Co-funded by the Erasmus+ Programme of the European Union

5. Synchronised Candles

5. Synchronizované sviečky

34th IYPT 2021

5. Synchronised Candles

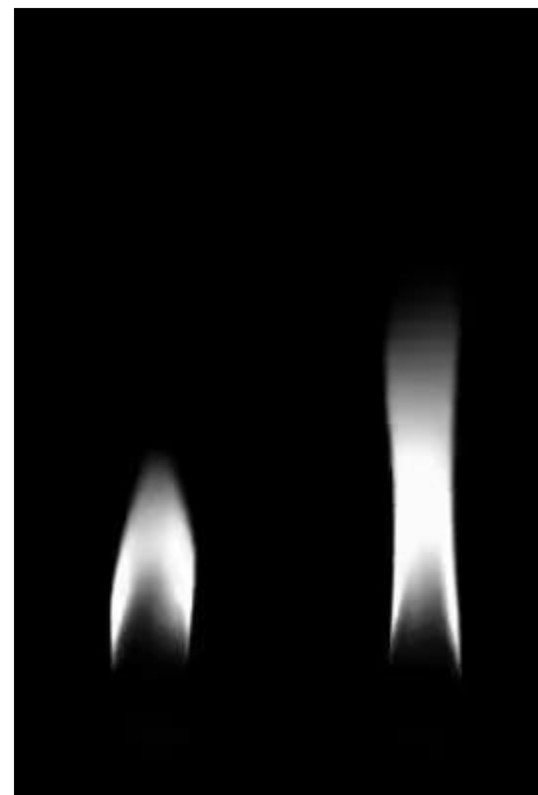
Oscillatory flames can be observed when several candles burn next to each other. Two such oscillators can couple with each other, resulting in in-phase or anti-phase synchronisation (depending on the distance between the sets of candles). Explain and investigate this phenomenon.

anti-phase synchronisation

Slow motion video
~ 15x (11 Hz)

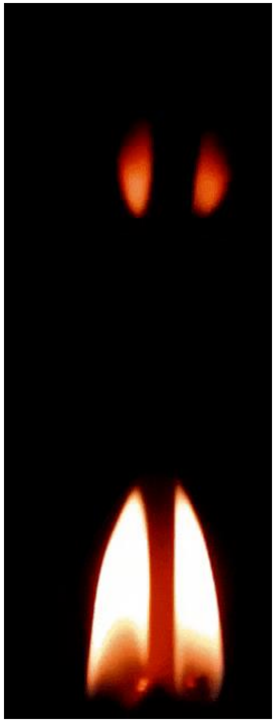
in-phase synchronisation

[Chen2019]



Candle oscillators

Several candles –> oscillatory flames = > at least 2 candles in bundle - > candle oscillator



2 candles

4-candles oscillator

10-candles oscillations

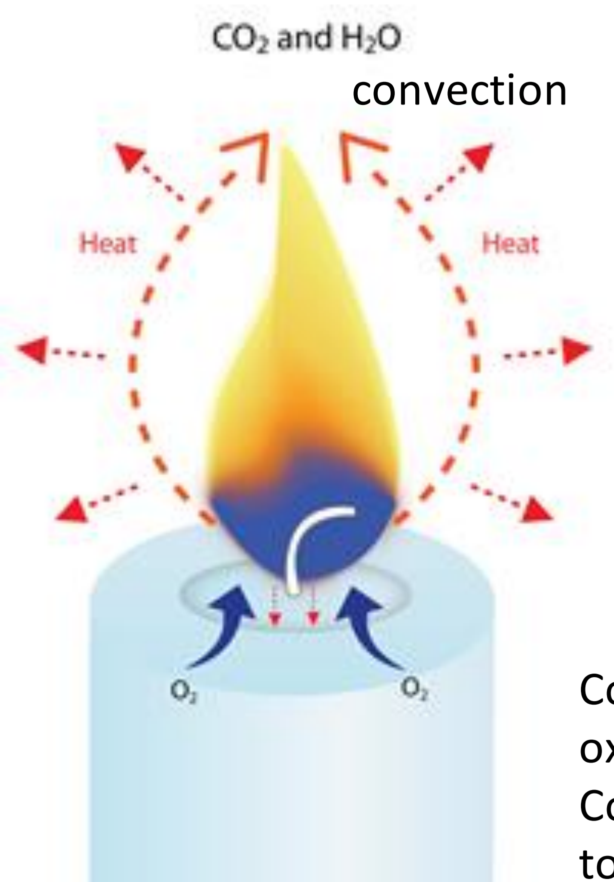
[Forrester2015]

Applications in combustion engines for aerospace,
combustion processes in chemical industry

Physics of candle

Wax (paraffin) – hydrocarbons - fuel melting point 40°C – 90°C

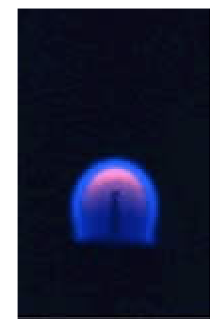
liquid wax is drawn up the wick by capillary action



vaporized hydrocarbon molecules react in flame with oxygen from the air to create heat, light, water vapor (H2O) and CO2.

Normal gravity on Earth

in microgravity



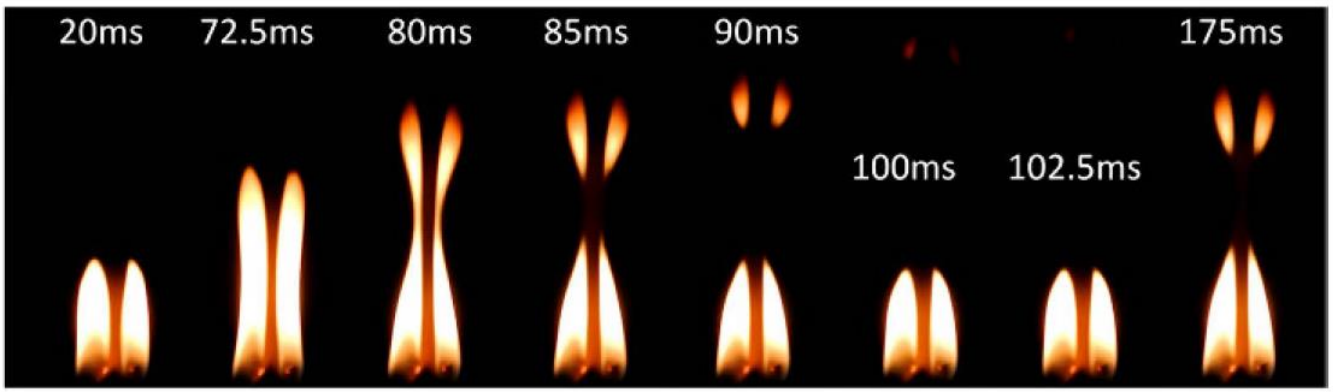
Convection draws hot wax vapors out from the wick and sucks oxygen from the surrounding air into the base of the flame.
Conduction carries heat down the wick to melt more wax at the top of the candlestick (it also carries down into the solid base of the candle).
The flame gives off heat also by IR radiation and thermal diffusion.

Glowing part of the flame radiates ¾ of its energy as light.

Candle oscillator

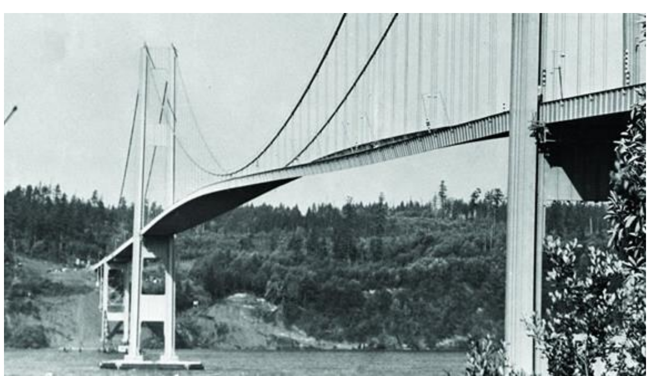
Self – oscillations
Limit- cycle oscillations
Complex non-linear problem
Nonlinear oscillations – flame brightness / height

Possibly not only by periodic lack of oxygen, but also by the convection vortices over the flame.



[Forrester2015]

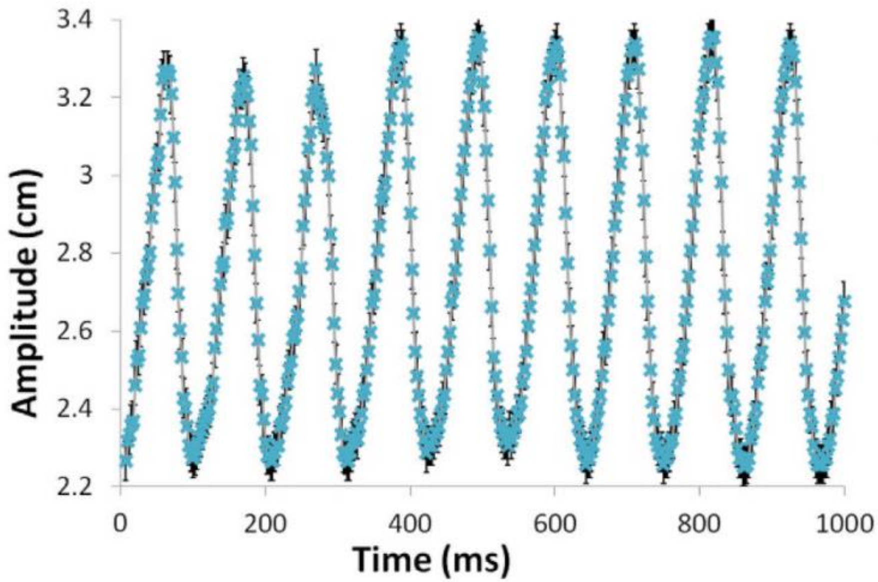
Other examples of non-linear self-oscillations



Tacoma
Narrows
Bridge

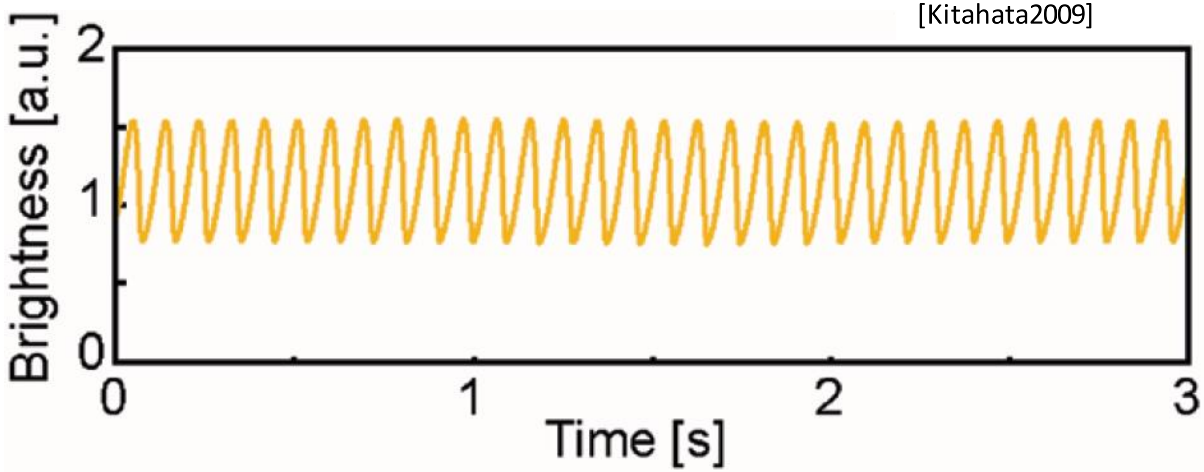
Tree leaves dancing in the wind

[Forrester 2015]



From experiments:
frequency gradually decreases as the number of candles increases in case of isolated oscillator

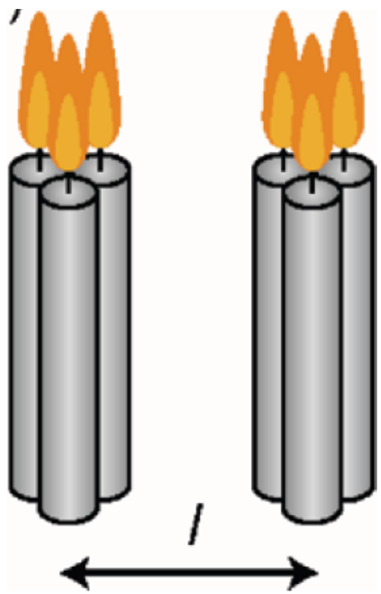
[Kitahata2009]

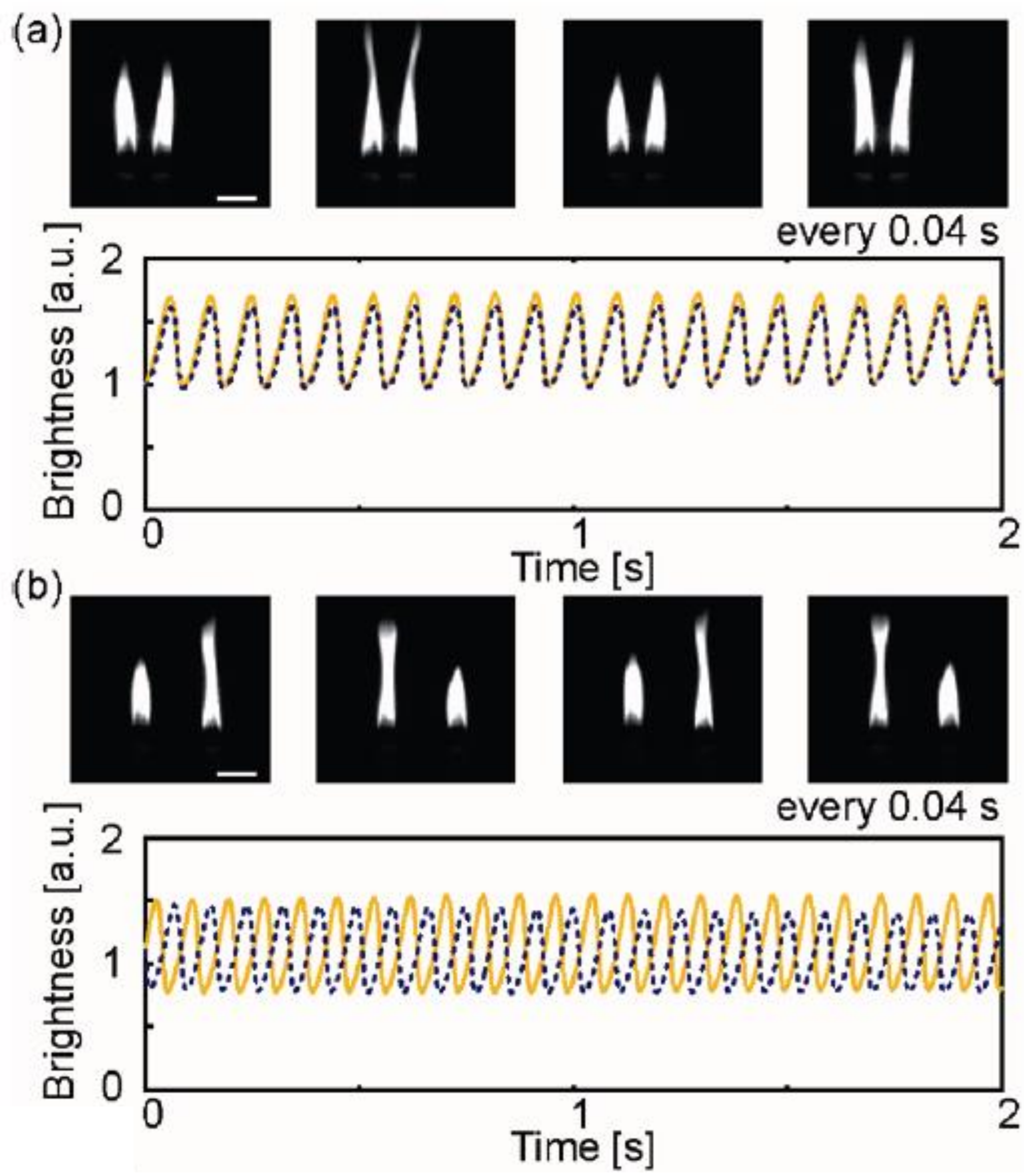


In-phase and anti-phase synchronisation on closer and larger distances

[Kitahata2009]

in-phase synchronisation 2 -3 cm

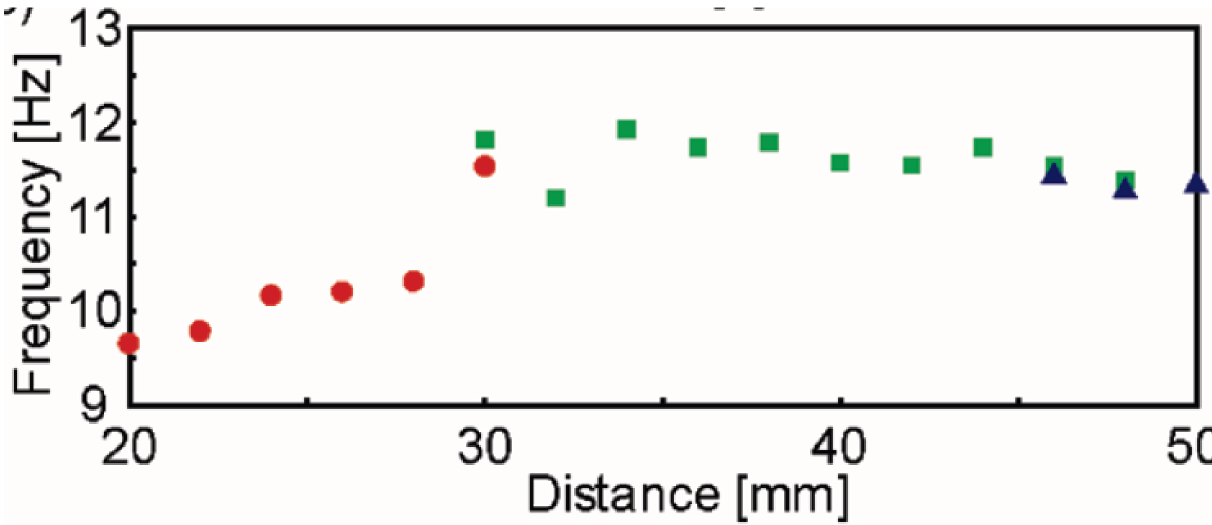




antip-hase synchronisation 3- 5 cm

desynchronisation > 5cm

At D ~ 3cm two modes coexist and frequency of oscillations jump.



[Kitahata2009]

What is the coupling between the two oscillators ?

Heat transfer via convection, thermal diffusion , radiation.
The coupling between oscillators is dominated by thermal radiation.
Thermal diffusion is too slow for synchronisation of oscillation with period ~0.1s.
Not via convection – no lateral air flow between oscillators. But …

Turbulence occurrence above the flames and convection flow not included in model

Quantitative model

Radiation interaction

$$C\frac{\mathrm{d}T_i}{\mathrm{d}t} = \omega_1\left[h(T_0 - T_i) + \beta a n_i \exp\left(-\frac{E}{RT_i}\right)\right] - \boxed{\sigma\frac{\mu}{L^2}\left(T_j^4 - T_i^4\right)}$$

$$\frac{\mathrm{d}n_i}{\mathrm{d}t} = \omega_2\left[k(n_0 - n_i) - a n_i \exp\left(-\frac{E}{RT_i}\right)\right]$$

$i,j = 1,2 \ (i \neq j)$

[Kitahata2009]

$T(t)$ temperature of the flame
$n(t)$ oxygen concentration in air

C specific heat
R gas constant
E activation energy
T_0 ambient temperature
n_0 ambient oxygen concentration
h heat flow by convection
k oxygen supply rate by convection
β heat production in combustion
σ Stefan-Boltzmann constant

ω_1 temperature time constant
ω_2 oxygen change time constant

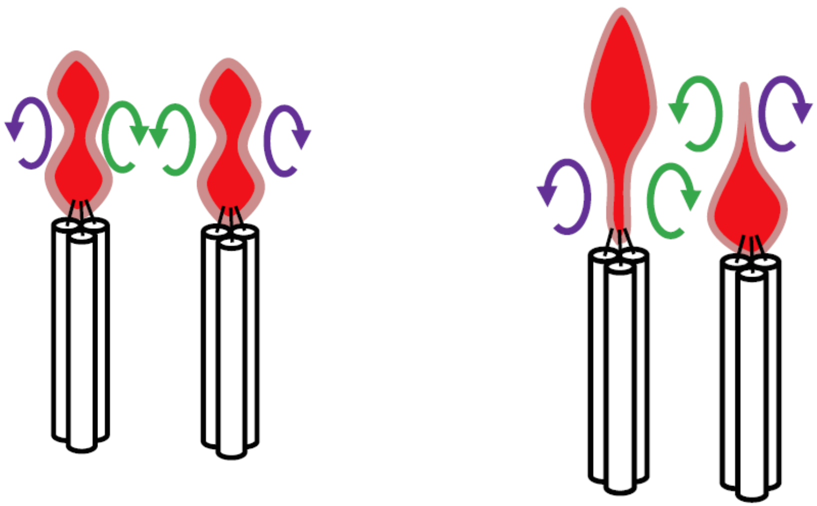
Recent reports provide evidence on the presence of intermediate "amplitude death" mode located between in-phase and antiphase modes – no oscillations.

Another mode : phase-flip bifurcation - sudden transition from in-phase to anti-phase

Role of time delay coupling [Manoj 2018]

With increase in number of candles in an oscillator, they observed a considerable reduction in the "amplitude death" zone.

Domination of fluid mechanics



Formation, evolution and detachment of toroidal vortices along flame sheets

Vorteces above the flame could affect synchronisation.

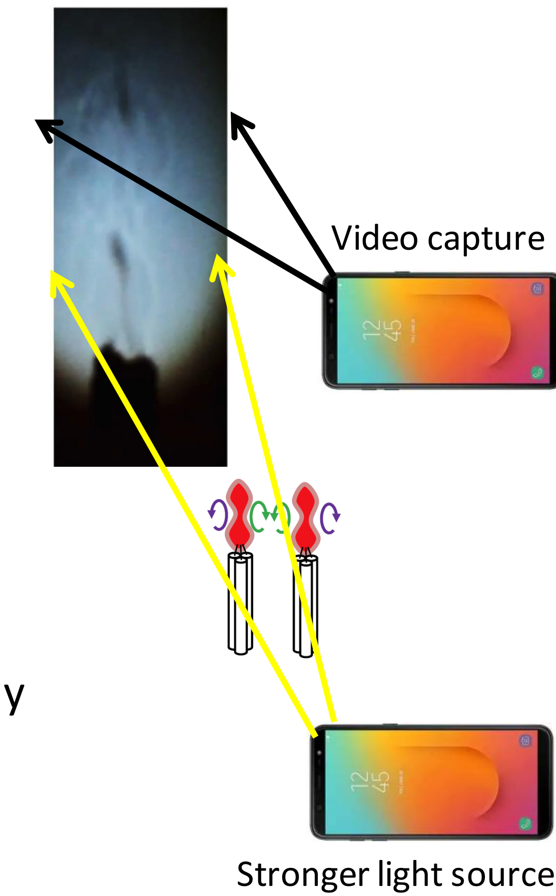
Closer distance – in-phase – unified vortex formed

Farther apart – anti-phase – two independent vortices

Experimental setup at “home” conditions

- Dark background
- Dark room
- No air flow
- Room T
- For high speed video use smartphone with video capture mode “slow motion” with at least 120fps, better above 200fpd.

- Try shadow video capture using stronger light projection on the white screen



In order to avoid transient effects let the oscillators reach a steady state - after each distance change apply waiting time e.g. 20s.

Fresh candle might need several minutes to stabilize.

Recommendation:

pre-burn your test candles, then the time for steady state can be shorter.

- wait few minutes after ignition for combustion process to stabilize
- flame may flicker or smoke initially

After stabilisation the flame of single candle will burn cleanly and steadily in a teardrop shape.

Flickering can be caused by

- impurities in the wax interrupting the flow in the wick,
- by a draft in the room,
- getting either too much or too little air or wax.
- the too long wick
  (wax has to travel a length that affects the stability of the flame)

Assuming stable conditions

single candle should not flicker,

no external interference – draught in the room, dust, etc

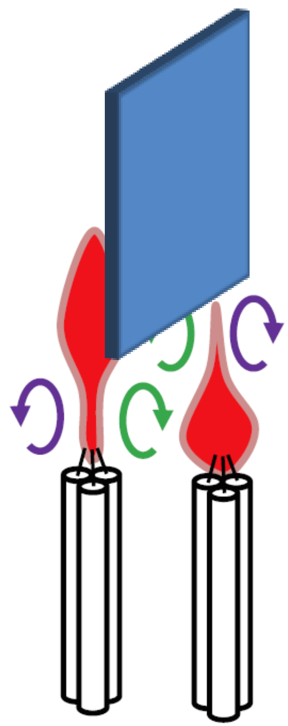
Experimental parameters

- Distance
- Number of candles in oscillator (compare to wick thickness, ratio to candle diameter)
- Different number of candles in each oscillator

- mass burning (loss) rate of the fuel $\Delta m/\Delta t$ ~ $\Delta Q/\Delta t$ effective heat release rate

  Differs in various oscillation modes?
  Necessary to measure over longer time – tens of minutes
  In-situ measurement on weighing scales?

- Regression rate $R = (\Delta m/\Delta t)(1/4\ \pi D^2 \rho)$ [mm/min]
- Flame height



Vorteces above the flame could affect synchronisation.
Closer distance – in-phase – unified vortex formed
Farther apart – antiphase – two independent vorteces

In shadow capture observation of laminar vs turbulent regions.
Inserting a barrier from above between the oscillators.

References

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SW for processing of video frames

Tracker **https://physlets.org/tracker/**

GNU Octave - a free software compatible with MATLAB
https://www.gnu.org/software/octave/index

https://iypt.ru/
https://stemfellowship.org/iypt-2021-references/synchronised-candles/

Thank you for your attention