SLOVAKIA
IYPT '13

10

Rising water

Nikola Illášová

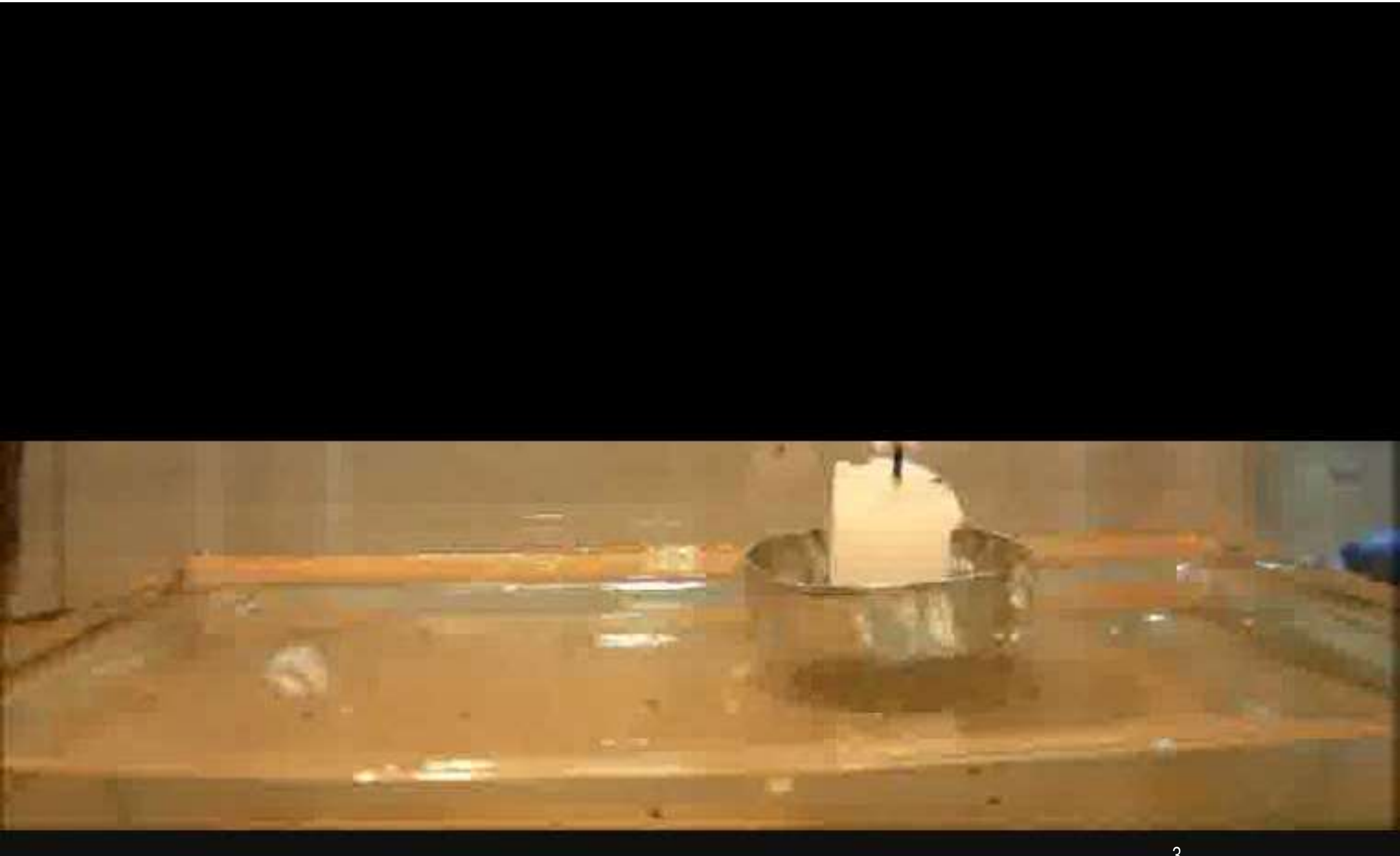
10. Rising water

Fill a saucer up with water and place a candle vertically in the middle of the saucer.

The candle is lit and then covered by a transparent beaker.

Investigate and explain the further phenomenon.

What does it look like?



Simple mechanism

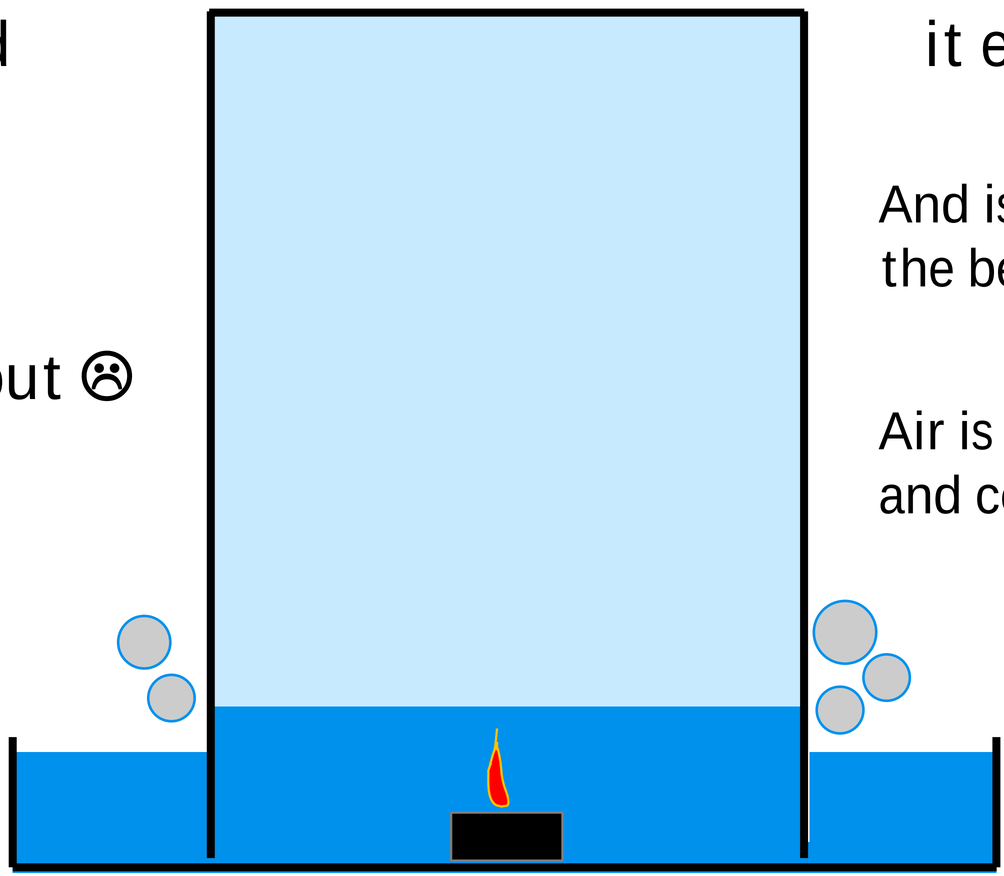
Air is heated

it expands

And is pushed outside the beaker

Candle dies out ☹

Air is cooled down and contracts



WATER RISES

Important questions to answer

1. How do p, V, T change?

2. How does the amount of gas change?
   – Combustion of oxygen

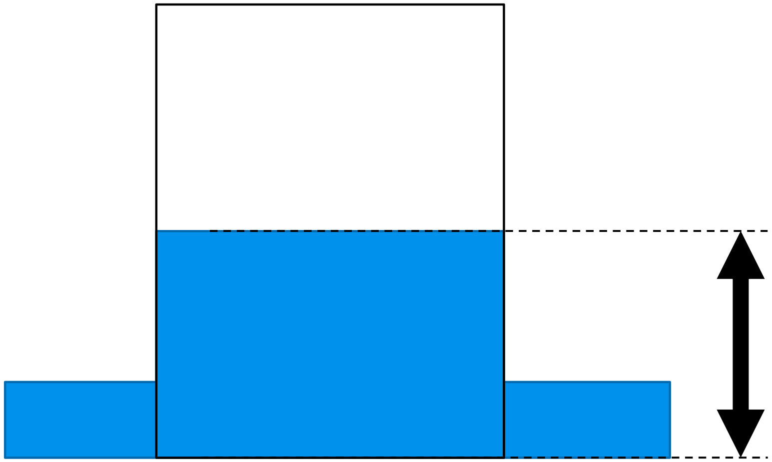
3. Where does heat from the candle go?
   – Heating of the air, losses

1. IDEAL GAS LAW QUANTITIES

Pressure Temperature Volume

Pressure inside the beaker

Changes of water level (hydrostatic pressure) compensate gas pressure changes



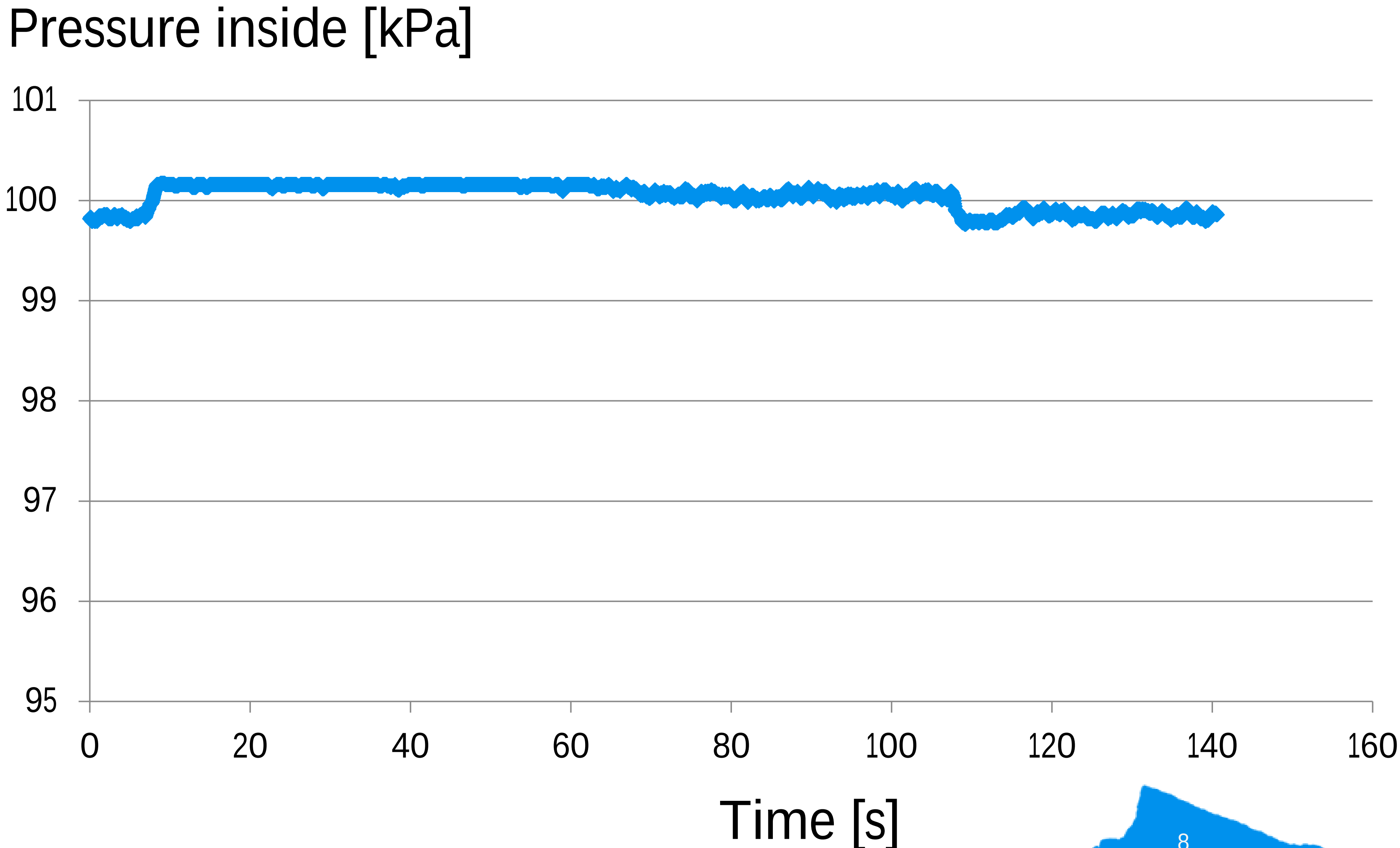
$$\Delta h < 0.1\mathrm{m}$$

$$\Delta p = \Delta h \rho g < 0.01 p_{ATM}$$

Pressure does not change significantly

→ Isobaric process, Gay-Lussac law $V \propto T$

Pressure measured – changes negligibly



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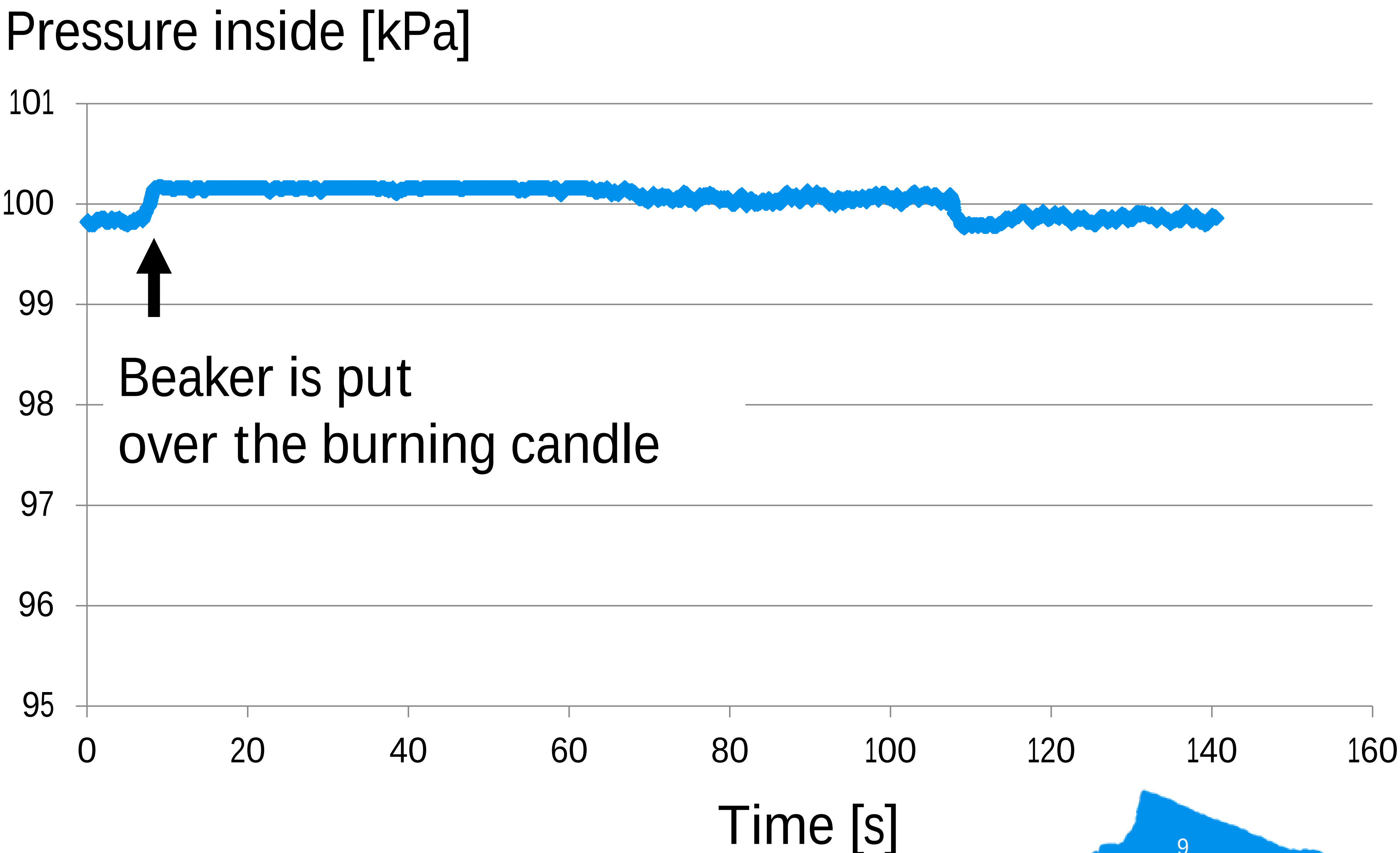

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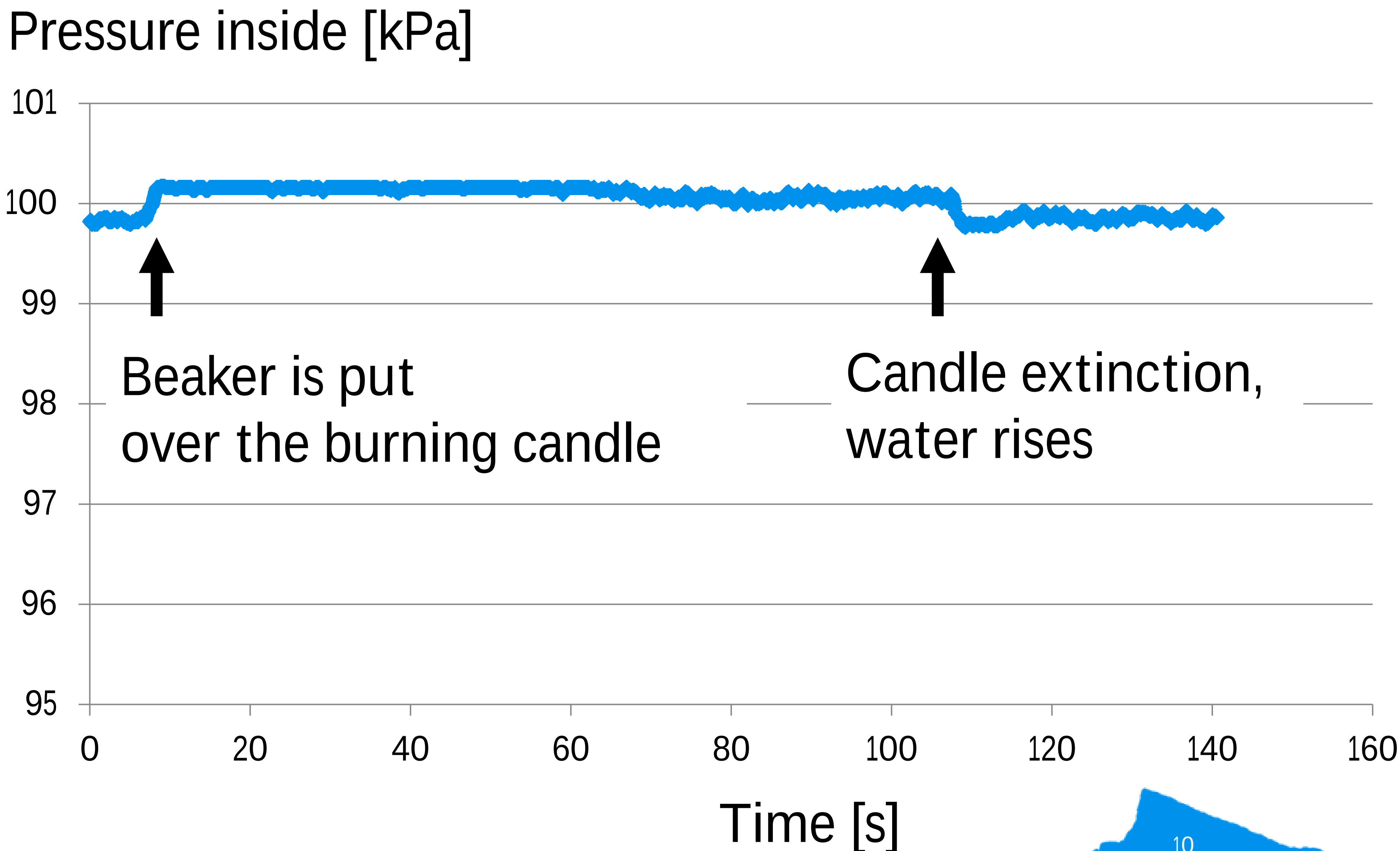

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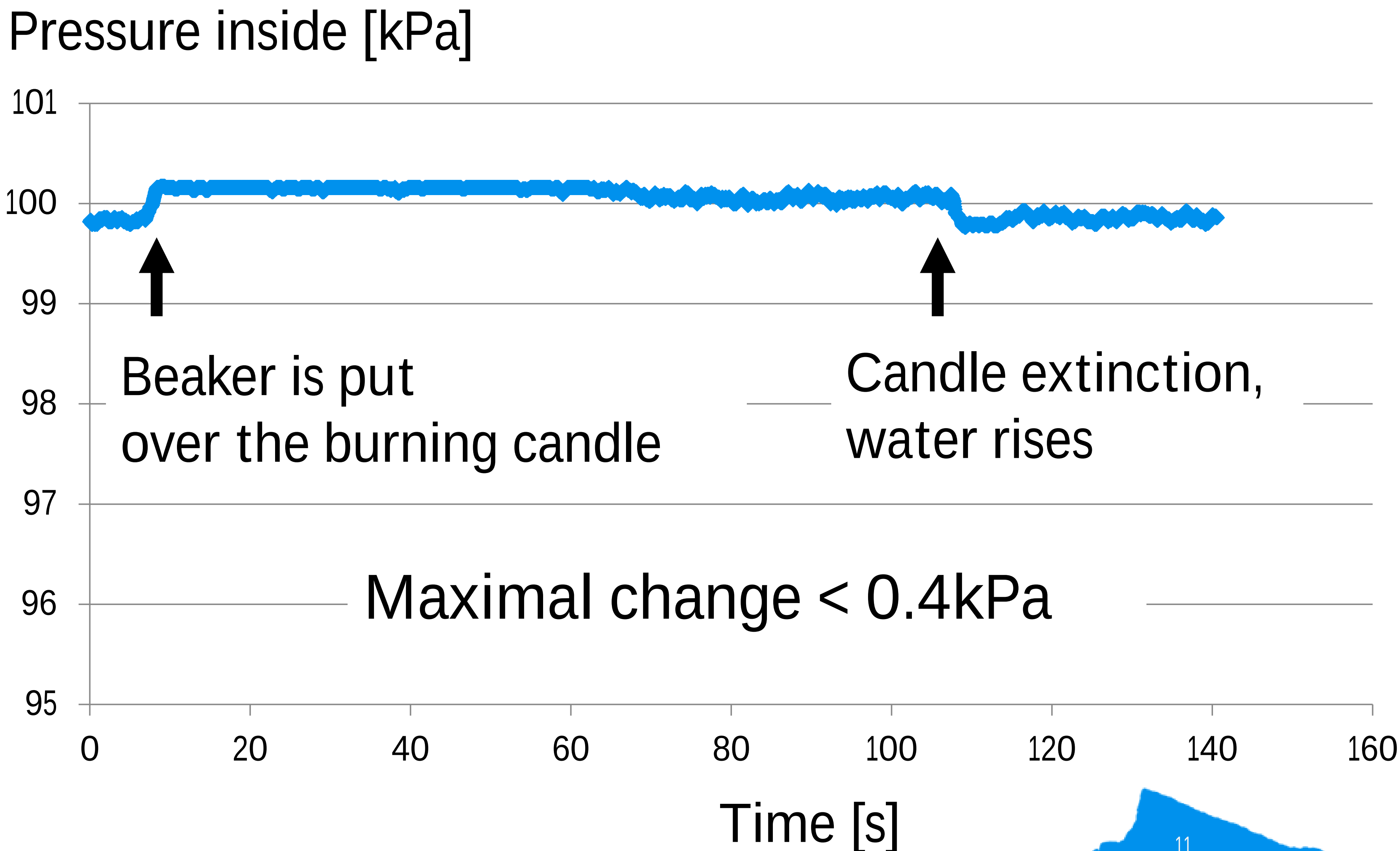


1. IDEAL GAS LAW QUANTITIES

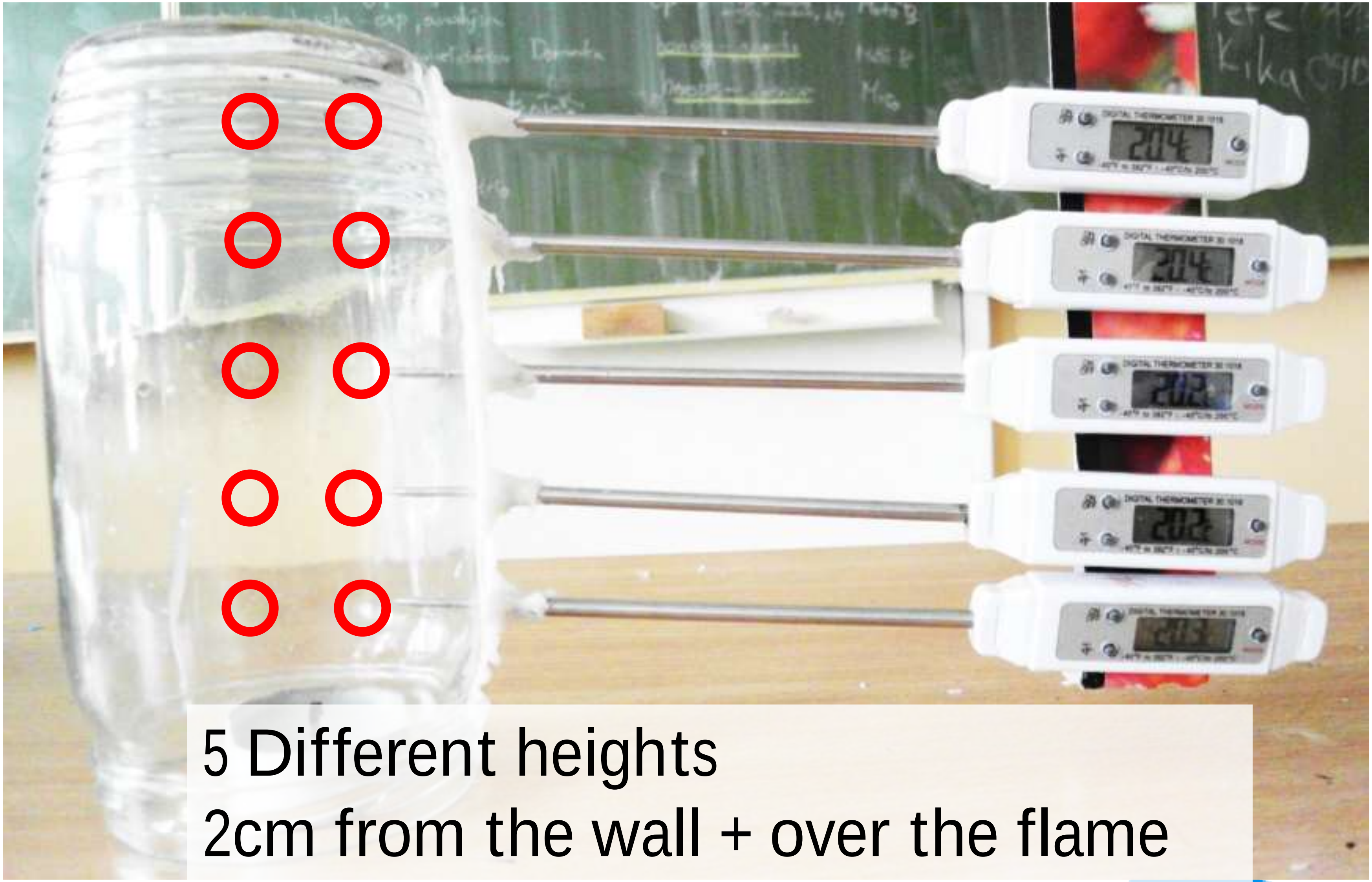
Pressure Temperature Volume

Temperature inside the beaker

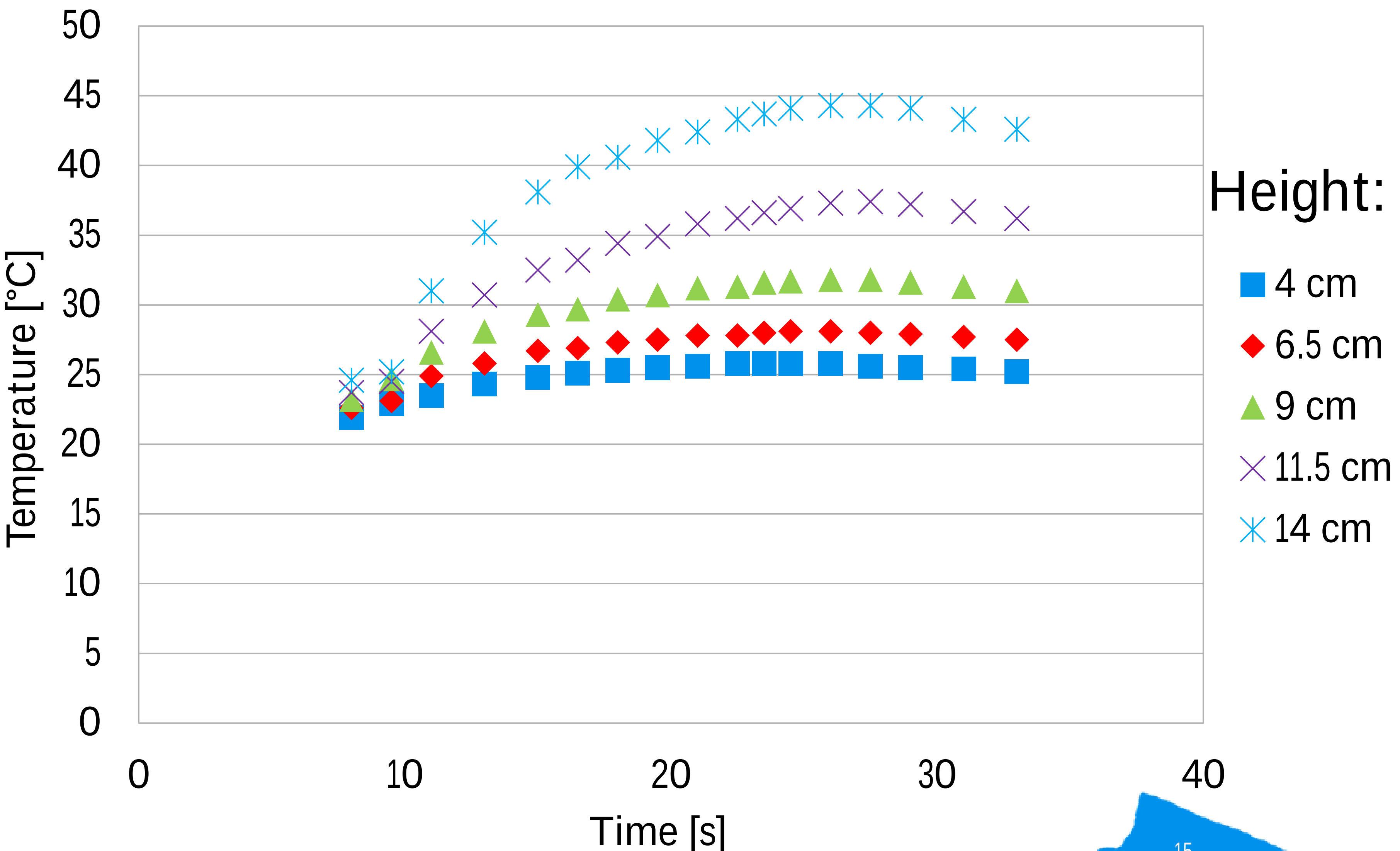
- Complex temperature profile

- Observations:
  - Hot column over the candle
  - Hot air accumulates at the top
  - The rest – slightly warmer than environment

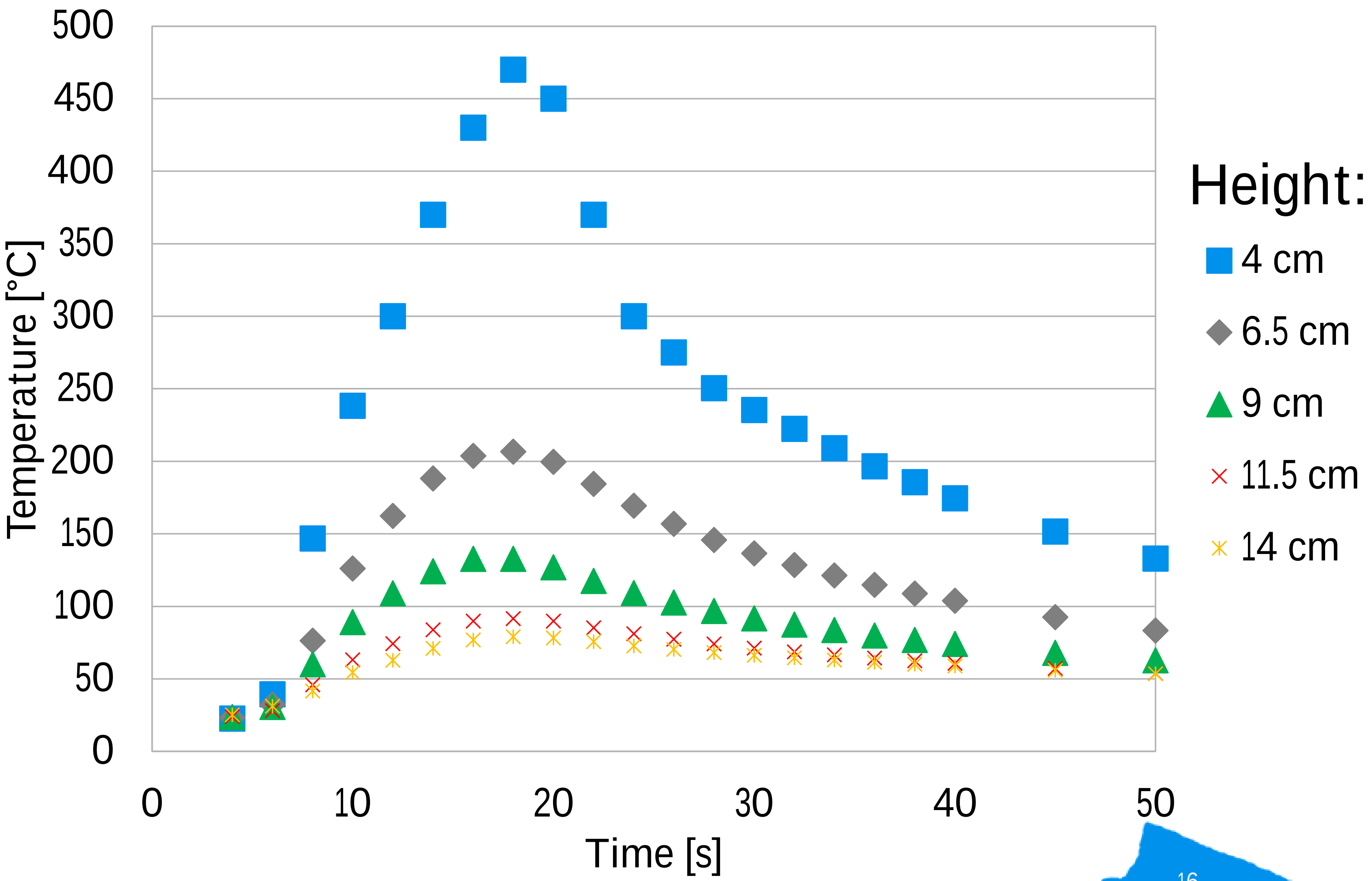
Temperature measurements



Temperatures – 2cm from the wall



Temperatures – over the flame



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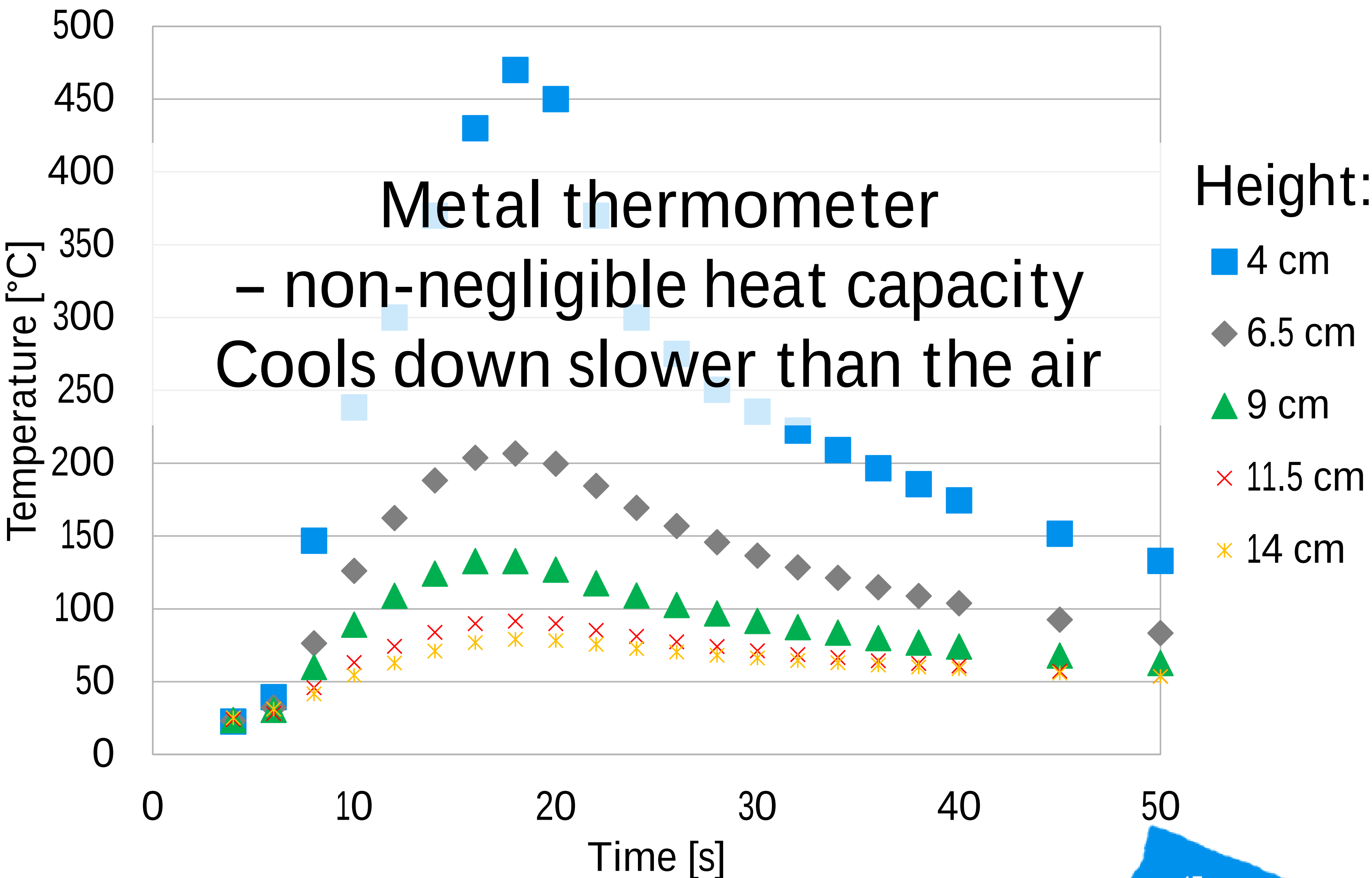
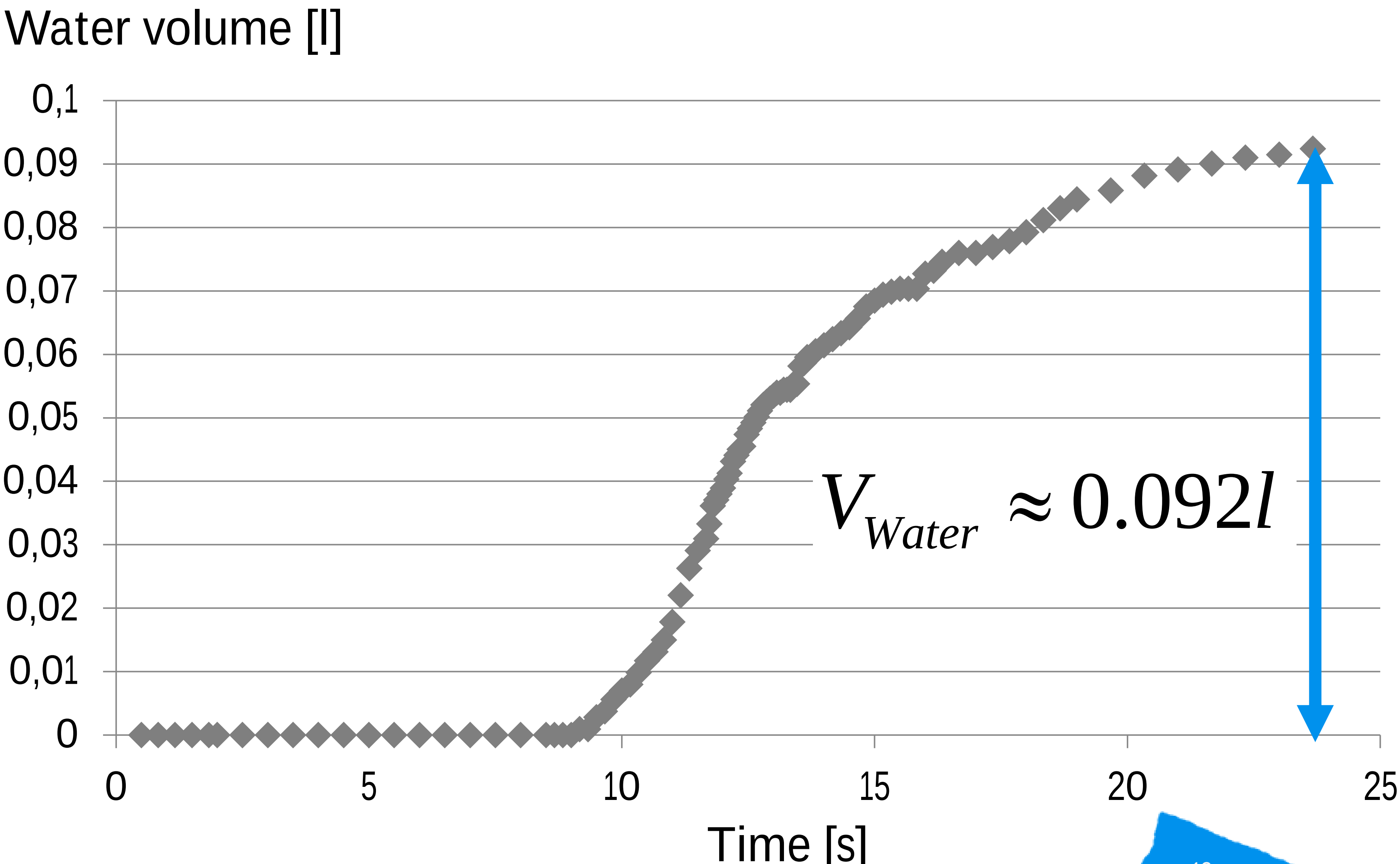


Metal thermometer
– non-negligible heat capacity
Cools down slower than the air

1. IDEAL GAS LAW QUANTITIES

Pressure Temperature **Volume**

Water volume inside the beaker



Volume of water rise

Isobaric process – Gay-Lussac law: $V \propto T$

Before the candle extinction: $V_{Beaker}\,,T_{Max}$

After the water rise: $V_{Beaker}-V_{Water}\,,T_{Env}$

Resulting volume:

$$V_{Water}=V_{Beaker}\left(1-\frac{T_{Env}}{T_{Max}}\right)$$

Volume of water rise

$$V_{Water} = V_{Beaker}\left(1 - \frac{T_{Env}}{T_{Max}}\right)$$

- Maximal average temperature measured: 55°C

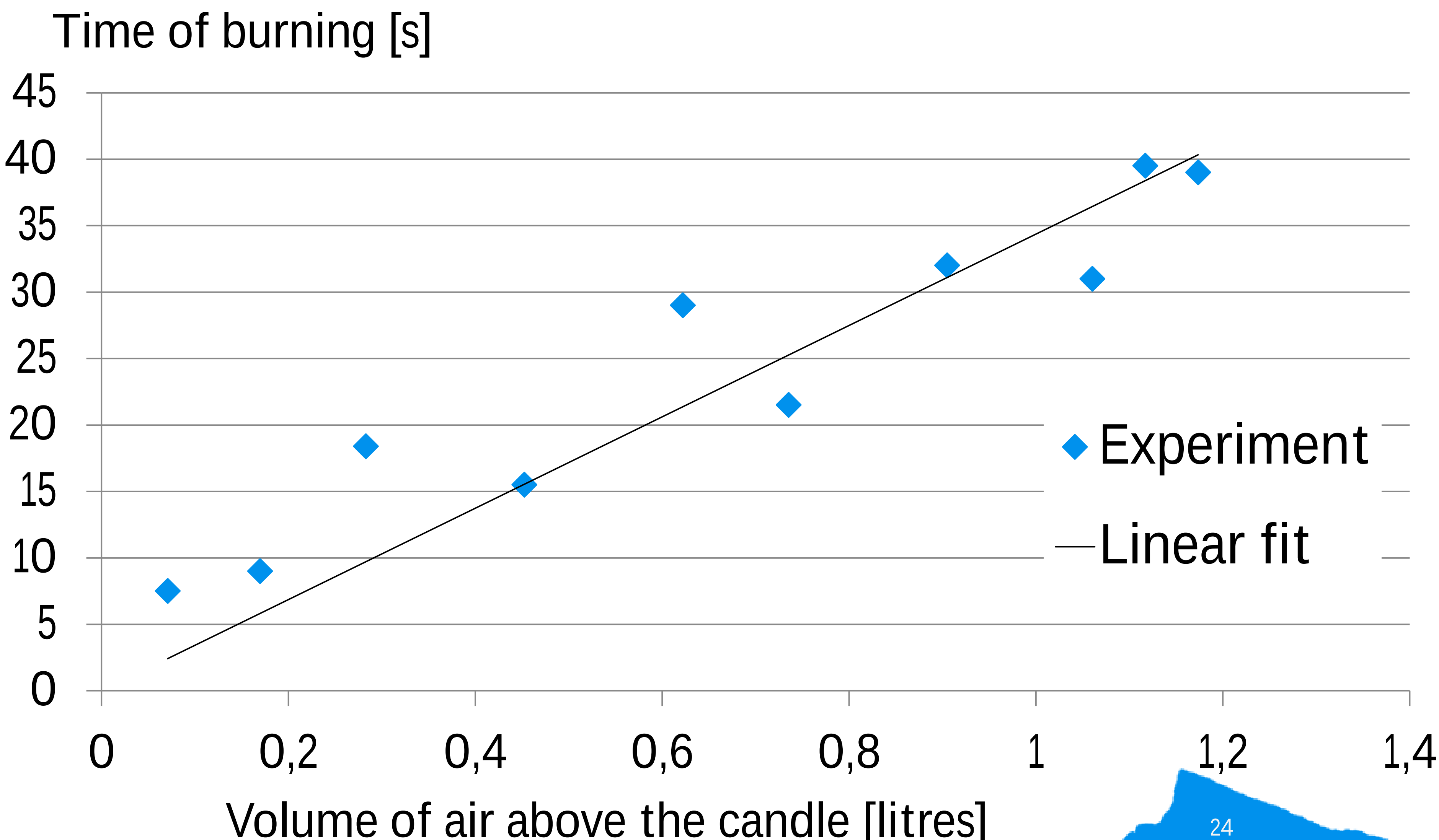
- Experiment: $V_{Water} = 0.092l$
- Based on maximal temperature: $V_{Water} = 0.075l$
  - Difference due to unknown exact temperature profile

2. NUMBER OF MOLECULES

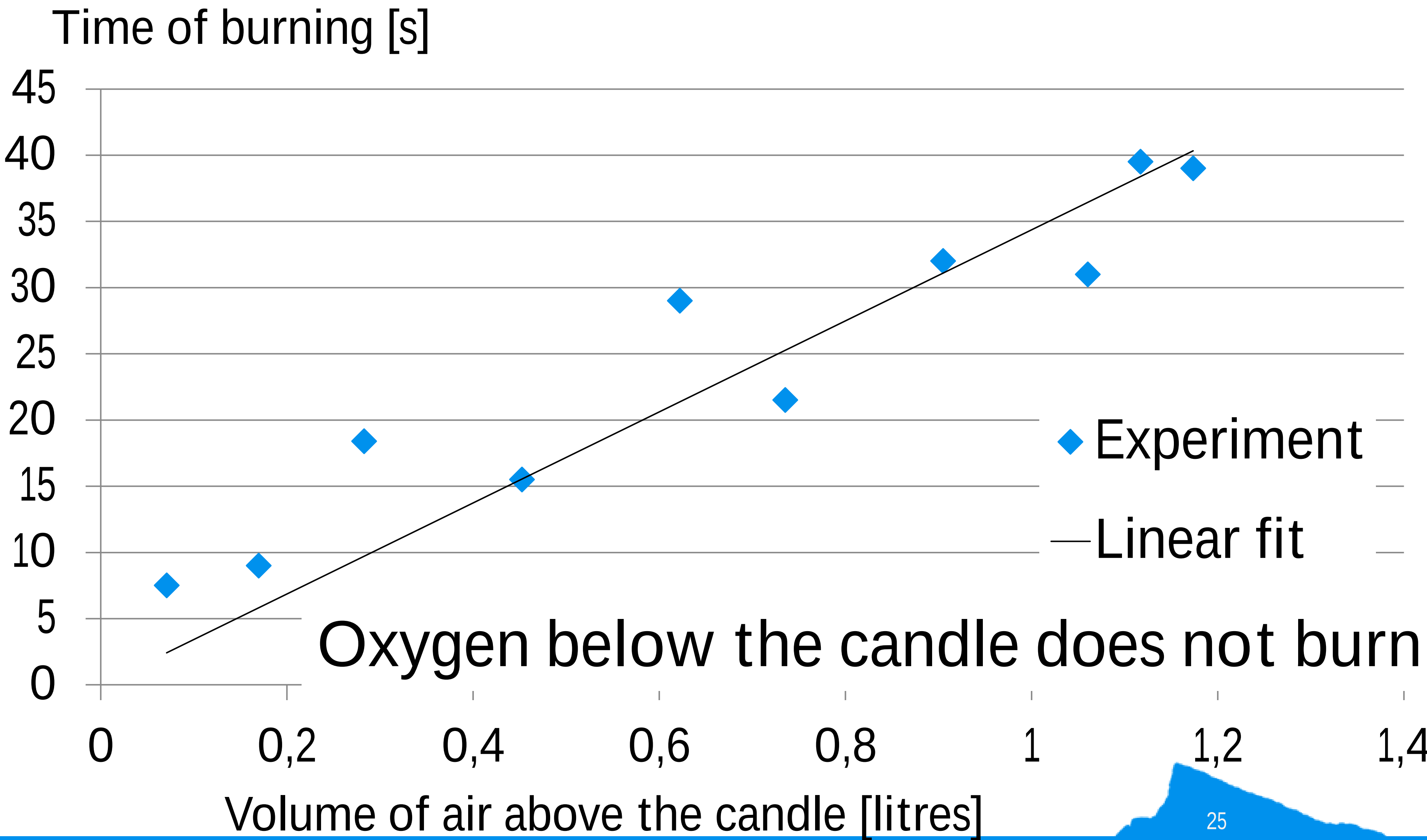
How much oxygen actually burns?

- Measuring cylinder, changing height of the candle
- Changing volume of air above the candle

Time of burning vs. volume of air



Time of burning vs. volume of air



Burned oxygen depending on time

$$C_{25}H_{52} + 38O_2 \rightarrow 25CO_2 + 26H_2O$$

Heat of combustion of paraffin	H = 46MJ/kg
Power of the candle	P = 30W
Ratio of paraffin and O_2 burned	1/38 molecules

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Ratio of paraffin and O_2 burned 1/38 molecules

$$t = \frac{Hm_{par}}{P} \qquad m_{par} = M_{m\ par}\frac{n_{O_2\ burned}}{38}$$

$$n_{O_2\ burned} = 38\frac{Pt}{HM_{m\ par}}$$

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What fraction of the oxygen burns?

Time of burning vs. volume of air

$$n_{O_2\ burned} = 38\frac{Pt}{HM_{m\ par}}$$

Fraction of O_2 in air 21%

Time of burning vs. volume of air

$$n_{O_2\ burned} = 38\frac{Pt}{HM_{m\ par}}$$

Fraction of O_2 in air	21%
Fraction of O_2 burned	k

Time of burning vs. volume of air

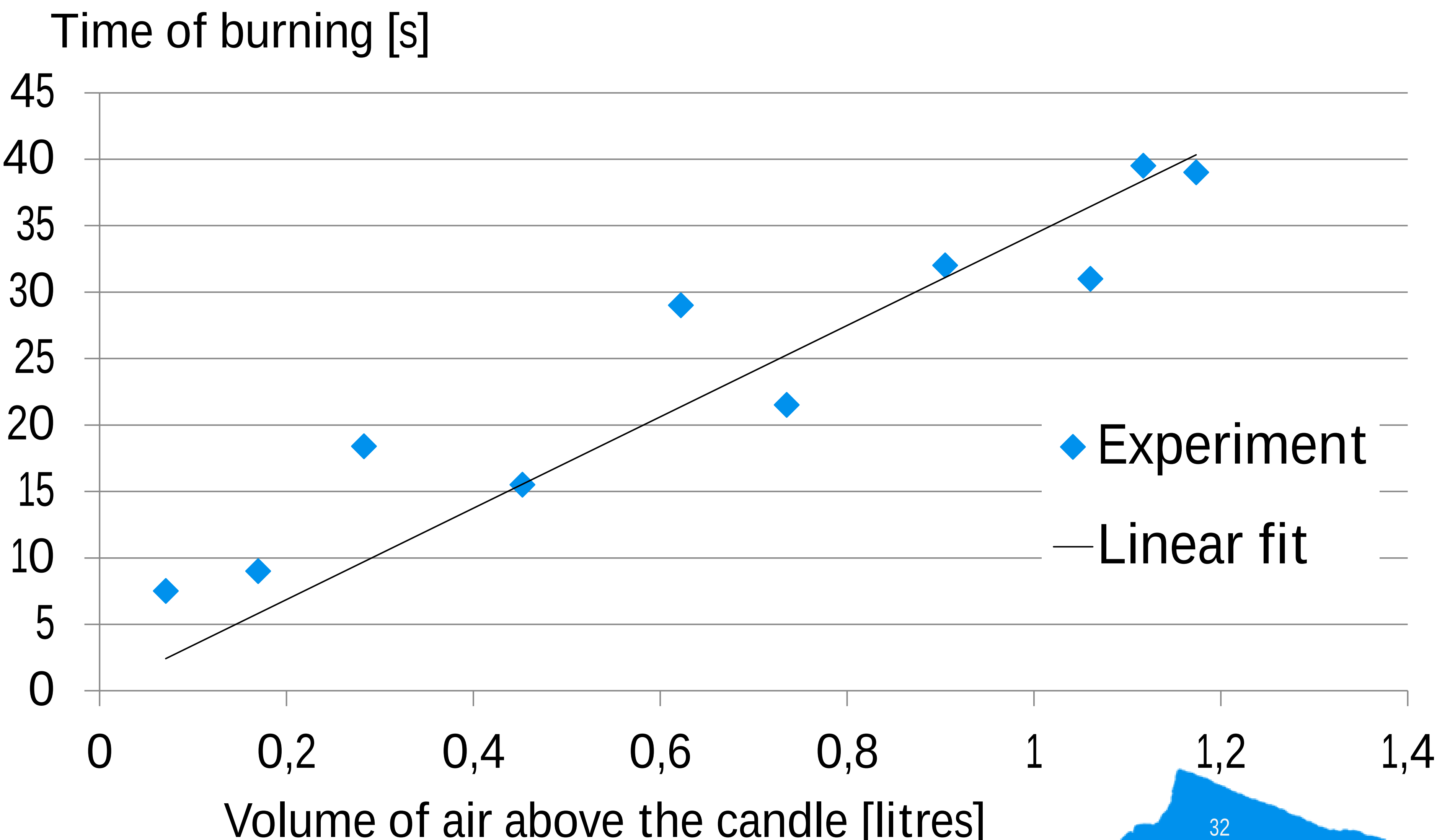
$$n_{O_2\ burned} = 38\frac{Pt}{HM_{m\ par}}$$

Fraction of O_2 in air	21%
Fraction of O_2 burned	k

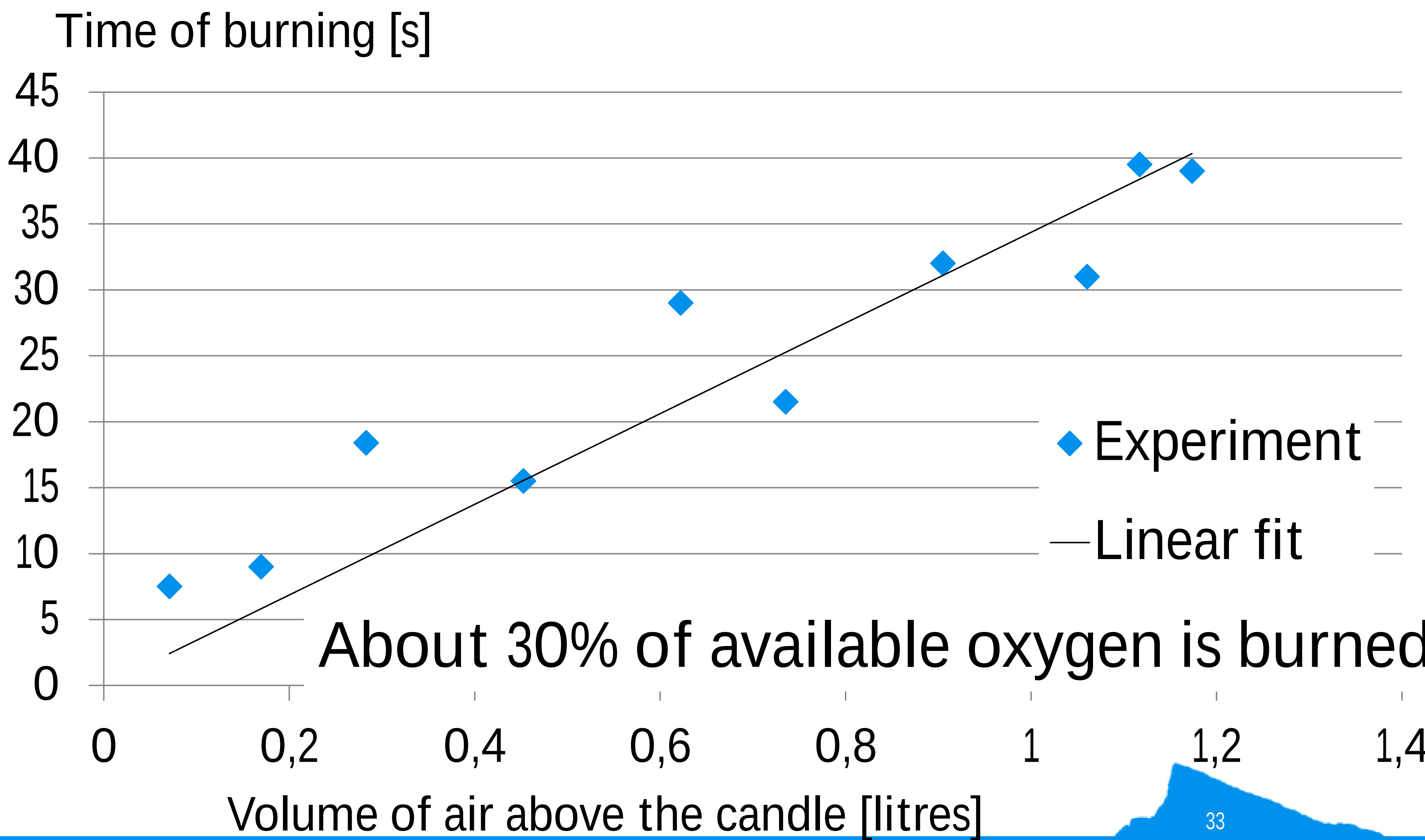
$$n_{O_2\ burned} = k\frac{21}{100}\frac{pV}{RT}$$

$$t = k\frac{21}{3800}\frac{HM_{m\ par}\,p}{PRT}V$$

Time of burning vs. volume of air



Time of burning vs. volume of air



About 30% of available oxygen is burned

Molar number change

Approximately 30% of oxygen burns

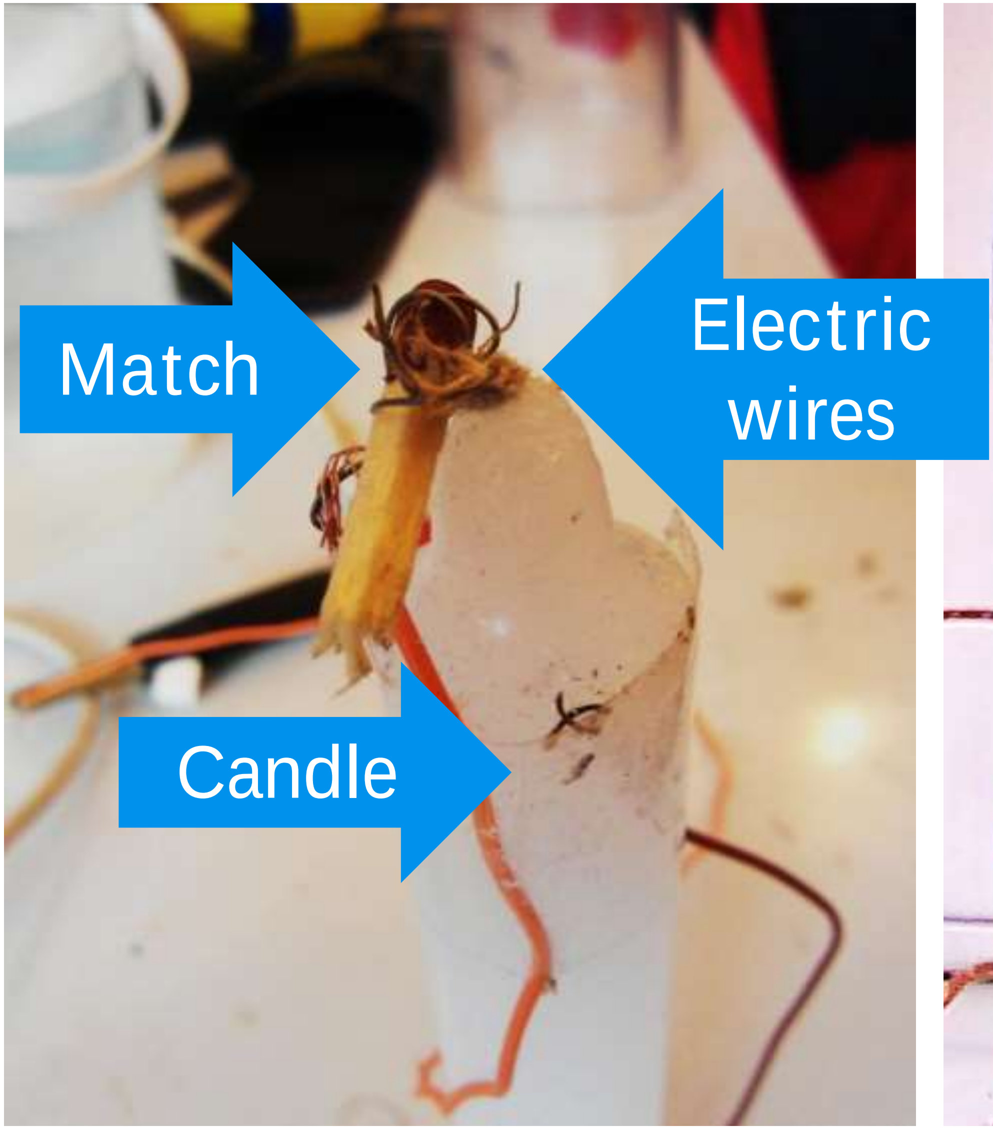
(oxygen comprises about 21% of air)

$$38\,molecules \to 51\,molecules$$

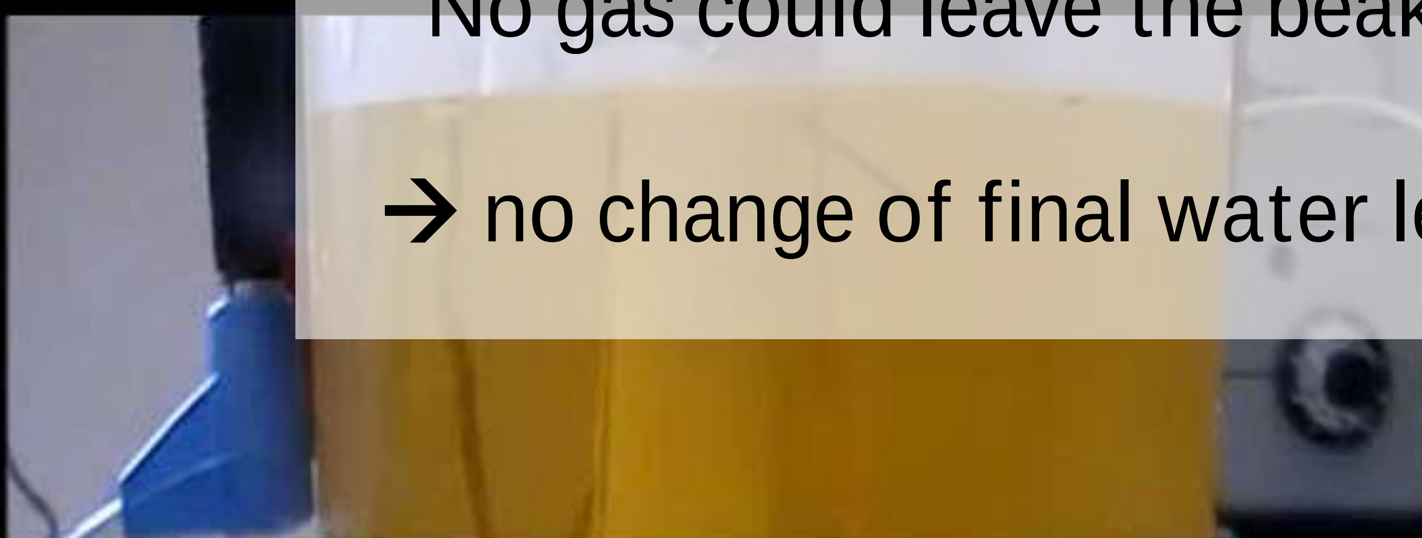
Increase of molar amount ≈ 2%

Change of molar amount is negligible

Experimental proof – no molar change



Experimental proof – no molar change



No gas could leave the beaker

→ no change of final water level

3. ENERGY ANALYSIS

Heat from the candle

- Heats up the air in the beaker
- Losses to the material of the beaker

If the candle burns long enough, equilibrium is reached

How long does it take?

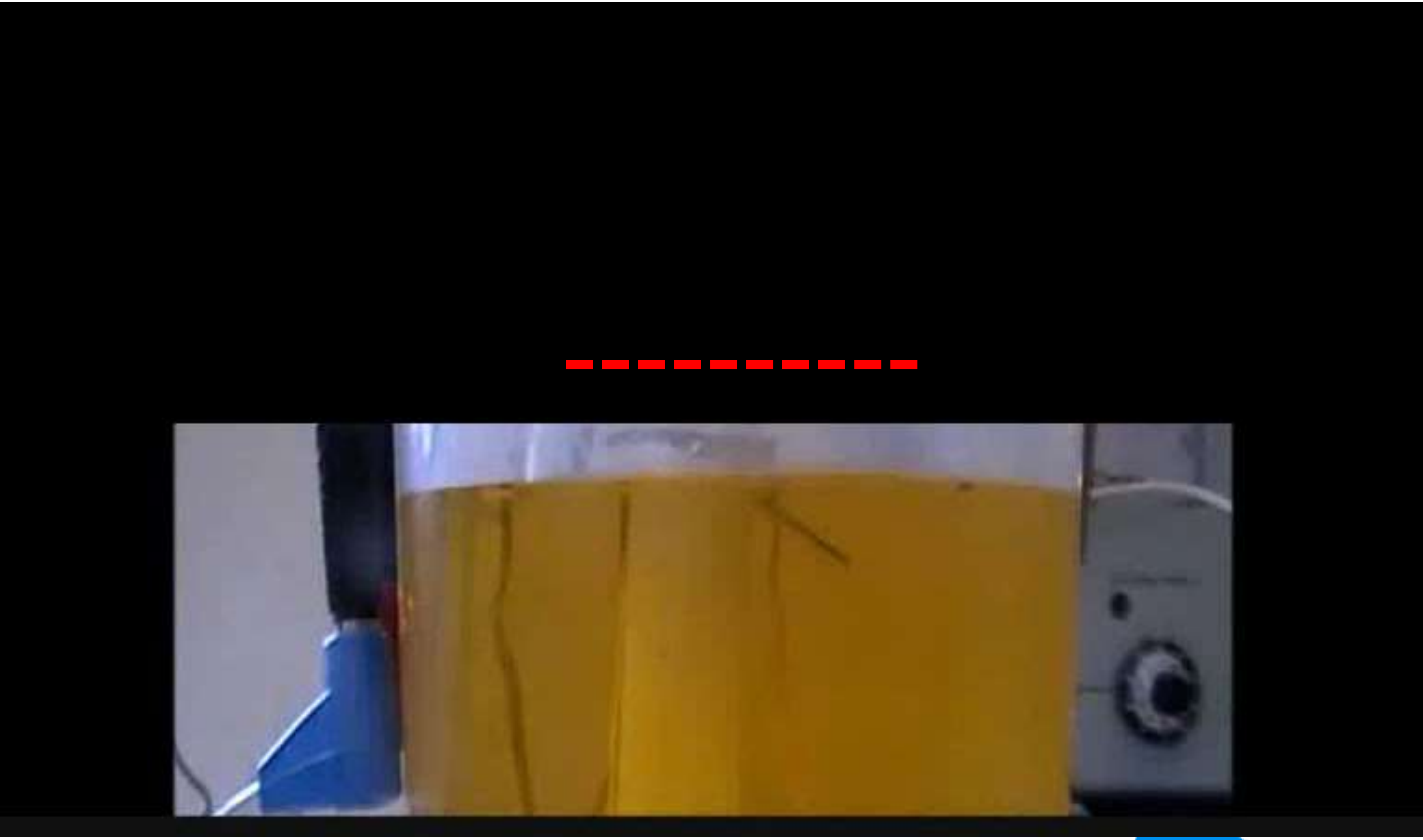
Time to heat up the air

- Power of the candle $P \approx 30\,\mathrm{W}$
- Volume of the air inside $V \approx 0.7\,\mathrm{l}$
- Specific heat capacity $c_P \approx 12.47\,\mathrm{J\,mol^{-1}\,K^{-1}}$
- Change of temperature $\Delta T \approx 75K$
  - Based on water rises during experiments

$$t \approx \frac{Q}{P} \approx \frac{V\rho c_P \Delta T}{PM_m} \approx 0.9s$$

The candle burns much longer
→ Equilibrium is reached

Equilibrium state



Final volume of water rise

- Isobaric process: $$V_{Water} = V_{Beaker} \frac{\Delta T}{T_{env} + \Delta T}$$

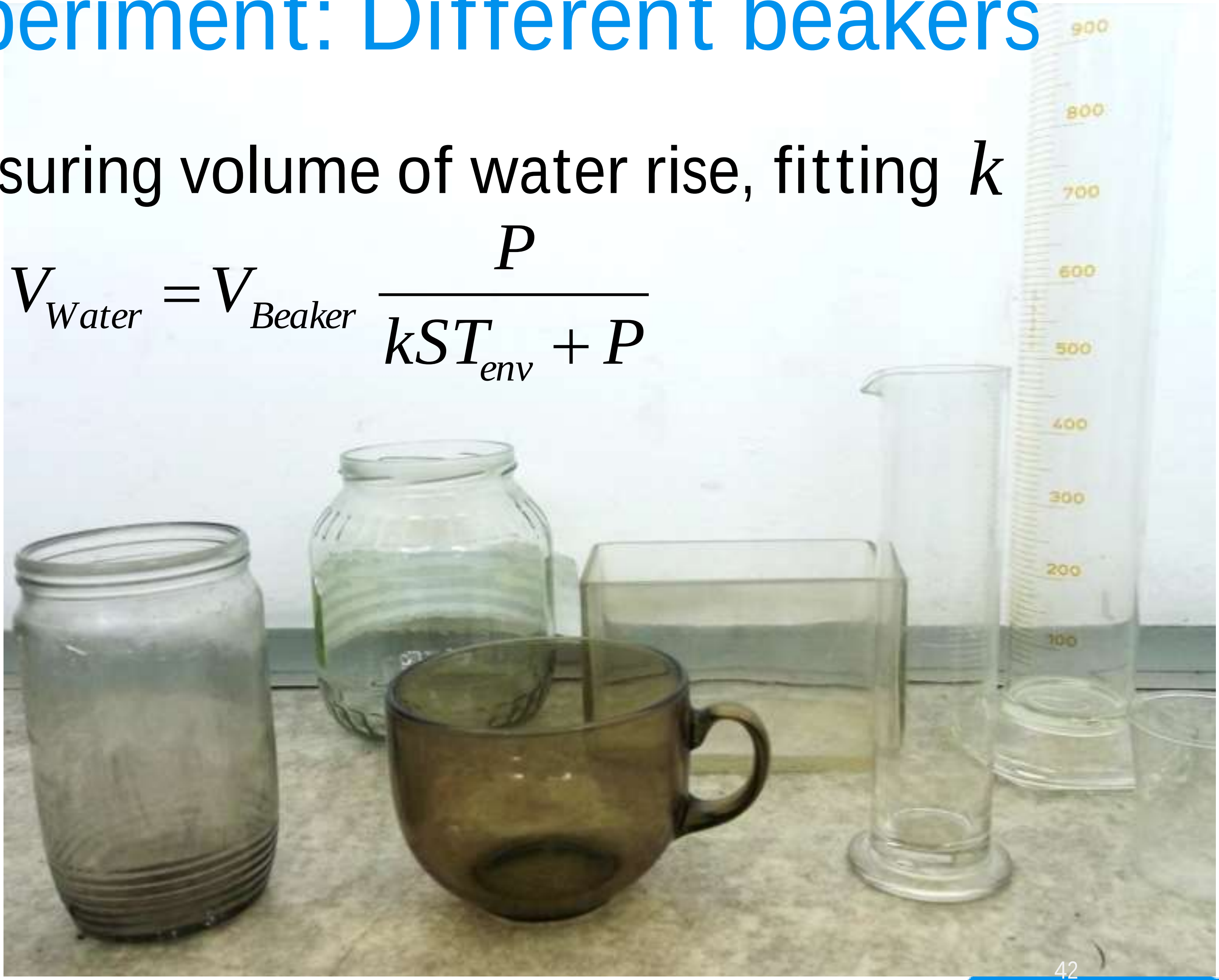
- Losses to the beaker approximation: $P = kS\Delta T$
  - ΔT...temperature difference between air inside and beaker

$$V_{Water} = V_{Beaker} \frac{P}{kST_{env} + P}$$

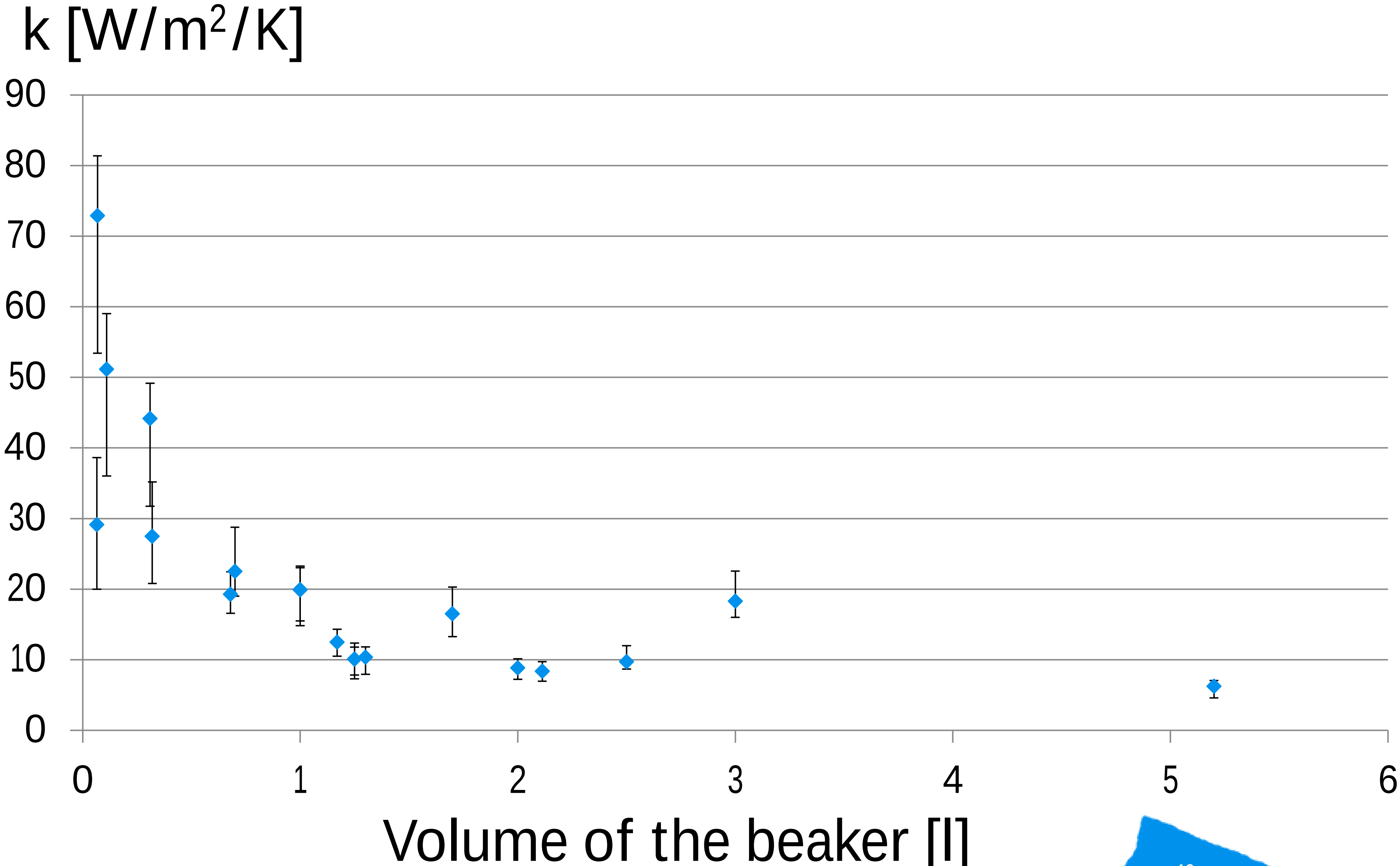
Experiment: Different beakers

Measuring volume of water rise, fitting k

$$V_{Water} = V_{Beaker} \frac{P}{kST_{env} + P}$$



Different beakers: k vs. volume



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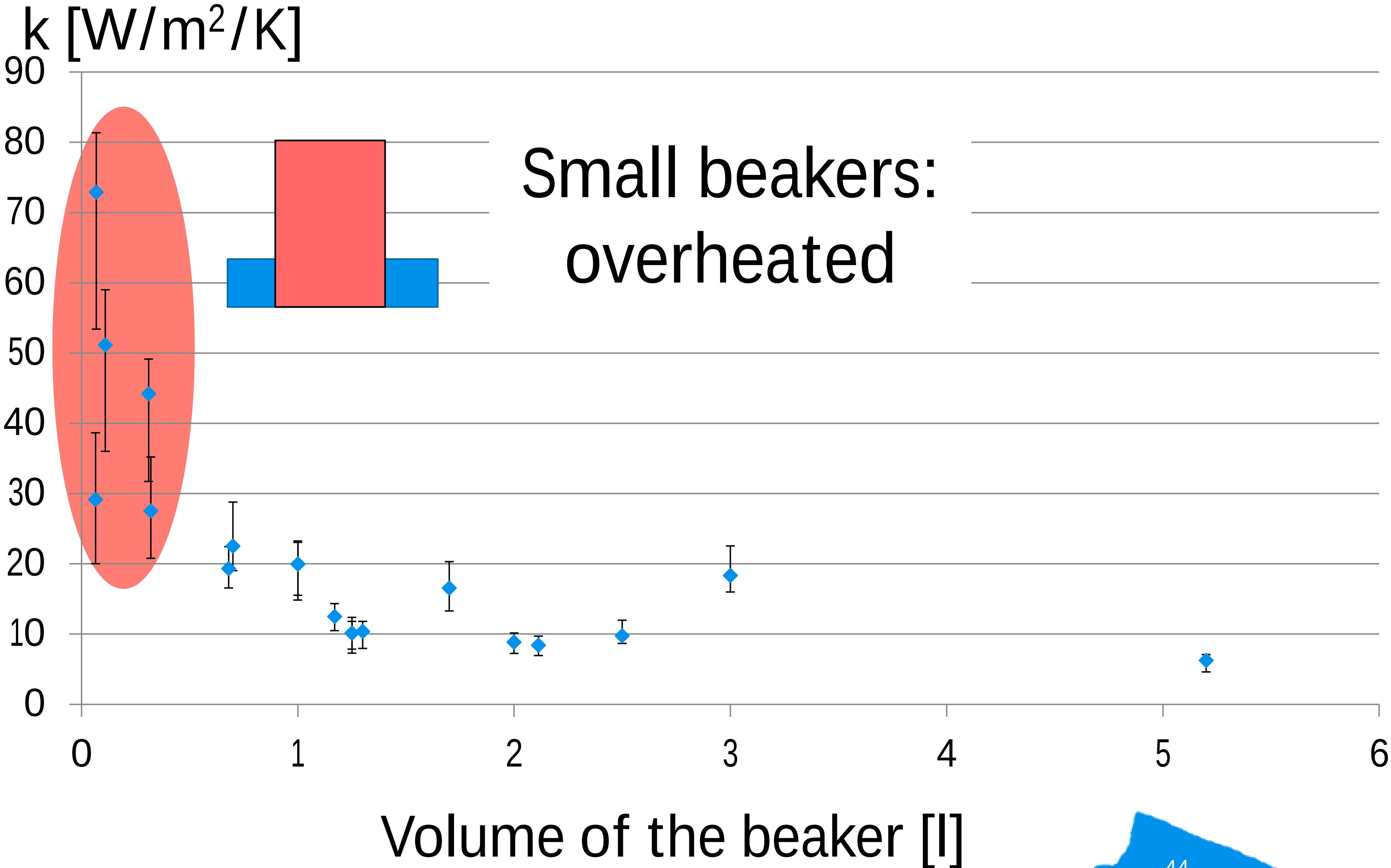

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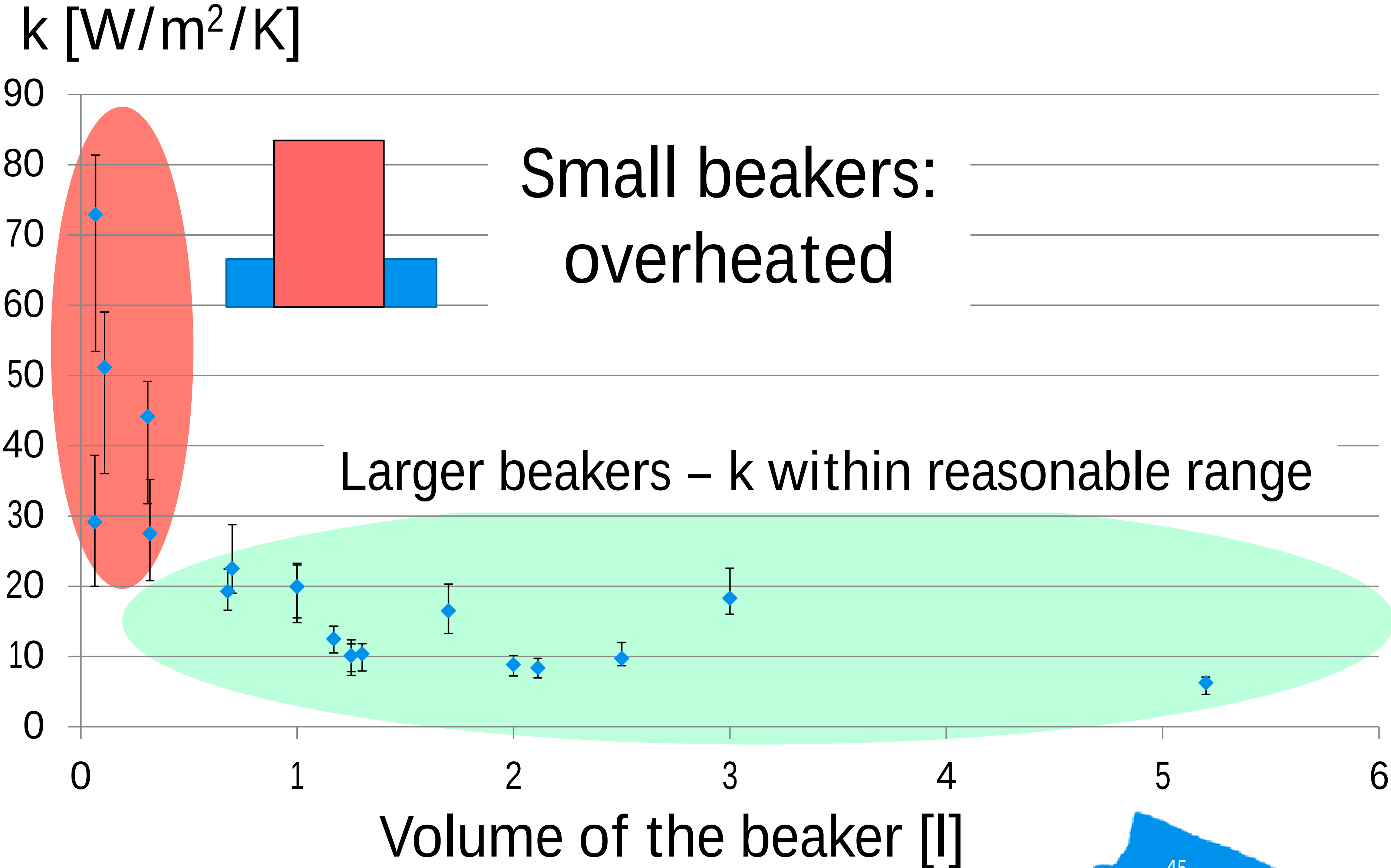
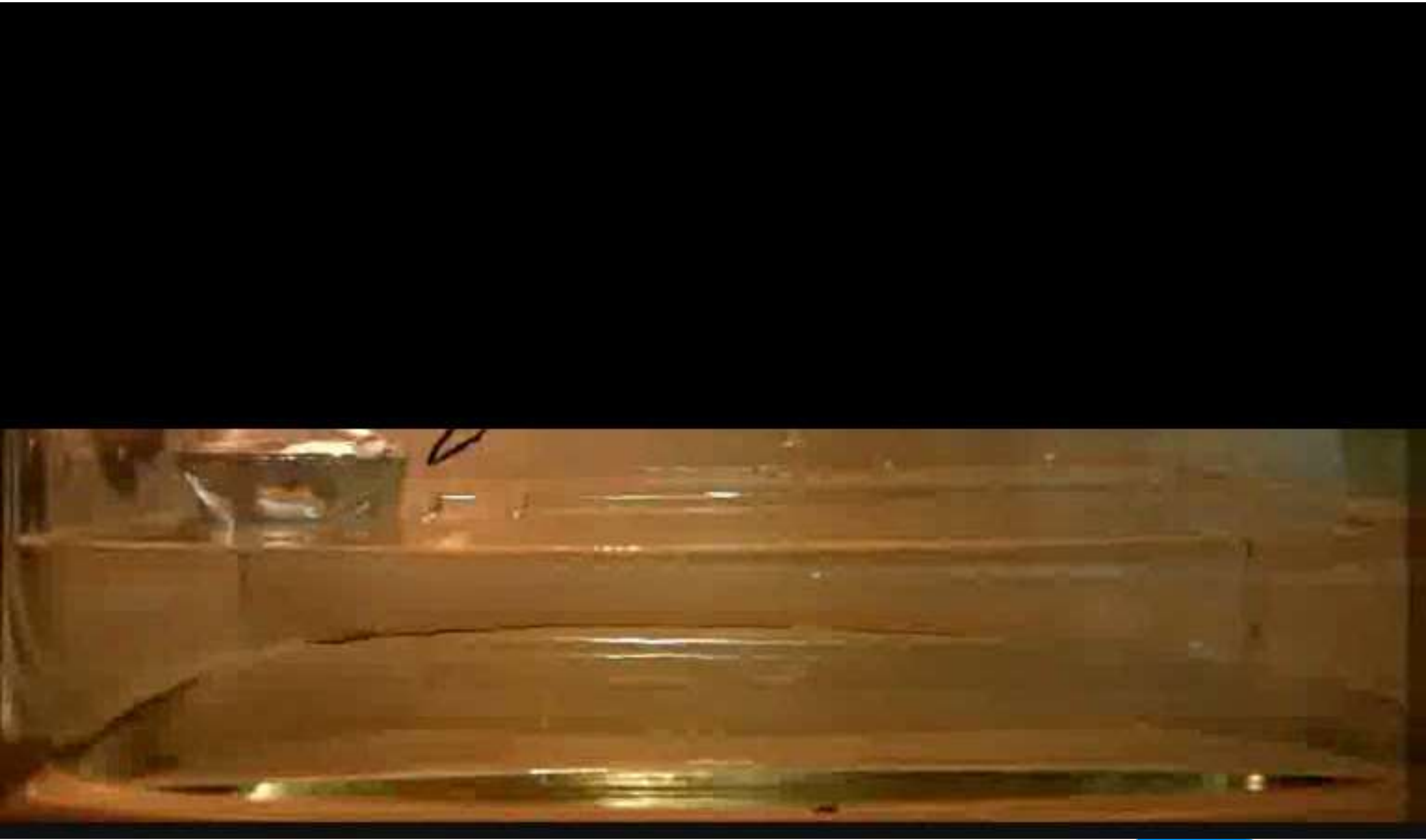


Experiment: changing power

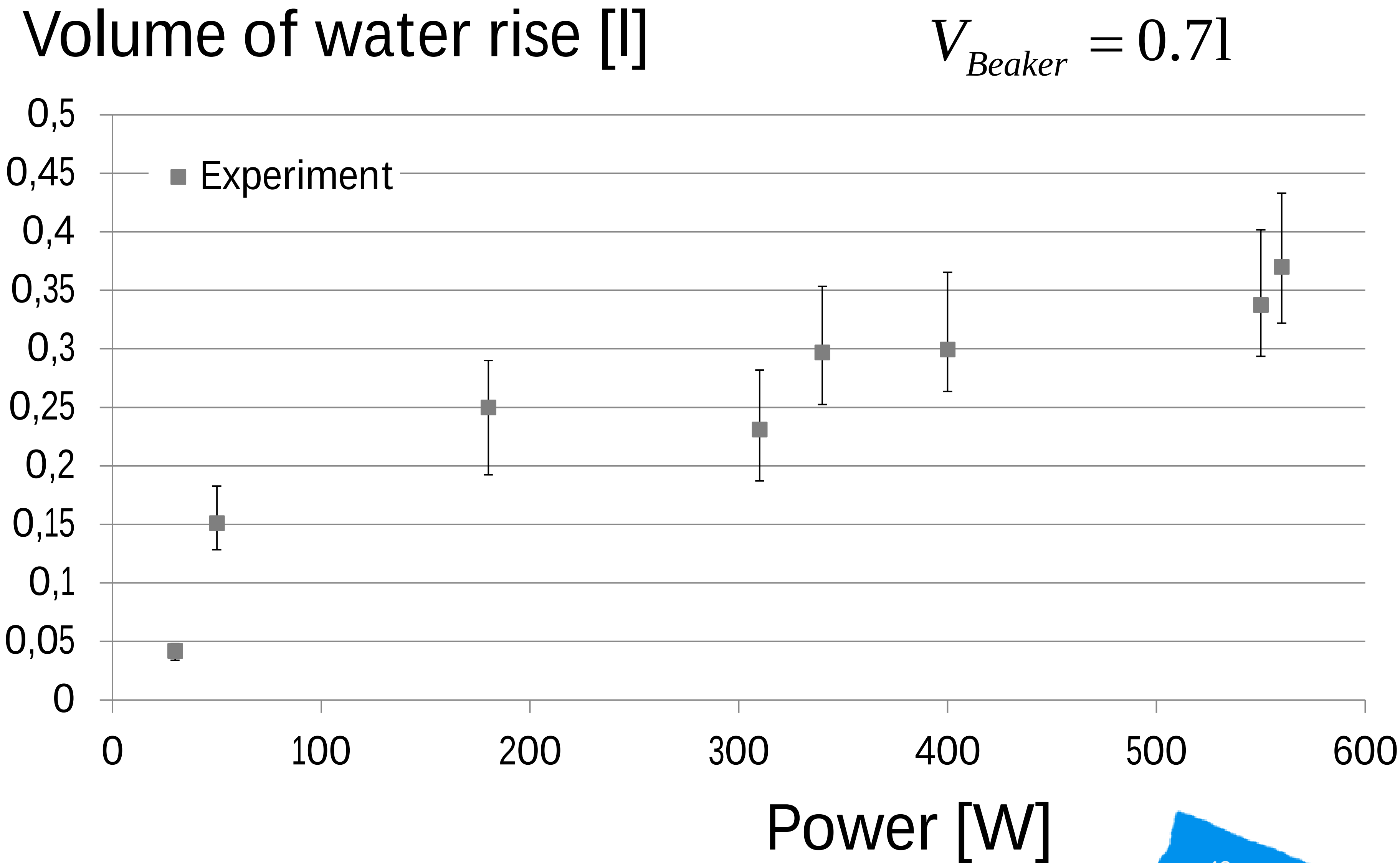
- Using “Pepo,” solid fuel instead of a candle to achieve high powers
- Measuring volume of water rise

High power



Power dependence – glass jar

$$V_{Beaker} = 0.7\,\mathrm{l}$$



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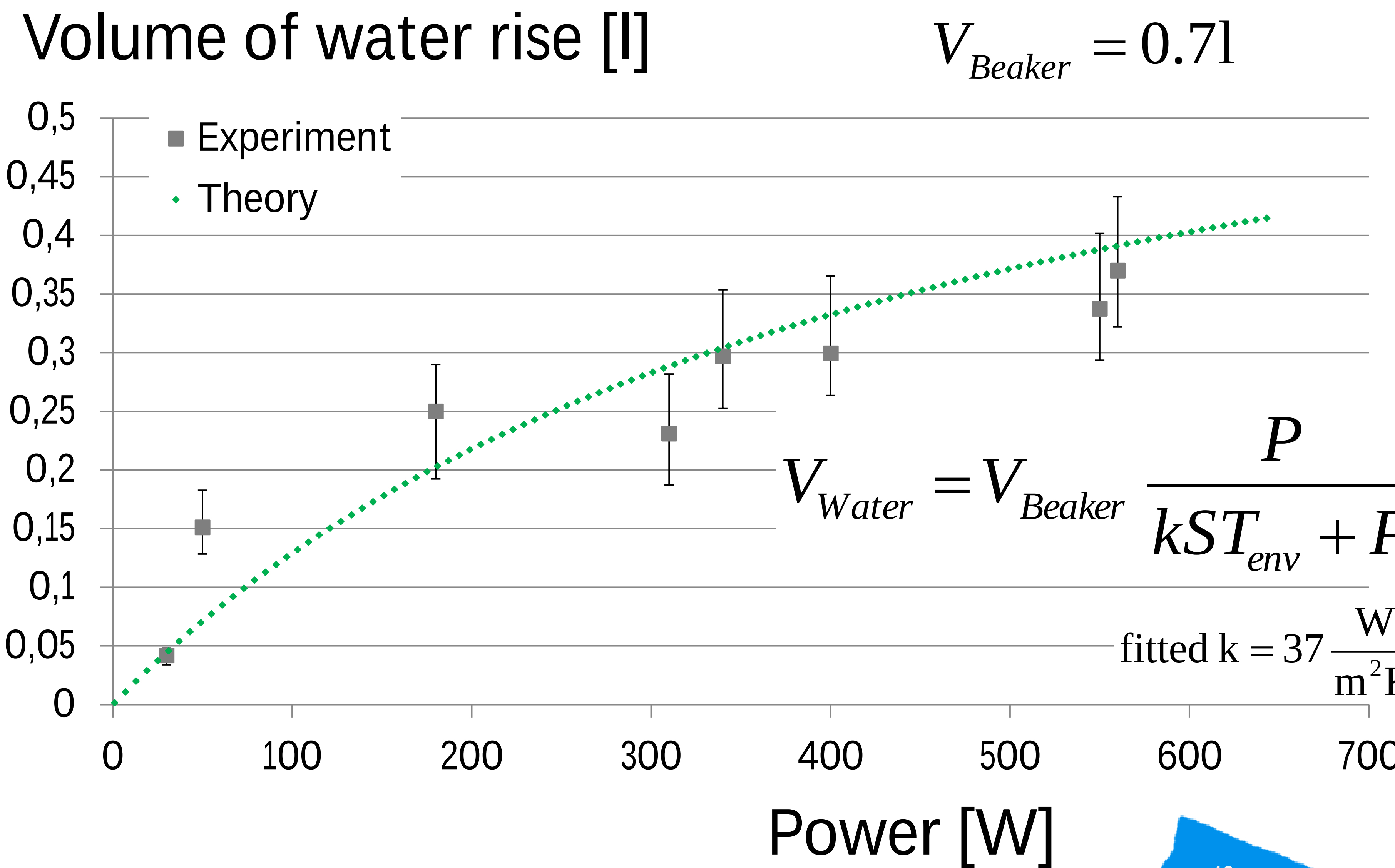
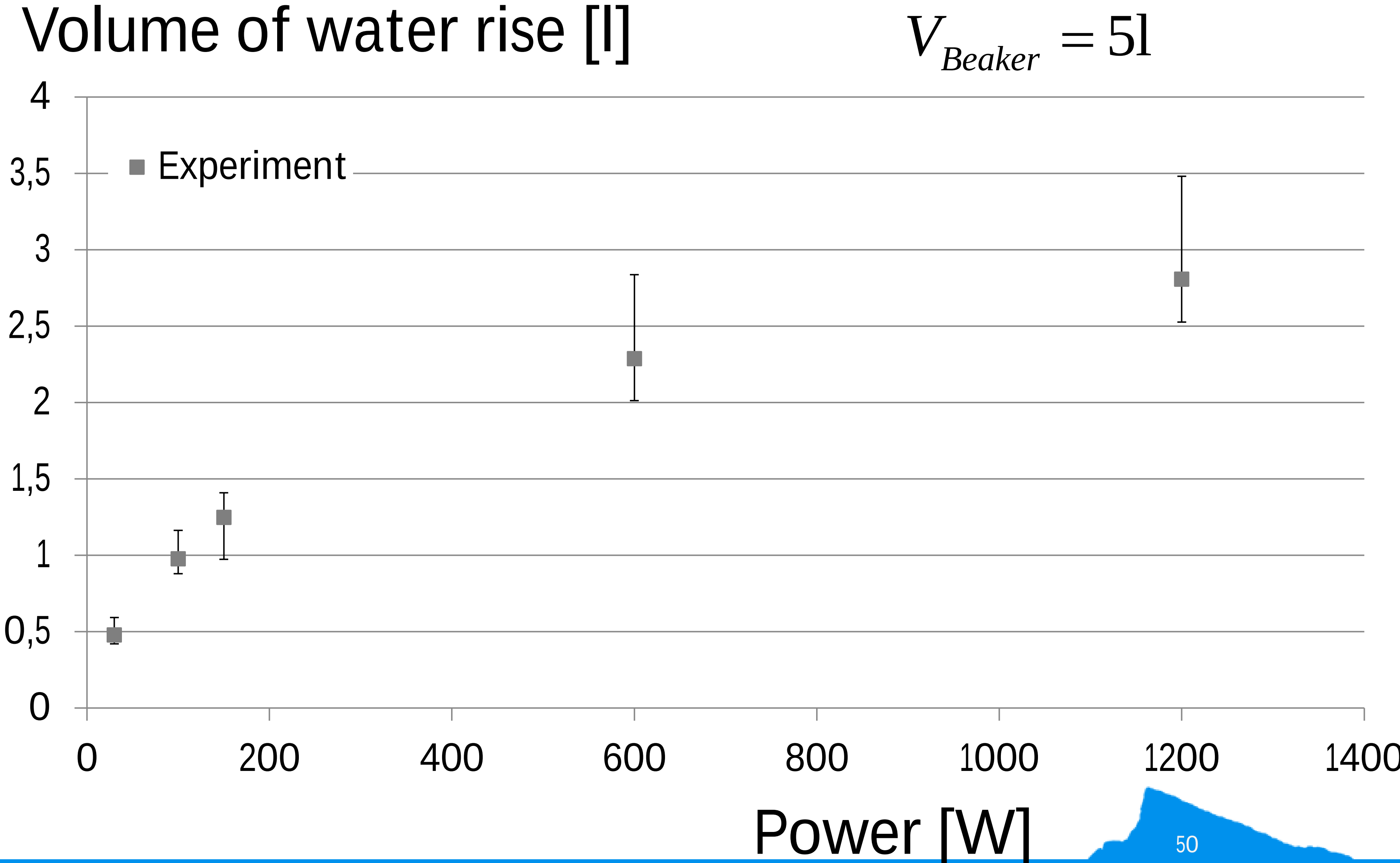


$$V_{Water} = V_{Beaker} \frac{P}{kST_{env} + P}$$

$$\text{fitted k} = 37 \frac{\mathrm{W}}{\mathrm{m^2K}}$$

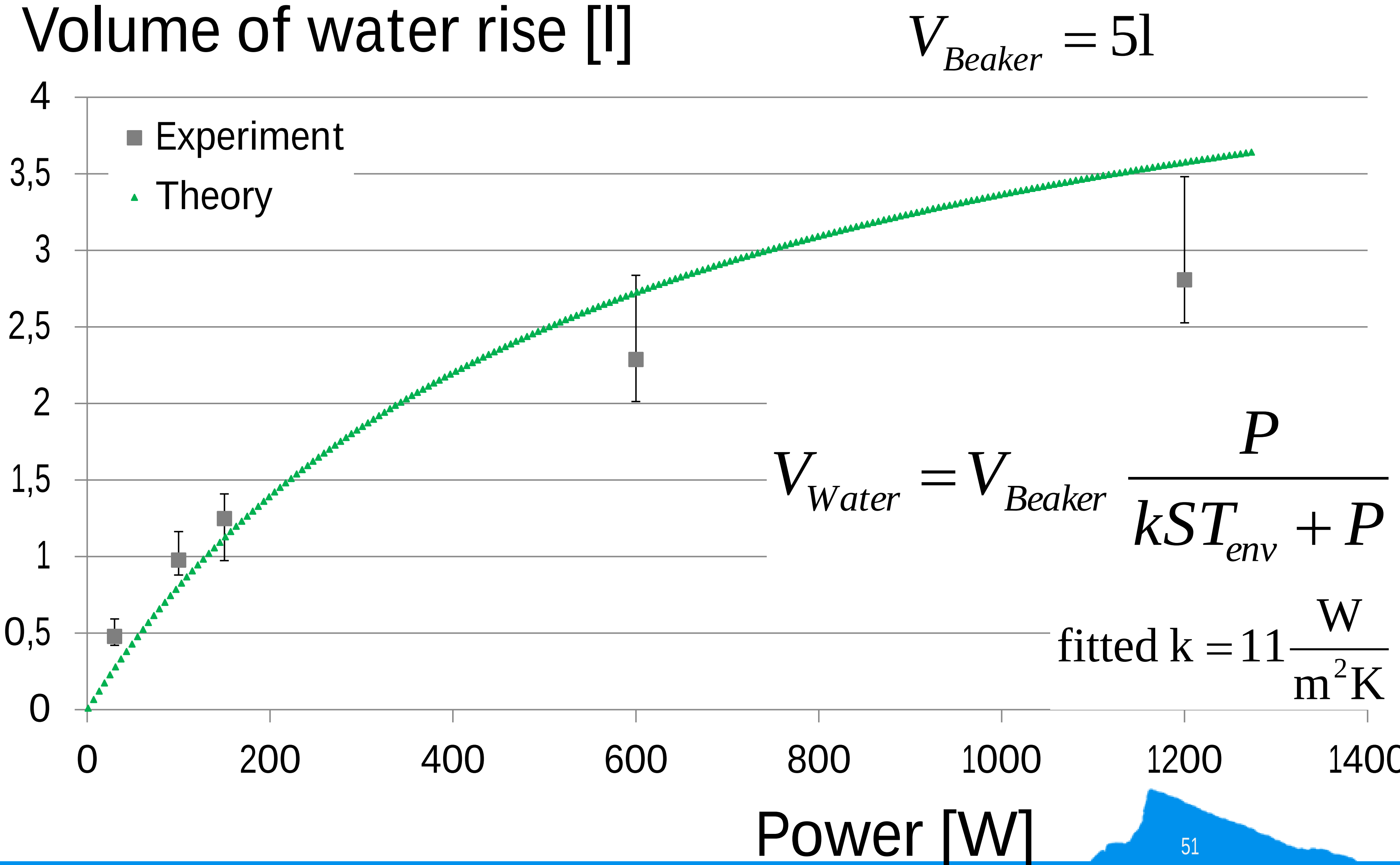
Power dependence – plastic bottle

$V_{Beaker} = 5\text{l}$



Power dependence – plastic bottle

$$V_{Beaker} = 5\,\mathrm{l}$$

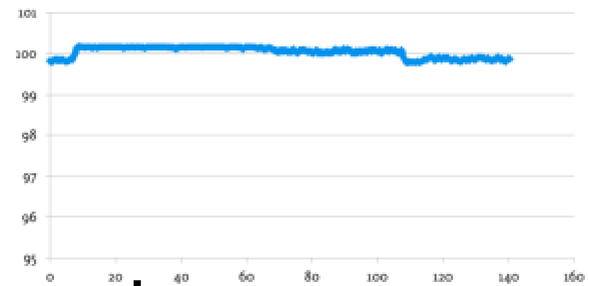


$$V_{Water} = V_{Beaker} \frac{P}{kST_{env} + P}$$

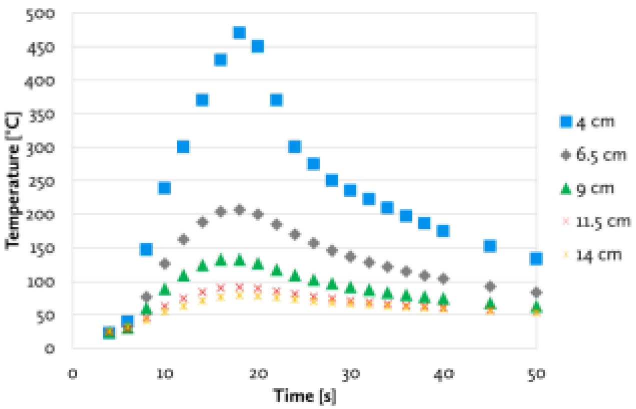
$$\text{fitted k} = 11 \frac{\mathrm{W}}{\mathrm{m^2 K}}$$

Summary – ideal gas law

- Δp is negligible



- Temperature measured



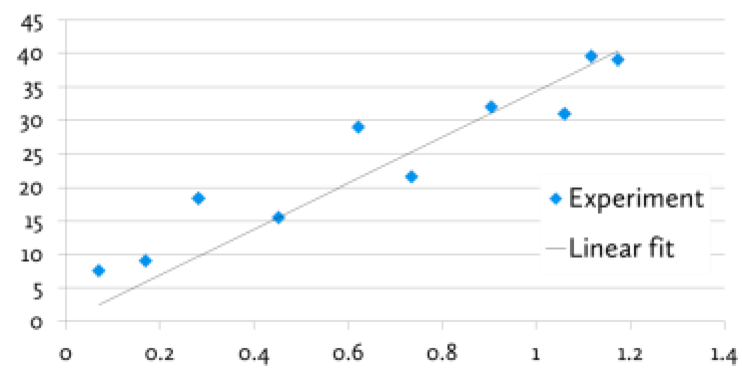
- Volume of water rise measured + calculated

$$V_{Water} = V_{Beaker}\left(1 - \frac{T_{Env}}{T_{Max}}\right)$$

Summary – molar number

Height of candle experiment

- 30% of oxygen above the candle is burned



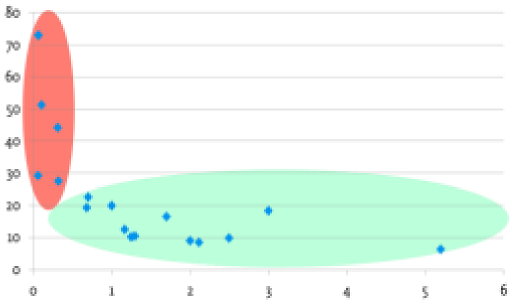
- Molar number does not change significantly

Summary – energy analysis

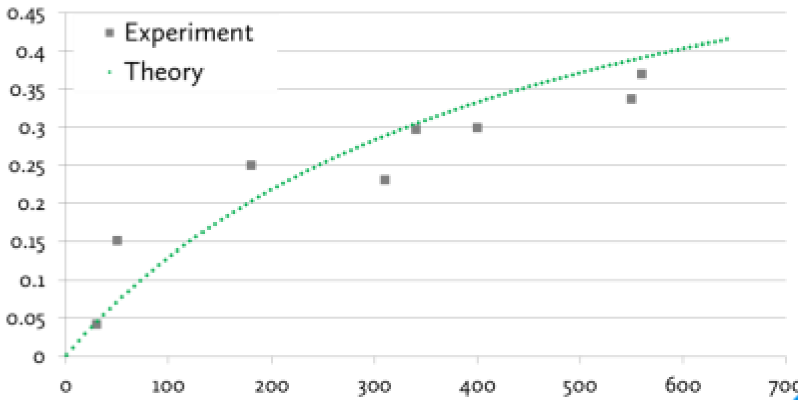
- Equilibrium state is quickly achieved

$$V_{Water} = V_{Beaker} \frac{P}{kST_{env} + P}$$

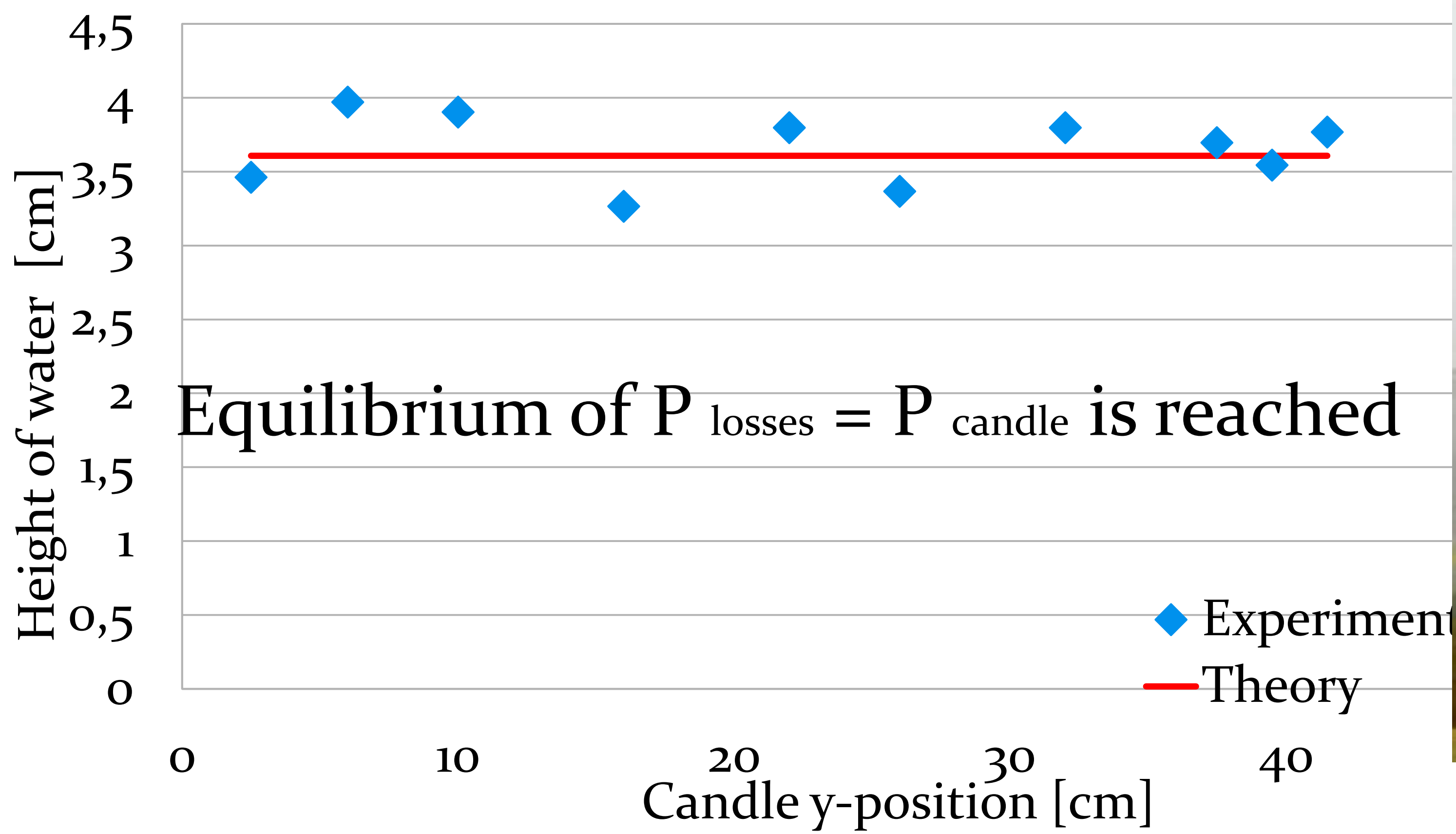
- Different beakers



- Solid fuel used to enhance power



Water rise from y-position of candle



Equilibrium of P $_{losses}$ = P $_{candle}$ is reached

Thank you for your attention

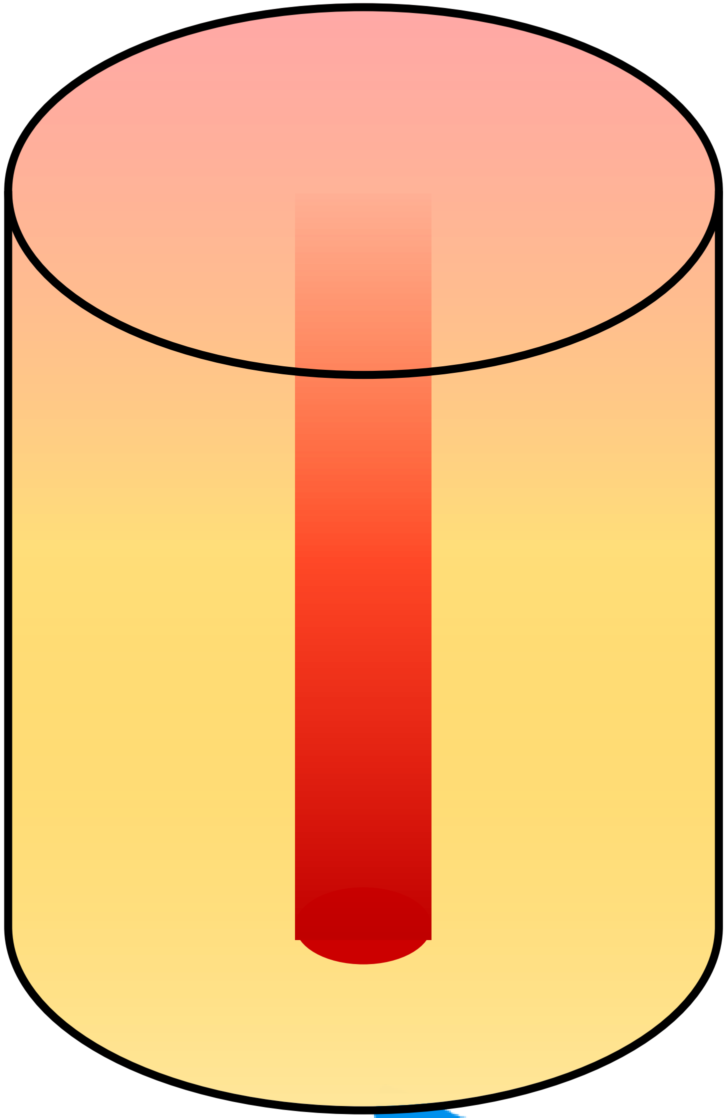
- Theoretically and experimentally proved:
  - Gas pressure & amount changes are negligible
- Temperature changes are crucial
- Complex temperature profile measurement
- Quantitative predictions of water rise and time of burning from all relevant parameters
  - Power, beaker volume, position of candle
  - Experimentally proved

Temperature profile

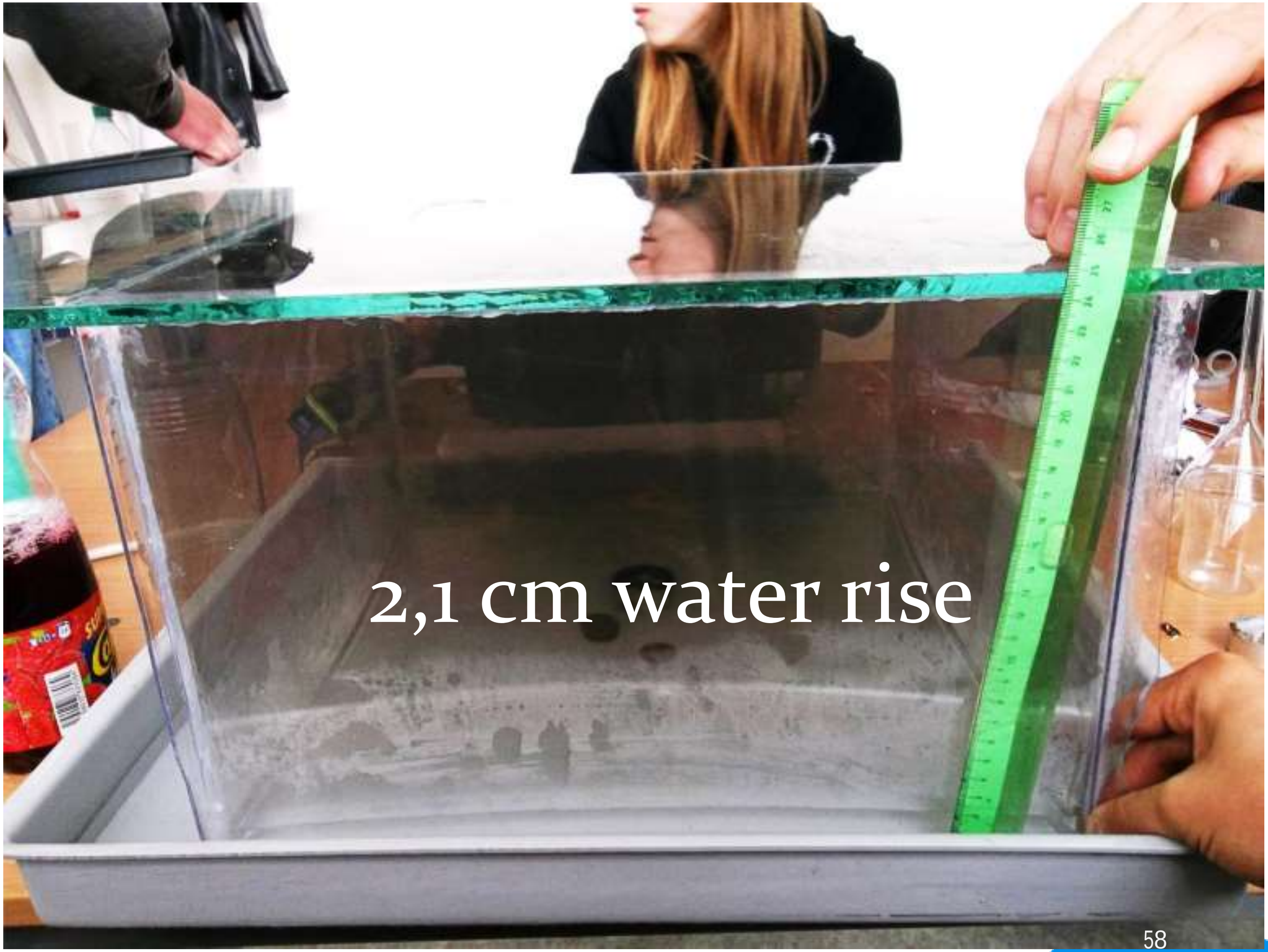
- At the top (50 °C)
- - everywhere the same

- Over the candle (300 °C)
- - thin column of hot air

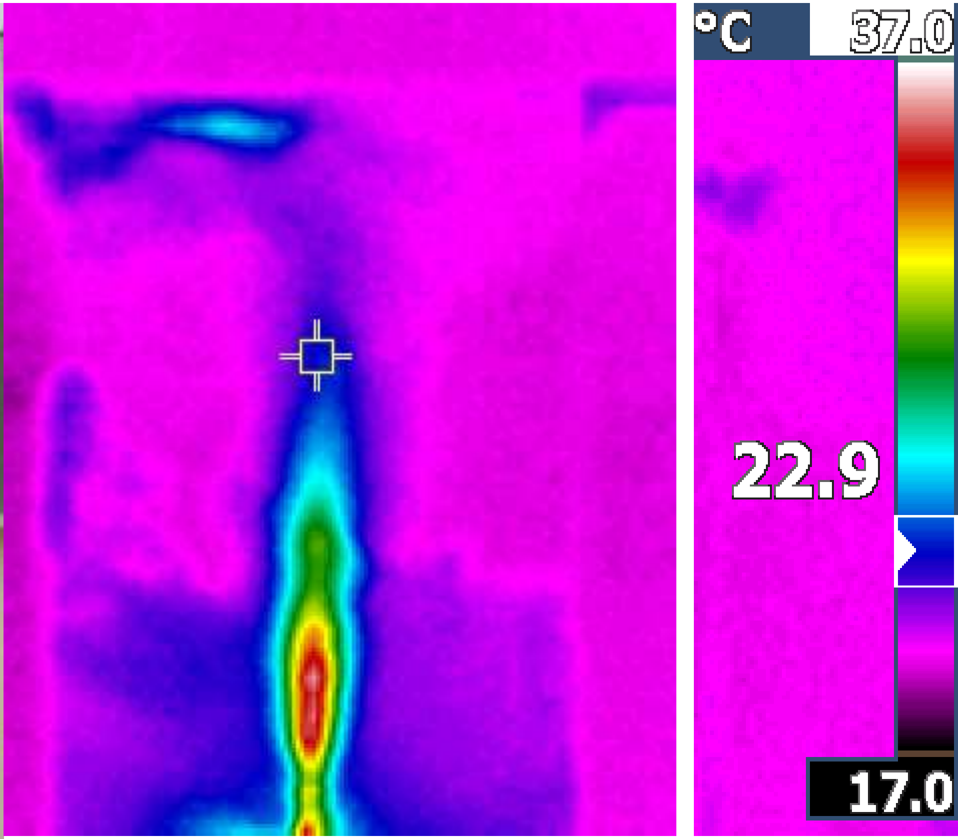
- Everywhere else (30 °C)
- - only a slight change



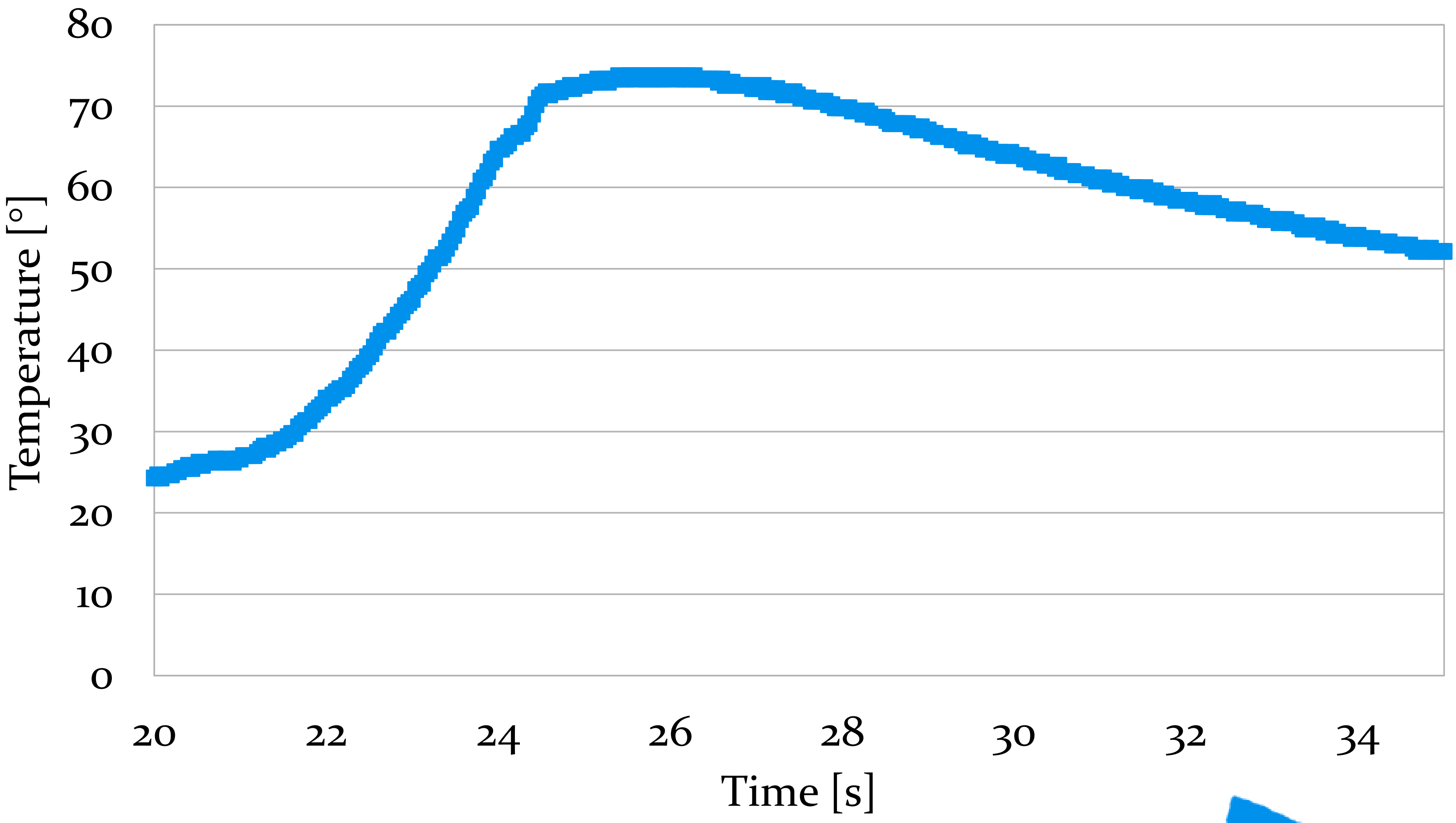
Largest "beaker" 37 x 37 x 25 cm



Visualization of hot column



Temperature goes constant



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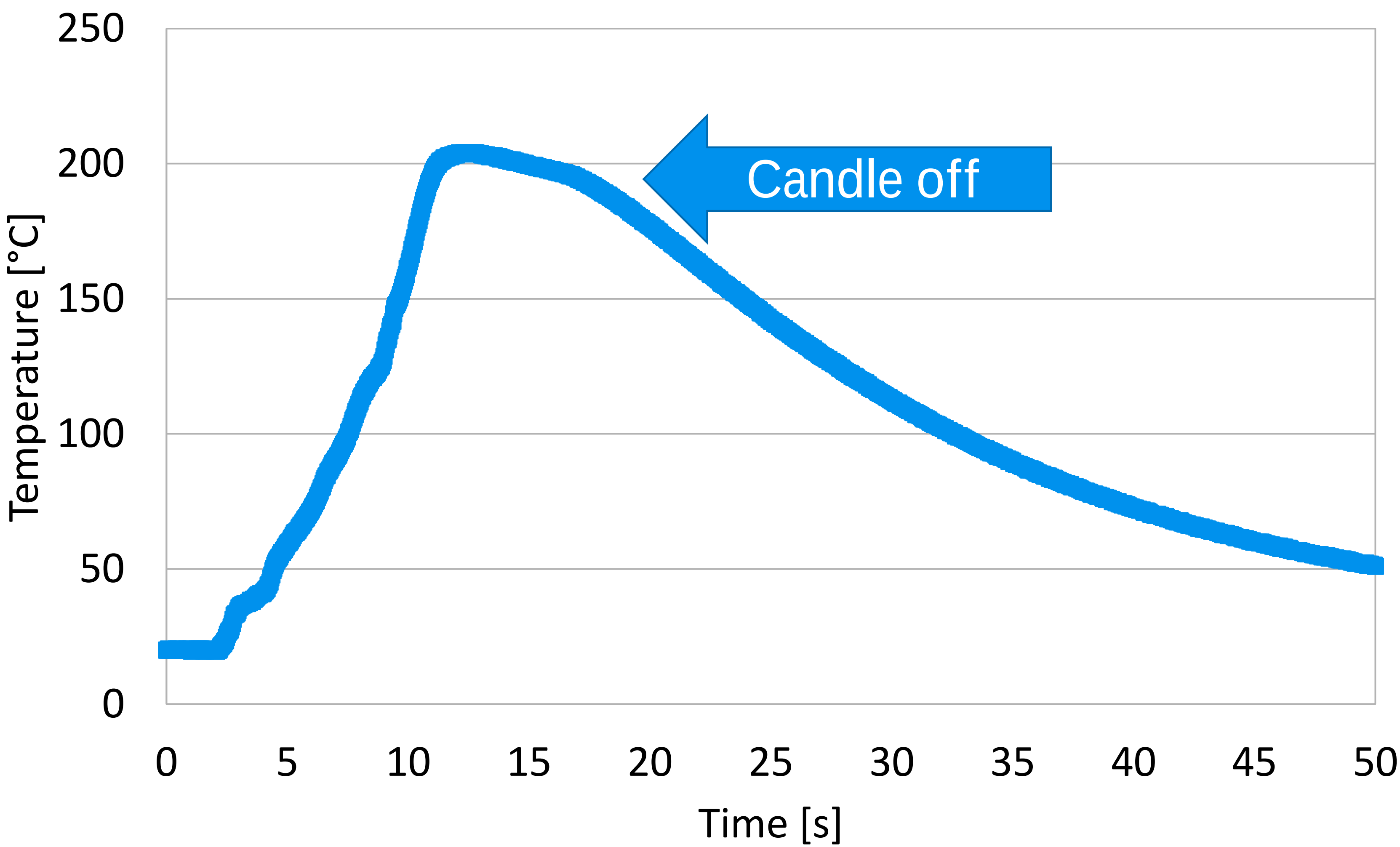

Temperature profile measurement

					°C
20			60		
17		80	100	80	
13	70	85	140	85	70
10	70	90	167	90	70
7	60	140	250	140	60
4	55	100	370	100	55
1	40	90	500	90	40
cm	-2	-1	0	1	2

- Max. temperatures measured
- Hot air forms very thin column
- Warm air forms a cone