Japanese-German Workshop: Emerging Phenomena in Spatial Patterns, Magdeburg, 22rd September, 2014

Mechanism of Candle Flame Oscillation:
Explosive and Periodic Combustion Induced by Air Turbulence above the Candle Flame

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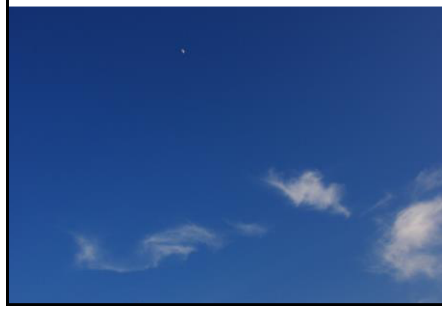
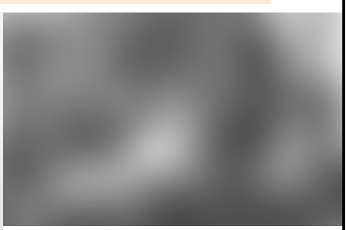
1. Introduction: Scientific History of a Candle



(1) Chemical History of A Candle: 19th Century

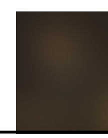


"There is no better, there is no more open door by which you can enter into the study of natural philosophy than by considering the physical phenomena of a candle"

Xmas Lectures (Since 1826),
M. Faraday

Michael Faraday (1791-1867): His Carrier

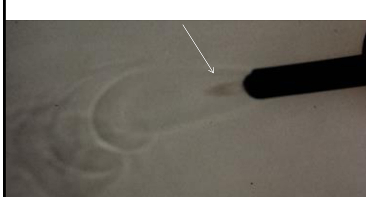
- 1791年(0) :Born in London, UK
- 1804年(13) :A Deliveryman of Book Maker , An Apprentice: A Laboratory in a Garret (Self-education)
- 1813年(22) :Assistant of The Royal Institute
- 1816年(25) :First Scientific Paper
- 1825年(34) :Chief of The Royal Institute, Discovery of Benzene
- 1826年(35) :Starting X-mas Lecture
- 1831年(40) :Electromagnetic Induction
- 1833年(42) :Professor of The R. I. Discoveries of Law of Electrolysis and Faraday dark part.
- 1845年(54) :Discovery of Faraday effect
- 1846年(55) :Electromagnetic Wave Theory of Light
- 1861年(70) :Lecture of Candle
- 1862年(71) :Experiment on magnetic field effect of light
- 1867年(76) :Died (76 years old)
- 1966年 :TV-broadcasting of the X-mas Lecture
- 1973年 :Faraday Museum (The Royal Institute, London)



Shadow of the Candle Flame in a Sunny Place

Dark Place ＝The Strongest Brightness Place in Candle Flame

Visualization of Convection Structure by Shadow-Graph Method



(2) Physical Approach to Candle: 20th Century

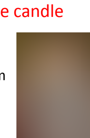
「Atoms, Electrons, and Change」
(Peter William Atkins, 1991)

・Nature is a complex system, however, not a matter beyond our understanding. All conversions among materials can be understood by chemical reaction, which is a location change of atoms. This book picks up the carbon, which is important for the living system.

・Science of 20th Century challenges to understand the candle conversation through Quantum Mechanics.

A paradigm shift is necessary from Newton Mechanics to Quantum Mechanics to understand the details of chemical reaction.

http://en.wikipedia.org/wiki/Peter_Atkins



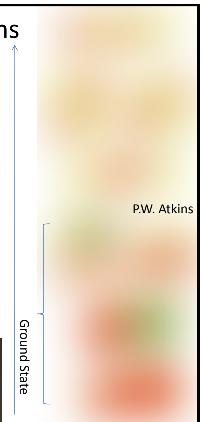
Science of Candle by P. W. Atkins

§ 2 Chemical Reaction

Molecular Orbitals

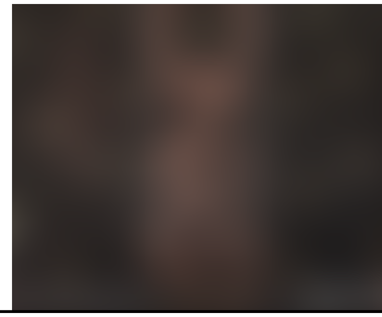
- Electron pairs of chemical bounding occupies the mixed orbital.
  → Pauli exclusion principle works.
- 2p orbital of C + 1s orbital of H
  Instructive bounding =1σ MO
  Destructive bounding =2σ MO
  → Interference of material wave
- 8 Molecular orbitals caused by 2 Carbon atoms (Right Figures).
- Ground State :1σ(2), 2σ(2), 1π(2)
- Excited state→Ground state + hν
  → Blue Light Emission

P.W. Atkins



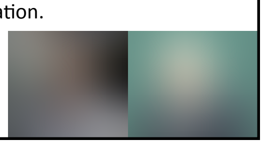
⑶ New Approach to Candle Science: 21st Century

SYNC: The Emerging Science of Spontaneous Order (2003)



Great similarity between the sync of oscillators and the phase transition : emphasized point

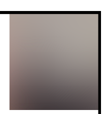
- A. Winfree discovered an unexpected link between biology and physics. He realized that mutual synchronization is analogous to a phase transition.
  ＝ Statistical physics can be a key to solve the great variety of synchrony in nature.
- Y. Kuramoto simplified Winfree's model and obtained the exact solution. The model revealed the essence of group synchronization.



Similarity between the sync of oscillators and the phase transition

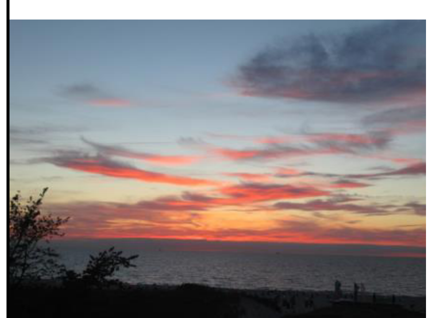
- Winfree's model: $\dot{\phi}_i = \omega_i + Z(\phi_i)I(t), \quad I(t) = \frac{K}{N}\sum_{j=1}^{N} V(\phi_j)$
- Kuramoto's model: $\dot{\phi}_i = \omega_i + \frac{K}{N}\sum_{j=1}^{N} \sin(\phi_j - \phi_i)$

Important Points of SYNC



- Analogy between group synchronization and phase transition had been established.
- S. Strogaze proposed a concept of "Oscillator Fluid" to solve the stability problem of the incoherent equilibrium state. The answer was "neutrally stable".
- Reductionism may not be powerful enough to solve all the great mysteries we're facing :Cancer, Consciousness, The Origin of Life, AIDS, Global Warming, ・・・
- Nonlinear dynamics is central to the future of science.
  Chaos → Complexity → Emergence → What comes next？

Ⅱ. Candle Flame is a nonlinear Oscillator !



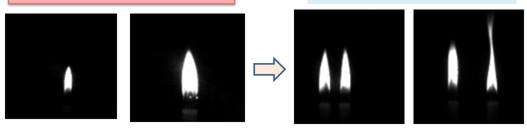
Rhythm of Candle Flame＝Nonlinear Oscillator

- Flame Brightness Oscillation （Ishida, Harada, 1990）

・Oscillations and Synchronization in the Combustion of Candles, H. Kitahata et al., J. Phys. Chem, 113(2009), pp.8164-8168

A bundle of two candles oscillate.

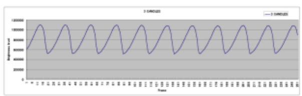
SYNC between two oscillators



Single Candle | Bundle of 3 Candles | In phase SYNC | Anti phase SYNC

Pictures of High Speed Camera (250 Hz)

Transition from in phase to anti phase SYNC



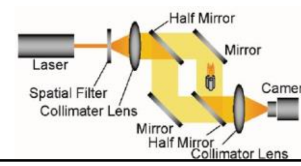
Nonlinear Oscillation of Flame Brightness

Oscillation and Synchronization in the Combustion of Candles

J. Phys. Chem., 113 (2009)

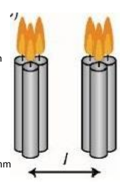
Visualization of flow structure by Mach-Zehnder interferometer

- Experiment：
  - Chiba : H. Kitahata, T. Sakurai
  - Yamaguchi: J. Taguchi, A. Osa, H. Miike
  - Kyoto: Y. Sumino, M. Tanaka
- Model & Numerical Analysis：
  - Kanazawa: M. Nagayama, Y. Ikura
  - Gakushuin: E. Yokoyama

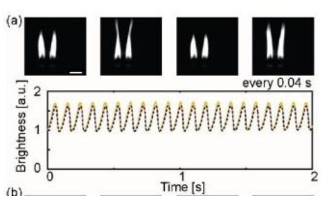


In-phase synchronization between two candle flame oscillators

- Close Distance（l = 2～3cm）

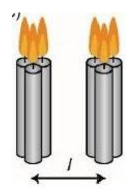


Induced In Phase Synchronization

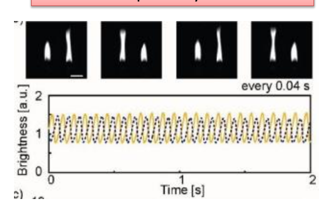


Anti-phase synchronization between two candle flame oscillators

- Moderate Distance （l = 3～5cm）

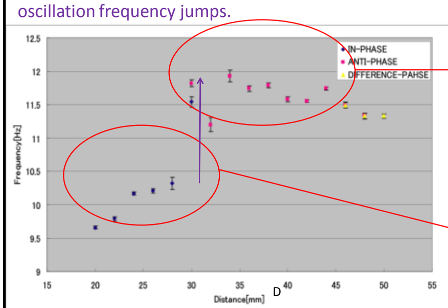


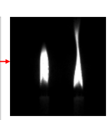
Induced anti phase synchronization



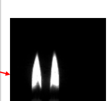
Depending on the distance parameter D, synchronization between two oscillators changes from **in-phase** to **anti- phase**.

→ At around critical distance Dc, two phases coexist, and the oscillation frequency jumps.





Anti phase



In phase

Model for the candle flame oscillator

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

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

Interaction by Radiation

Flame oscillation caused by periodic oxygen lack by combustion

Reproduce In phase and anti phase SYNC: see next Figures（c）,（d）

- a： ロウの供給率
- C： Specific Heat
- R： Gas constant
- E： Activation Energy
- T_0： Outside Temperature
- n_0： Outside Oxygen Concen.
- ω_1： Time const. (T change)
- ω_2： Time const.（O2 change）
- h： Radiation Rate
- k： 酸素供給率
- β： Heat Conversion Rate of
- σ： Stefan-Boltzmann Constant
- T_i, T_j： Reaction Field Temperature
- n_i, n_j： Reaction Field O2 concentration
- $i, j = 1,2 (i \neq j)$

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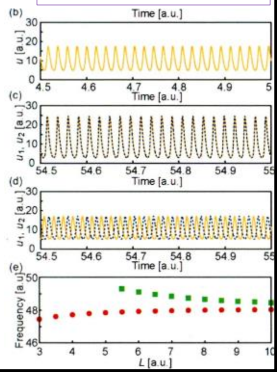
Kanazawa University

Problems of the proposed model

- Temporal shape of the numerical oscillation is not coincide with the experiments（b）.
- Difference in the coexisting region of in-phase sync and anti-phase one between the experiments and the model is recognized（e）.
- Mutual correlation caused by the thermal radiation is not directly confirmed by experiments.
- Convective flow（ascending current ） and turbulence caused by the flame are not directly taken into account in the model.

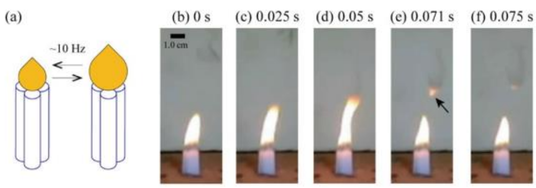
Results of the numerical analysis by the proposed model.



Ⅲ. Progress in Experiments: New Findings

(1) Descending turbulence above the candle flame.
(2) Explosive and periodic combustion with soot.

Oscillation of the length of the candle flame (- 10Hz): The mechanism of the oscillation is not well understood.

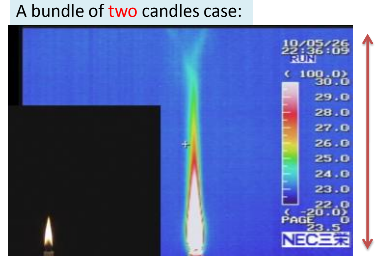


(a): The schematic drawing of the oscillation.
(b)-(f): Time-series of optical images recorded by a high-speed digital video camera.
The black arrow indicates the torn-off flame with soot.

（1）Observations by a thermal camera

- An eddy like convection appeared above the candle flame.
- The oscillation began to start when the eddy touch down the candle flame.

A bundle of two candles case:



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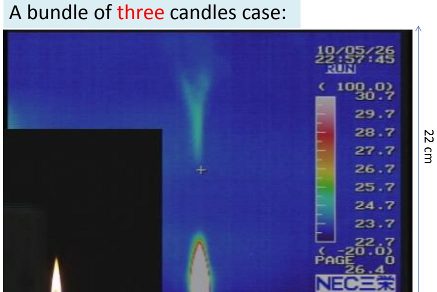
Observation of candle flame oscillation by a thermal camera

Turbulent area has low temperature.

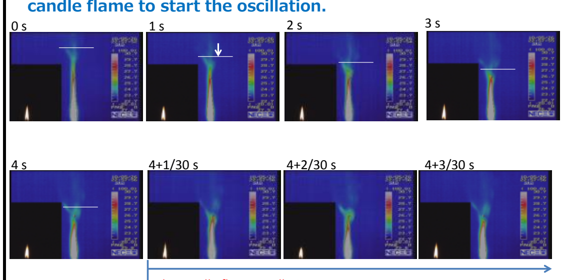
Descending the low temperature area induces the oscillation.

A bundle of three candles case:

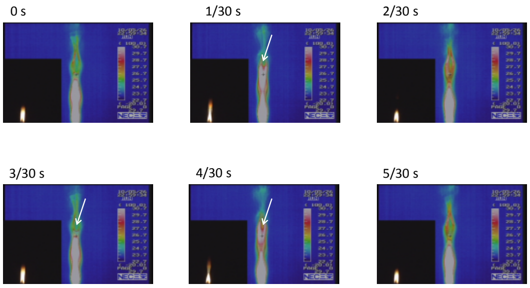


Observation before candle flame oscillation

- **Turbulent current of upper air part above the flame has lower temperature. The cold upper air descends to the top of the candle flame to start the oscillation.**



Observation sufficiently after the oscillation starts



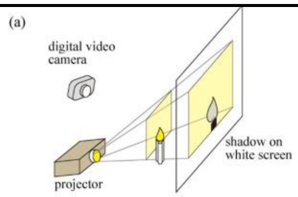
Low temperature region penetrates into the center of the flame.

(2) New Observations by High-speed Camera (300 frames/sec): Shadow Graph & Velocimetry

Eddy like convection is also confirmed above the candle flame.

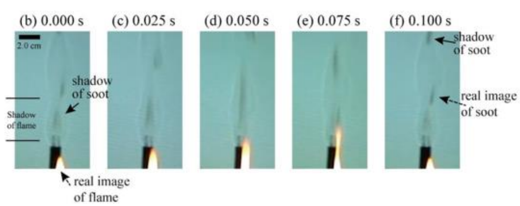
Turbulence starts from the upper air part above the flame.

Descending of the low temperature area induces oscillation.

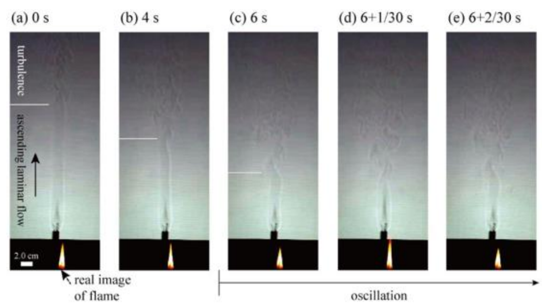


Observation of the shadow of the oscillating flame using the high-speed digital video camera.

(a): The experimental setup for recording the shadow graph.
(b)-(f): Time-series of the shadow graph images of the oscillating flame. The scale bar in (b) is for the shadow of the flame.



Time-series of the shadow graph images of the turbulence above the flame, before and after it starts to oscillate.



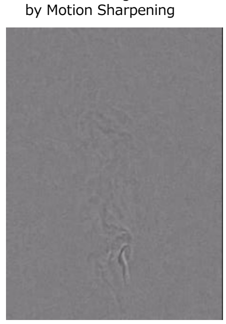
- The scale bar in (a) is for the shadow of the flame.
- The white lines in (a), (b), and (c) indicate the boundary between the turbulence and the laminar flow. **The turbulent region is propagating or descending to the top of the flame.**

Visualization of Air Turbulence by Motion Sharpening

Shadow graph image

Enhanced image by Motion Sharpening

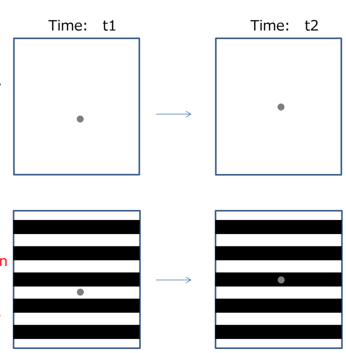
4 cm



Velocity Analysis : Spatial Filtering Velocimetry

Original image sequence.

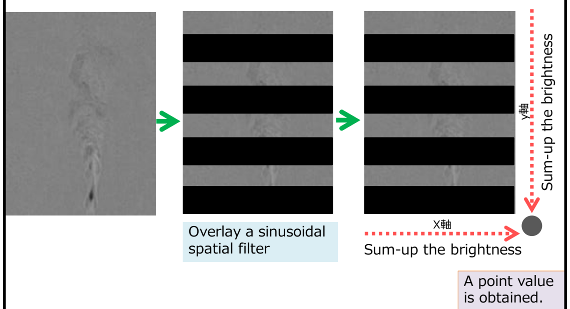
Overlay a periodic slit pattern on the image sequence.



The velocity is measured by detecting the frequency of the total brightness change,

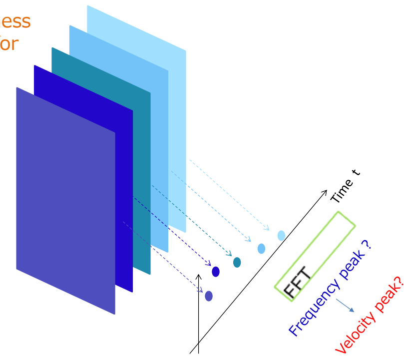
Velocity Analysis : Spatial Filtering Velocimetry

For every frame

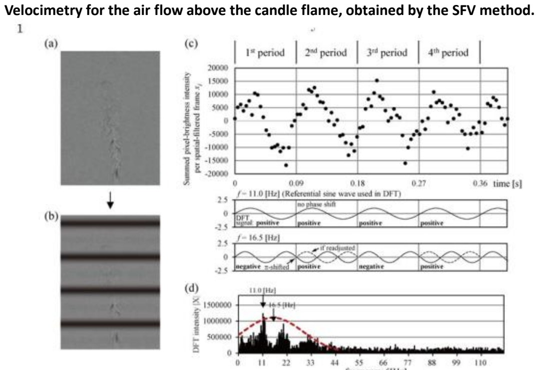


Velocity Analysis : Spatial Filtering Velocimetry

Calculate the filtered brightness accumulation for the respective image frames

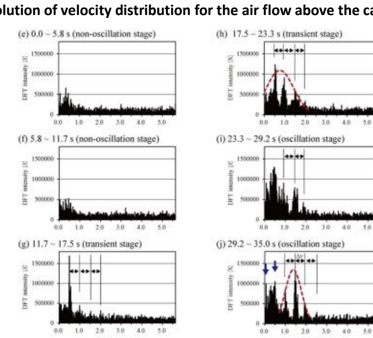


Velocimetry for the air flow above the candle flame, obtained by the SFV method.



(c) Time-series of numerical data created by integration through the pixel-brightness intensities per spatial filtered frame x_j. (d) The DFT result for (c): Power spectrum.

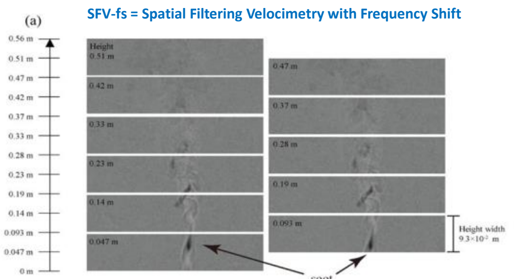
Time evolution of velocity distribution for the air flow above the candle flame.



- (e)-(f): before the flame oscillation, (g)-(j): developing phase of the oscillation. The mean velocity of the ascending air flow increases with time. The velocity distribution is modified by the periodic brightness change with -10 Hz.

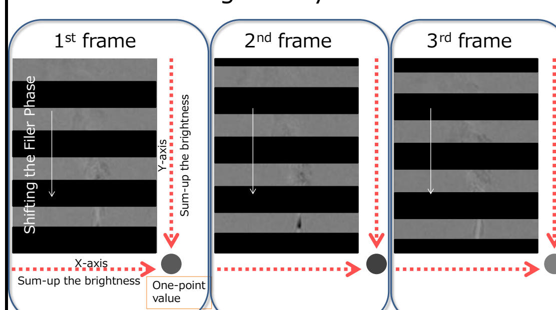
Height-dependence of the velocity distribution of the air flow above the flame during the stationary oscillation stage, obtained by the SFV-fs method.

SFV-fs = Spatial Filtering Velocimetry with Frequency Shift

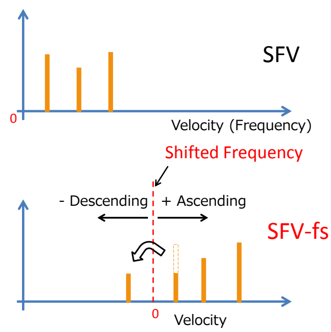


(a) A scene in the movie of the contrast-enhanced shadow graph, which is divided by a height width 9.3 × 10^{-2} m. The position of height 0 m is at the bottom of the candle flame.

Discriminate between ascending flow and descending one by SFV-fs method.



Discriminate between ascending flow and descending one by SFV-fs method.



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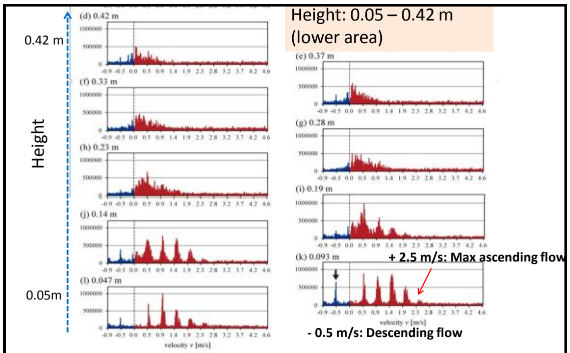
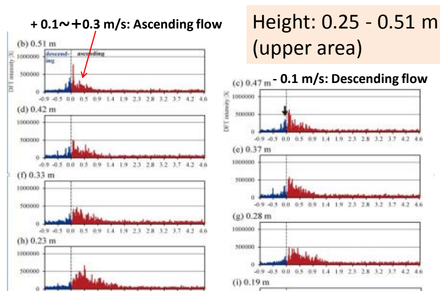


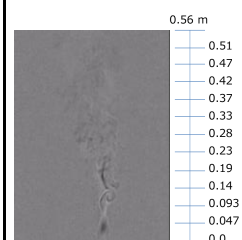
(b)-(l) The velocity distribution showing the ascending and descending velocities for respective heights. The bold arrows in (c) and (k) indicate peaks for approximately -0.1 m/s and **-0.5 m/s**, respectively.



(b)-(l) The velocity distribution showing the ascending and descending velocities for respective heights. The bold arrows in (c) and (k) indicate peaks for approximately **–0.1 m/s** and -0.5 m/s, respectively.

Velocity of the spatial filter: 3 pixels/ frame

Summary of the velocity distributions above the candle flame



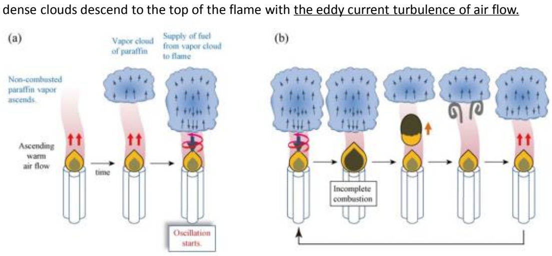
No influenced region by the flame oscillation
A gentle ascending flow: **0.1~0.3 m/s**
Descending flow ~0.1 m/s

Almost no influenced region
Ascending flow **~0.5 m/s**
Descending flow ~0.1 m/s

Influence region by the flame oscillation
Ascending flow **~2.5 m/s** (maximum)
Descending flow ~0.5 m/s

Nagamine Model: A mechanism of candle flame oscillation.

Candle vapor clouds develops above the flame because of imperfect combustion. The cold and dense clouds descend to the top of the flame with the eddy current turbulence of air flow.



(a)Non-combusted paraffin vapor cools down in the upper region far from the candle flame, and dense clouds develops to make the descending flow.
(b) A mechanism of the candle flame oscillation associated with paraffin clouds dynamics. The clouds descend to the top of flame and cause an explosive combustion, which induces the torn-off flame with soot.

Discussion

KH-instability

1. Candle flame oscillation is possibly caused not only by periodic oxygen lack with combustion but also by the eddy like convection appeared over the flame. The eddy structure can be originated by Kelvin-Helmholtz (KH) instability.
2. Synchronization between the flame oscillators can be induced by the interaction associated with the vortexes dynamics.

・Depending on distance of oscillators the synchrony changes from in-phase to anti-phase. The change can be caused by difference of the vortex dynamics.

In-phase (close): A unified vortex is developed.
Anti-phase (apart): Two vortexes keep independence.

Next Target: Hierarchical pattern dynamics in candle flame oscillators (CFO)

- What may happen in crowded CFO?