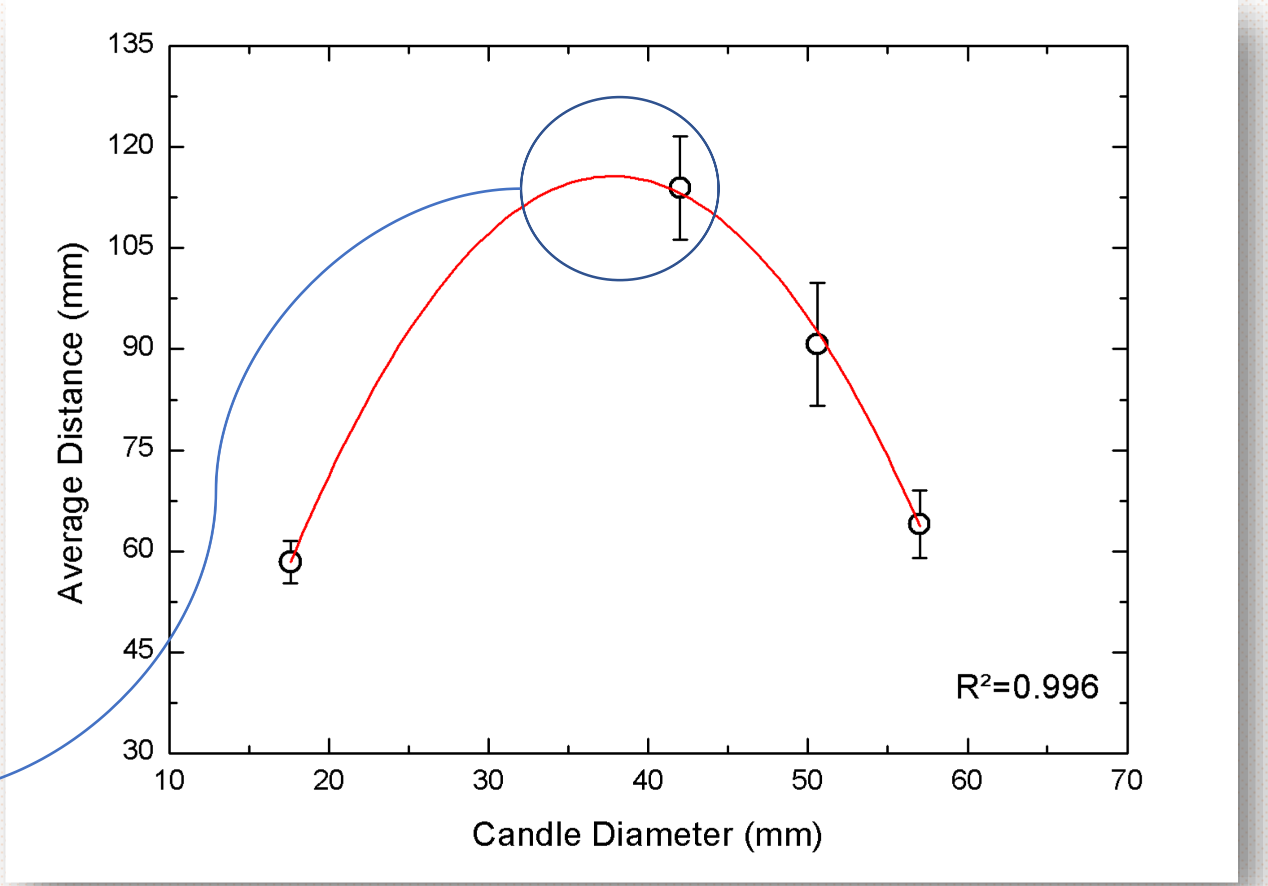
$$\underbrace{y = ax^2 + bx + c}$$

$a = -(0.14 \pm 0.02)cm$

b= $(11 \pm 2)cm$

$c = -(85 \pm 22)$cm

Diameter as an optimization parameter



Average behavior for distance in function of diameter

❑ Candle diameter

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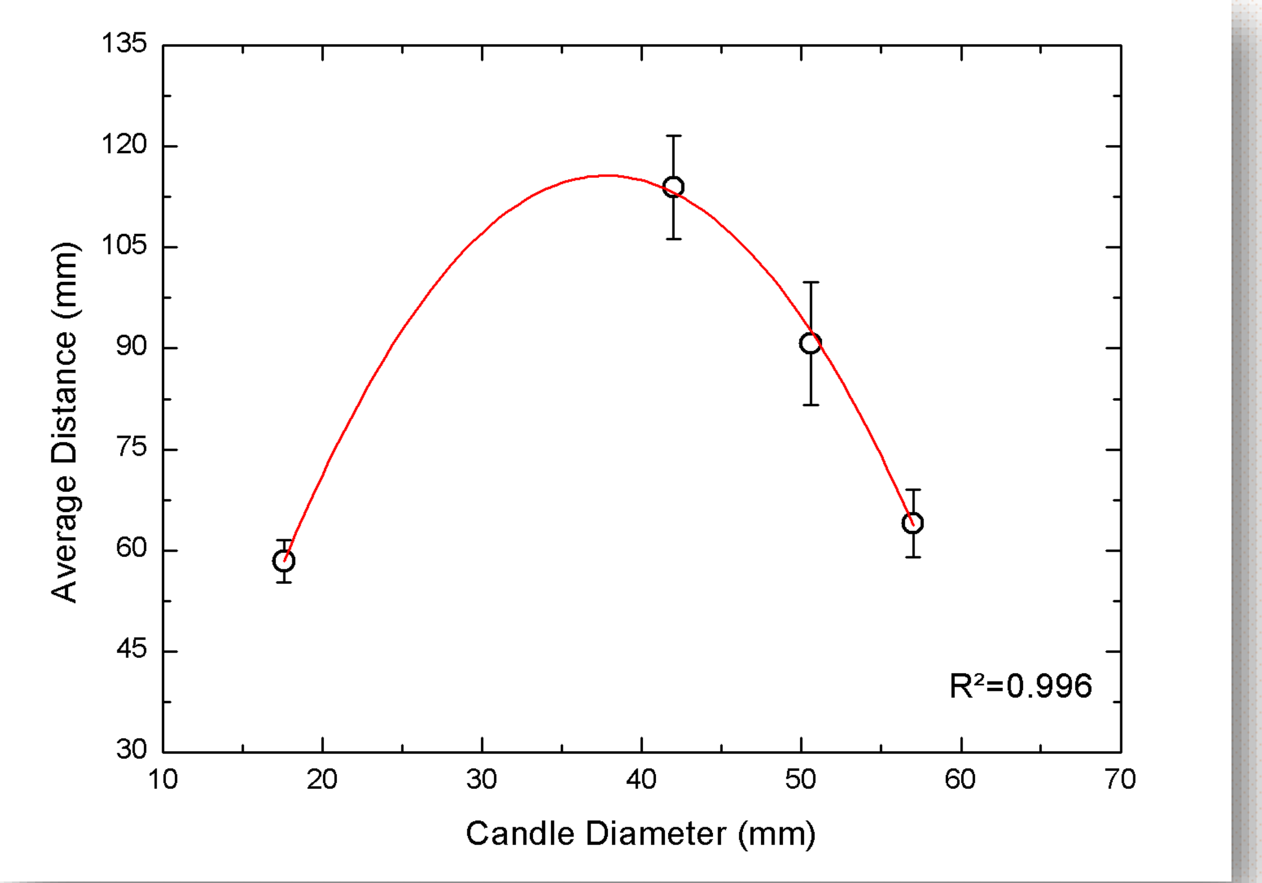
Candle Lighting Trick

- Diameter an average distance from the source

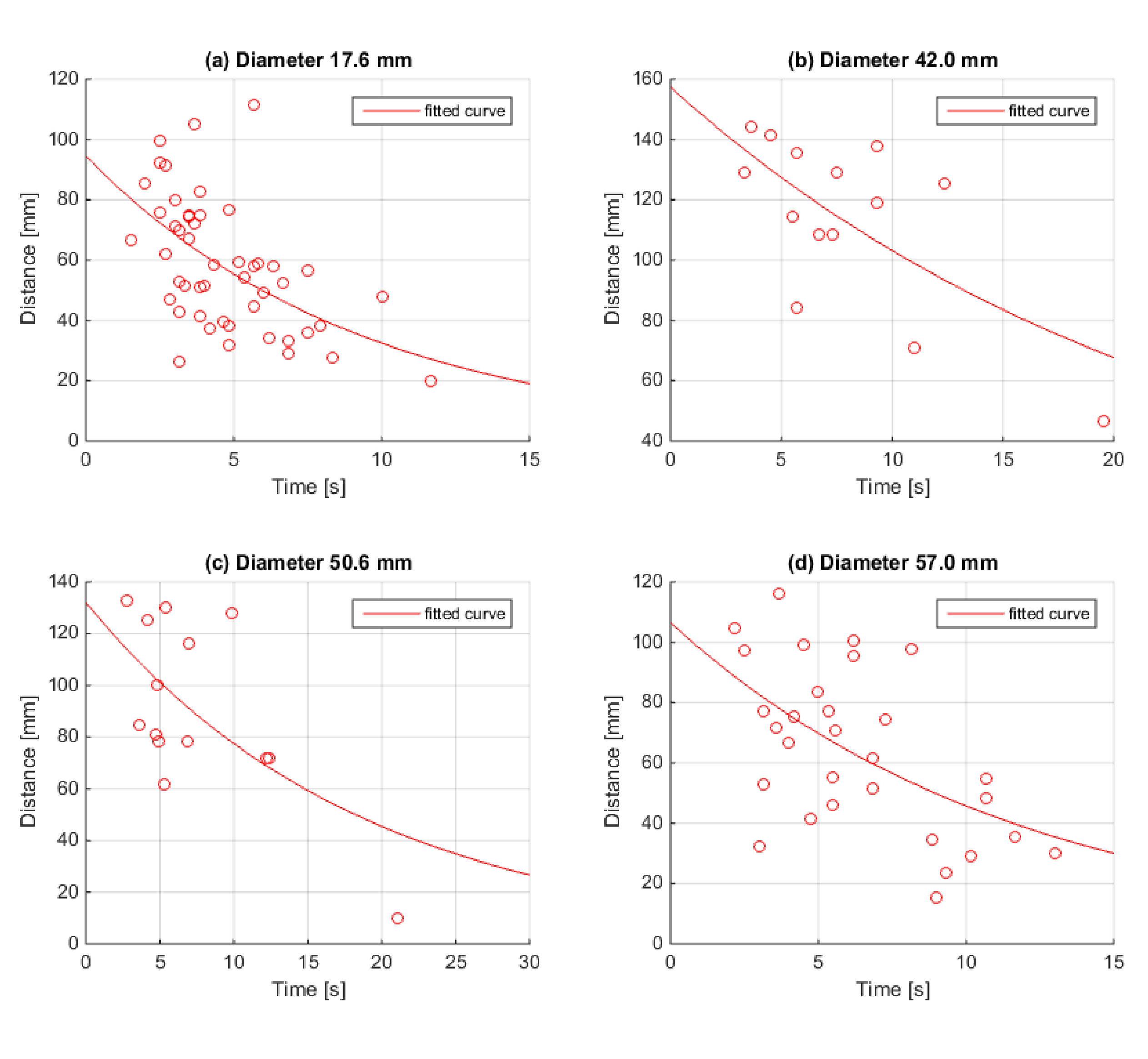
Optimal candle for greater distances
$$Diameter = (38 \pm 8)\text{mm}$$
$$Maximum\ height = (116 \pm 24)mm$$



Average behavior for distance in function of diameter

❑ Candle diameter

- Relation between time and distance
  - Poor correlation coefficient
  - Unrelated!
- Also expected considering randomness of external factors



Dispersion for distance in function of time with different diameters

❑ What can influence the maximum height?

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Candle Lighting Trick

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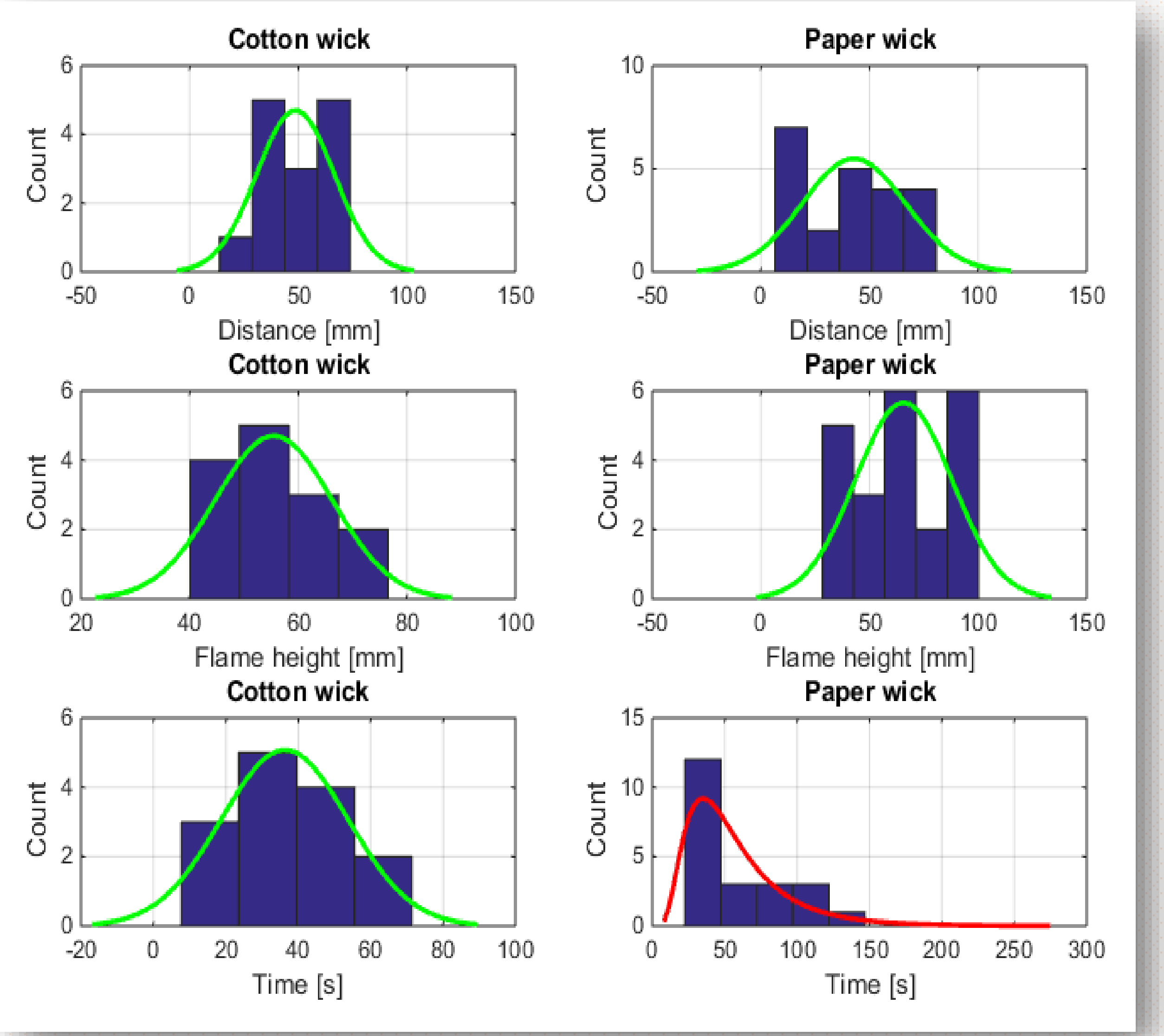
- Type of wick
  - Cotton wick
  - Paper wick



Distribution for different wick materials (paper and cotton)

Distance

Flame height

Time for relighting

❑ Experimental considerations

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Candle Lighting Trick

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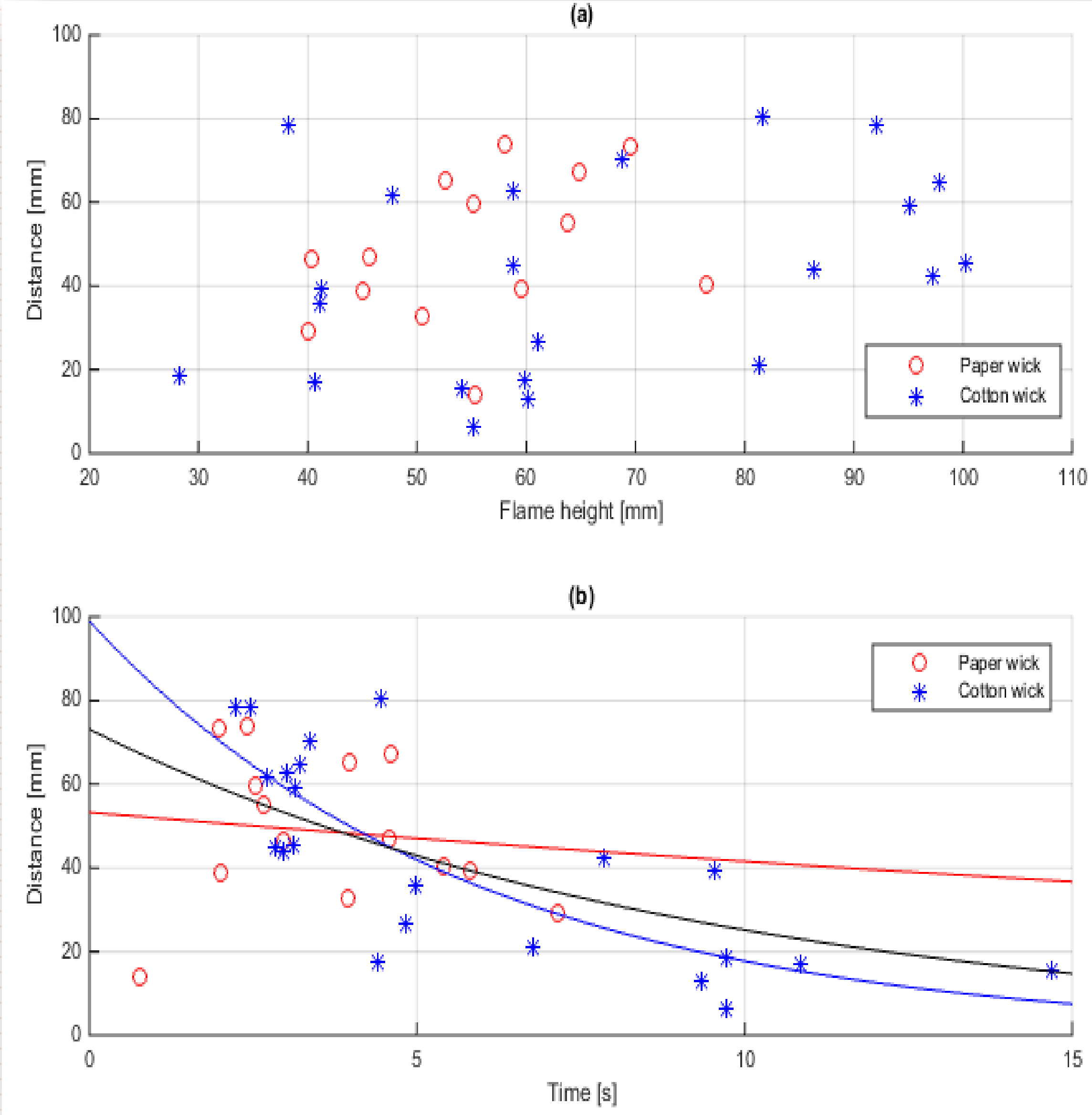
- We analysed the points dispersion
  - No apparent correlation between flame height or time for distance in any of the different wicks



Dispersion for different wick materials (paper and cotton)

❑ What can influence the maximum height?

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Candle Lighting Trick

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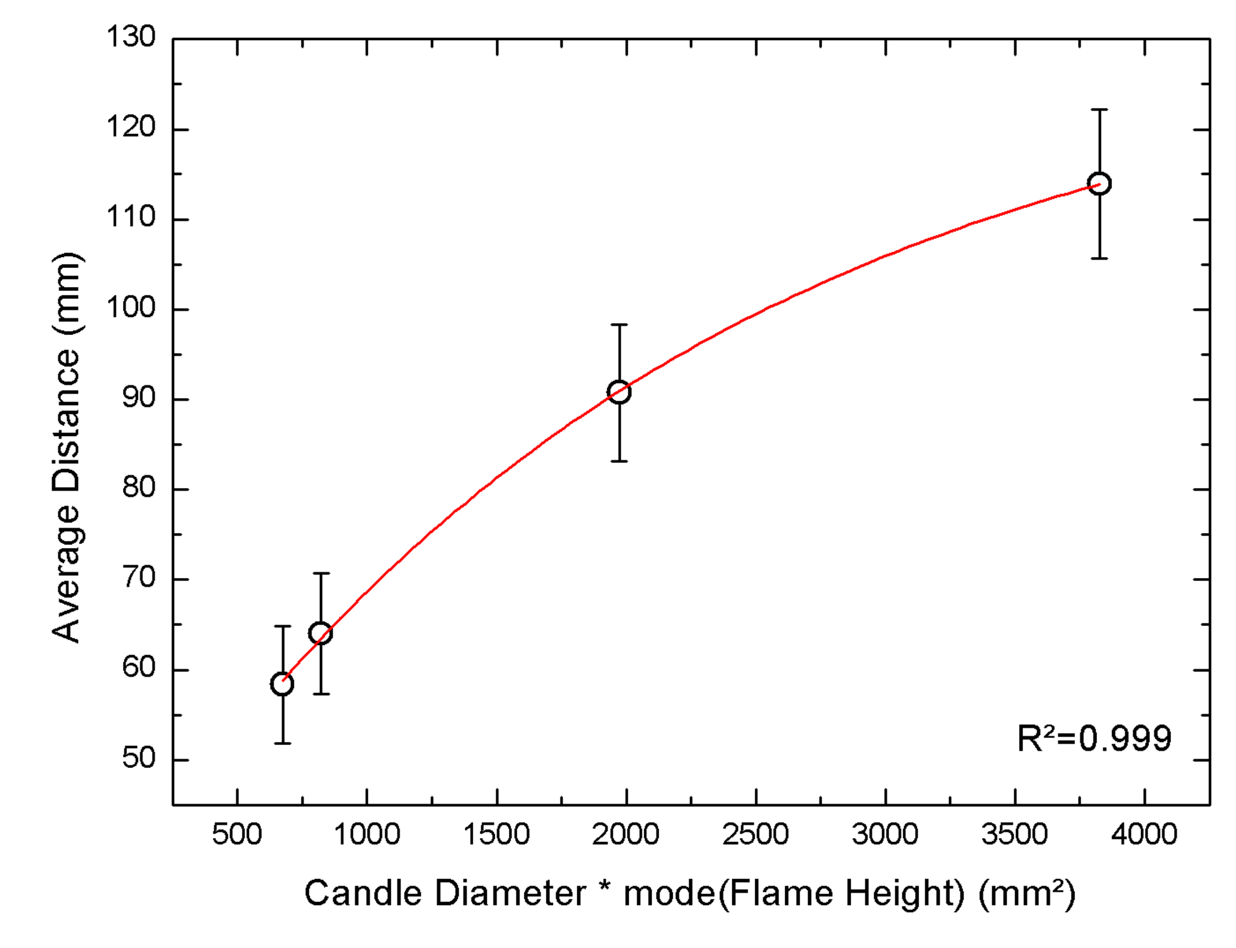
- **Combining parameterss!**
  - Common burn rate produces more wax (size of flame before being put out)
  - Candle diameter related to contact area between flame and solid wax (more vapor wax consumption)
  - Maximum height is proportional to the product between both parameters
- Experimental validation for influence in combined parameters
- Average distance proportional to diameter and flame height (wax consumption
- **Colocar o que é flame height!**



Relation between average distance and combined parameters

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Candle Lighting Trick

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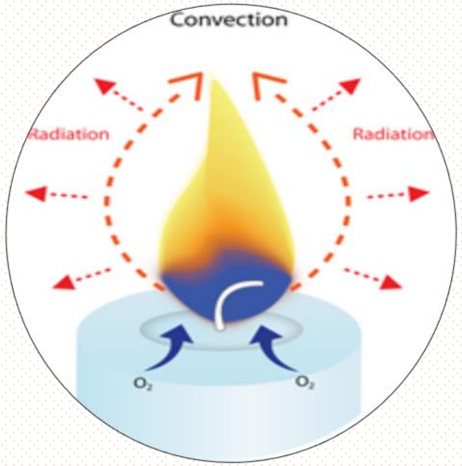
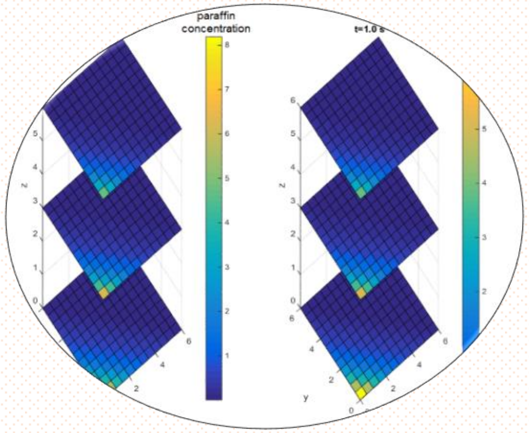
6/9/2018

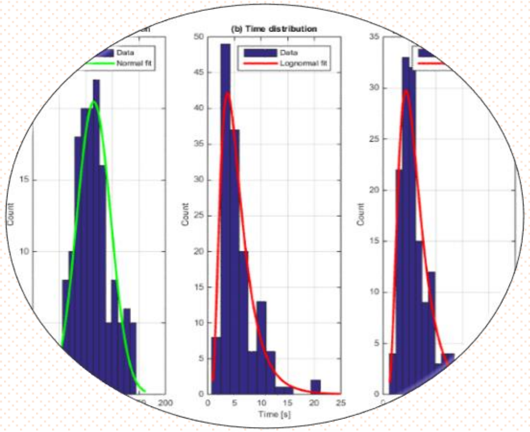
❑ Summary



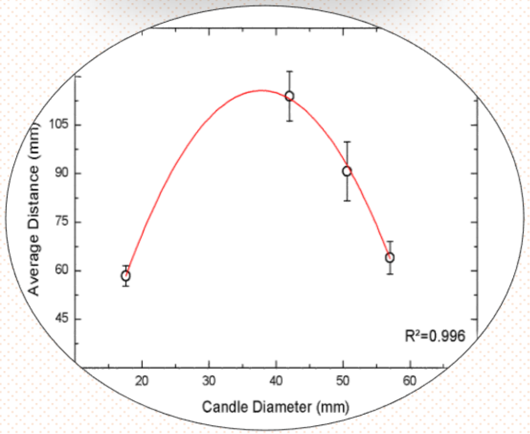
How does a candle work



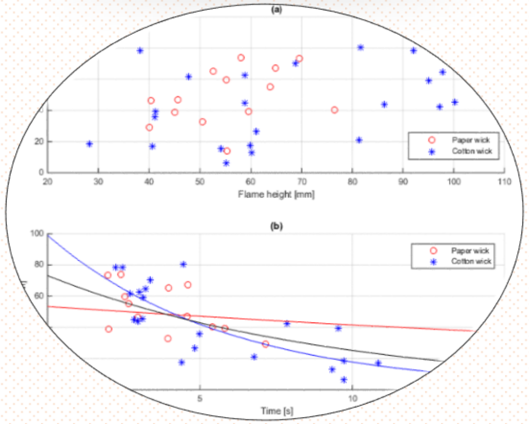
Simulation



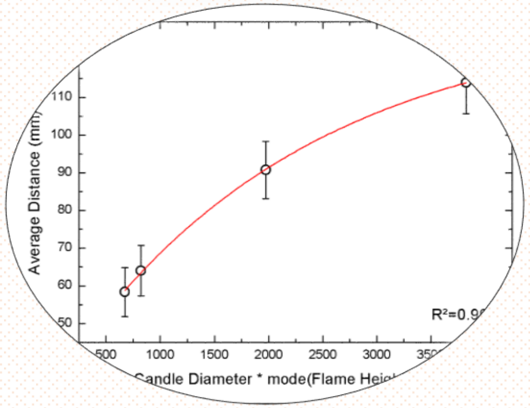
Statistical experimental approach



Optimal candle (diameter)



Different types of wick



Combined parameters

❑ References

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Candle Lighting Trick

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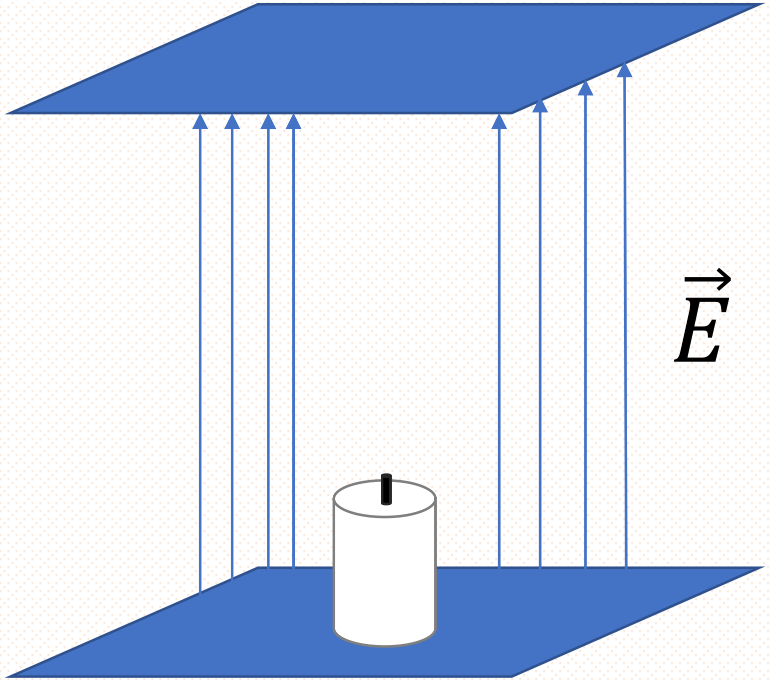
❑Appendix

❑ Other experimental setups



❑ Candles and gravity

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Candle Lighting Trick

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Candle at normal gravity

Candle at microgravity environment

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Candle Lighting Trick

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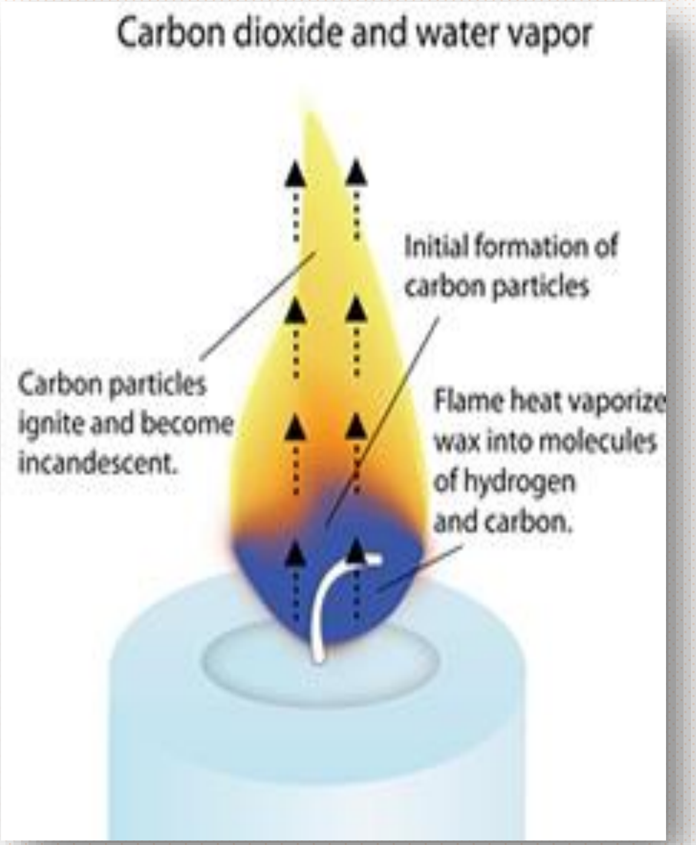
❑ Evolution of the flame & properties



The oxygen-rich blue zone is where the hydrocarbon molecules vaporize and start to break apart into hydrogen and carbon atoms.

The dark or orange/brown region has relatively little oxygen. This is where the various forms of carbon continue to break down and small, hardened carbon particles start to form. As they rise, along with the water vapor and carbon dioxide created in the blue zone, they are heated to approximately 1000 degrees Centigrade.

At the bottom of the yellow zone, the formation of the carbon (soot) particles increases. As they rise, they continue to heat until they ignite to incandescence and emit the full spectrum of visible light. Because the yellow portion of the spectrum is the most dominant when the carbon ignites, the human eye perceives the flame as yellowish. When the soot particles oxidate near the top of the flame's yellow region, the temperature is approximately 1200^{o} C.