Journal of Material Science and Mechanical Engineering (JMSME)
p-ISSN: 2393-9095; e-ISSN: 2393-9109; Volume 4, Issue 4; July-September, 2017, pp. 225-230

http://www.krishisanskriti.org/Publication.html

Stratified Flickering Behaviour in the Array of Diffusion Flames

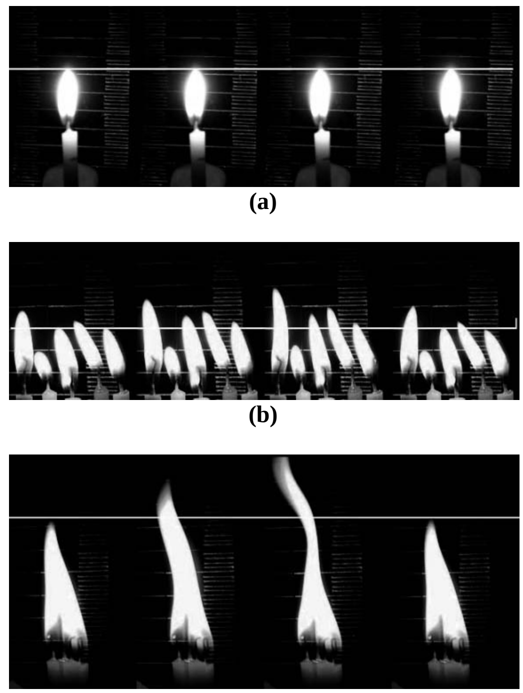
Rajbir Singh[1] and Vinayak Malhotra[2]*

[1,2]Department of Aerospace Engineering, SRM University, Chennai, India
*E-mail: [1]rajbirsandhu123456@gmail.com, [2]*vinn99@gmail.com*

Abstract—*Better combustion and considerable fire safety has/had been an acute area of concern over past few decades. The generalization of chemical energy for propulsion and practical applications have led to immense aspects surfacing to be emphasized upon. The flame spread behaviour is studied in the form of diffusion and premixed flames. Premixed flames have been well quantized however, the diffusion flames suffer the diverse qualitative and quantitative investigation. Similar to the premixed flames, the diffusion flames spreading under specific conditions reflects flickering which is an aspect which is yet to be comprehensively explored. The flickering behaviour is assisted by turbulent flow field and drastic changes in the localized temperature and velocity fields. Present work attempts to experimentally understand the heat transfer characteristics and stratifies flickering behaviour in the array of diffusion flames. A simple experimental setup is upraised, and candle is used as pilot fuel. Candles are varied in odd selections viz., 1,3,5,7 in equilateral triangle, pentagon, heptagon geometry around the pilot candle and effect of controlling parameters like separation distance, number of candles and orientations are observed with the flame behaviour.*

1. INTRODUCTION

Flickering of Flames is a very fascinating phenomenon in the study of diffusion flames. It is associated with the vortices in the flow with the flame. An elementary flame interaction is periodic in nature. The frequency of flickering is always of the order of around 10 Hz and is neither affected by the burner nor by other parameters. The formation of stratified layer between the hot gases of combustion and the cold quiescent ambient air initiates the flickering phenomenon, which further leads to the Kelvin-Helmholtz instability. Initially the flickering is non-continuous and shows wavering/intermittent (constantly changing) behaviour (Fig. 1). Distance has been divided into three zones i.e. nearby zone, intermittent zone and far away zone. The distance within 2.5cm from pilot candle is known as nearby zone, from 2.5cm to 7.5cm is the intermittent zone and beyond 7.5cm is called faraway zone. Flickering behaviour of diffusion flames is seen mostly in the nearby zone. Present study focuses on the behaviours of the flame within the nearby zone. Especially the Flickering behaviour by varying the number of candles (by fixing their orientation) and then by varying the distance is investigated. The response of the flame flickering to the number of candles in even and odd numbers is studied using the same setup and environment (Isolated).



(a)

(b)

(c)

Fig. 1: (a) Steady diffusion flame (b) pilot candle with 5 source candles in pentagon geometry and (c) shows the flickering behaviour with 3 source candes in equilateral geometry.

Following the classical work of Chamberlin et. al., [1] on flicker of luminous flames. Appreciable research efforts have resulted in significant advancement in the flame flickering phenomenon. The reviews can be found in Toong et. al., [2], Gebhart [3], Yuan et. al., [4], The works provide excellent assessments till the end of the century.

Kermit et. al., [5] carried out fluorescence measurements excited at 283.5 nm and detected at 400–447 nm in a series of steady and flickering methane, propane, and ethylene diffusion flames burning at atmospheric pressure in an axisymmetric, co-flow configuration. In the flickering flame experiments, acoustic forcing of the fuel rate was used to phase lock the periodic flame flicker close to the natural flame flicker frequency caused by buoyancy-induced instabilities. Waldemar [6] studied the main directions of changes in organization of combustion process in industrial power boilers.

The fiber optic system permitting the measurement of flicker of the single coal-dust burner as well as the influence of the input conditions (primary air, secondary air) on changes of flicker was explored. Sato et. al., [7], Kato, et. al., [8] carried out exhaustive studies over the flame flickering and its interrelation with other thermo-fluid phenomena. The studies pointed on the role of vortices, being generated at the base of the flame, which grew downstream to modulate the flame progressively. Yilmaz et. al., [9] performed flow visualization through the use of imaging provided visual data of the events that occurred as the flame oscillated. Tanoue et. al., [10] addressed the relationship between the flickering and the temperature field. The time course of the temperature field around the premixedflame was measured by using the laser speckle method with high-speed camera, paying attention to the flickering. Guo [11] investigated the stability of a laminar diffusion flame and the interaction of the flame with acoustic waves inside an acoustically excited cylindrical tube. Interesting phenomena were observed by studying both the infrasound and sound effect on the flame structure and dynamics. The loudspeaker was utilized to generate acoustic waves with different frequencies and intensities to excite the flame, which can make the flame relatively stable or unstable, even blow out. Different methods in both frequency domain and time domain were applied to analyze the flame stability affected by acoustic waves. Both infrasound and sound are tested. It was found that infrasound is able to take over buoyancy-driven flame flickering and make the flame flicker at the same frequency as the forcing infrasound. Blanchard [12] investigated Selfsustained thermoacoustic oscillations causing recurrent problems in numerous combustion systems. The work addressed instabilities, which couple the reacting flow dynamics and the system acoustics and remain difficult to predict at the design stage of a combustor.

In the light of above mentioned works, the quantification of Stratified Flickering Behaviour in the Array of Diffusion Flames is yet to be comprehensively established. The present work investigates these aspects and attempts to understand the role of key controlling parmeters.

2. EXPERIMENTAL SETUP AND SOLUTION METHODOLOGY

The experiments were conducted in quiescent purely convective environment with 21% oxygen concentration to avoid any moving air, noise and other disturbances (Fig. [2-4]). The experiment was conducted on a wooden table and markings were made on it using drafter (Fig. 2). The candles used for this experiment are with height (4.5cm) and diameter (0.5cm). Candles made of Wax and having simple wick were taken for the study. Markings were etched 1cm apart and time taken to burn the fuel was noted for each cm and collectively as well.

For calculating the flame height markings were made on a black paper with glitter pen. It was kept behind the pilot candle to note the flame height and variation in flame height while the flickering phenomenon took place (Fig. 3). For Even and odd number of candles the setup, environment was same but the markings on the table were changed accordingly.

Fig. 2: Pilot candles with the markings on it.

Fig. 3: The experimental setup.

Candles were first taken in Even numbers viz., 2,4,6 in diagonally opposite position, cruciform position, hexagon and then in Odd numbers viz., 1,3,5,7 in equilateral triangle, pentagon, heptagon geometry around the pilot candle. Time taken for each orientation and distance was noted. To take optical video 16-megapixel camera with Sony IMX 298 sensor with PDAF, f/2.0 aperture and Optical Image Stabilisation is used. Optical videos were taken at 30 fps to gather more data and to minimize the error. Pictures were extracted from the video afterwards using video to JPG converter.

The experiment was conducted in an isolated and closed chamber to avoid any disturbance due to air movement, noise disturbances or any other kind of aberrations while performing the experiment. Videos are taken at 30 fps for every setup. Frames are taken from the video using the app video to JPG converter. The spread rate was calculated by dividing the length of the candle burned divided by the time taken, measured in mm/s.

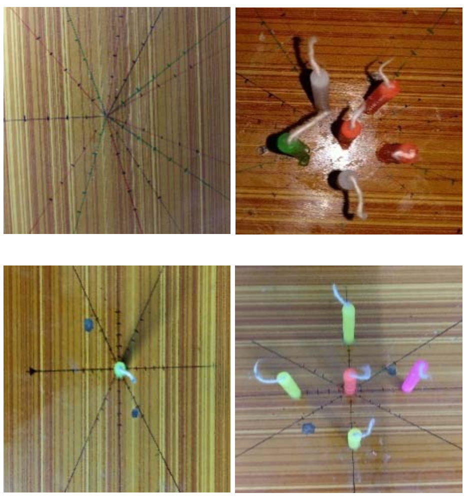


Fig. 4: shows the markings and candles setup for odd number (top) and even number (bottom).

The spread rate is very sensitive to the gas and the surface temperatures which are a part of solution procedure. In order to facilitate uniform horizontal ignition across the width, the fuel strip was cut at the top and ignition was done by exposing it to a pilot flame. The solid fuel strips were marked at regular intervals of 1 cm to track the smoldering front propagation with time. Every experiment was carried out within a range of 5 minutes to bring room atmosphere back to normalcy. Stopwatch was used to measure the split times across the markers. An optical setup was made to obtain shadowgraph of the propagating front which was digitally video graphed. The regression rate can be defined as the rate of decay of the subject of interest, in this case, the impure paraffin wax in the candle. The system of units we used for tabulating results in our experiments is millimetres per second. The flame spread rate (V_f) is calculated using linear method as:

$$V_f = \frac{l_s}{t_{av}} \qquad (1)$$

Where, "l_s" is the standard length of fuel taken (here, 1 cm) and "t_{av}" is the average time taken for all three marked distances. From classical theory of ignition spread, assuming unity width of fuel the regression rate (V_f) is defined by energy balance as:

$$V_f = \frac{\int q_{net}}{\rho_s \tau_s c_s (T_{Surface} - T_\infty)} \qquad (2)$$

Where,

$\int q_{net}$ = Net integrated heat transfer per unit time per unit area to the unburnt fuel.

c_s = Solid-phase specific heat.

τ_s = Solid fuel thickness.

ρ_s = Solid fuel density.

$T_{Surface}$ = Surface temperature.

$T_{Ambient}$ = Ambient temperature.

It is important to note that the readings were taken thrice for same distance and the average repeated value with was accounted. Ignition is primarily transition from a non-reactive material decomposition to a self-sustained reactive combustion. This transition is owing to an imbalance between the heat production and heat loss which relates to the energy stored in a volume as:

Stored energy change = **Energy Production-Energy loss**

$$\rho_s C_s V \frac{dT}{dt} = q_p - q_L \qquad (3)$$

The energy production is based on an Arrhenius approximation as:

$$q_p = \Delta H_c V C_i A^* e^{\frac{-E_a}{RT}} \qquad (4)$$

The associated heat energy loss is taken by assuming constant concentration of reactants in the volume (material not consumed prior to ignition) (Ci) indicating a uniform temperature:

$$q_L = hA(T - T_a) \qquad (5)$$

$q_p=$ Energy produced, $q_L=$ Energy loss, $V=$ Volume, $\Delta H_c=$ Heat of combustion, $C_i=$ Concentration of reactants, $A^*=$ Pre- exponential factor, $E_a=$ Activation Energy, $h=$ Convection factor.

3. RESULTS AND DISCUSSION

The Present Study explains the effect of heat transfer from source(s) on the main pilot candle when the number of candles are varied. The distance between the pilot candle and source candles are changed (by keeping number of candles fixed). The Experiment explains the behaviour of natural flickering of diffusion flames in candles with different number of source candles at different distances from pilot candle. To compare the changes, a single flame is taken as reference, for comparing spread rate and change in height of the flame.

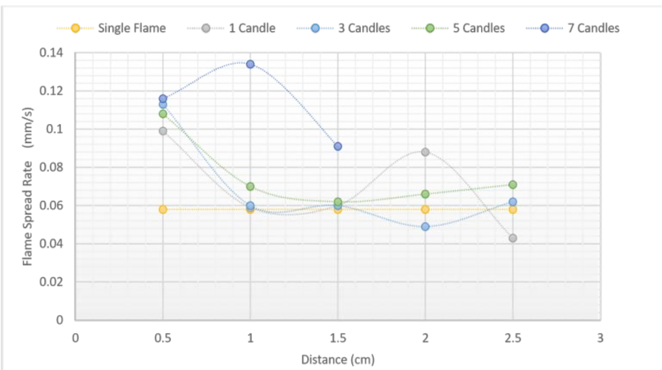


Fig. 5: Variation of flame spread rate with respect to distance (of source from pilot candle in cm) for odd number of candles.

Fig. 5 shows the spread rate variation with separation distance for odd number of candles. Spread rate (V_f) from 0.5cm has increased then V_f has dropped drastically except for 7 number of candles, at 1.5cm an unexpected trend is seen when all the lines tend to meet irrespective of the number of candles placed around the Pilot candle. At 2cm V_f increases for the case with single candle more than case with 5 number of candles whereas V_f for 3 number of candles decreases even below the case with single flame. At 2.5cm V_f for 5 number of candles increases but not much, V_f of 1 candle decreases drastically and it increases for 3 number of candles. The flame spread rates were **70.69%**, **94.83%**, **86.21%**, **100%** for 1,3,5,7 number of candles respectively at 0.5cm distance. At 1cm distance spread rate for 7 number of candles shows a different trend than others having maximum value of spread rate, which is **131.03%** more than the single flame. At 1.5cm a very interesting phenomenon is seen when all the spread rates tend to become same irrespective of the number of candles, **3.49%** ,**3.45%**, **6.90%** ,**56.90%** for 1,3,5,7 number of candles respectively. At 2cm case with 1 candle has maximum spread rate with **51.72%** increment and 3 number of candles showing minimum spread rate with **15.52%** decrease. At 2.5cm the **25.86%** decrease in 1 candle showing the minimum value, **6.90%** increase for 3 candles ,**22.41%** increase for 5 number of candles is seen.

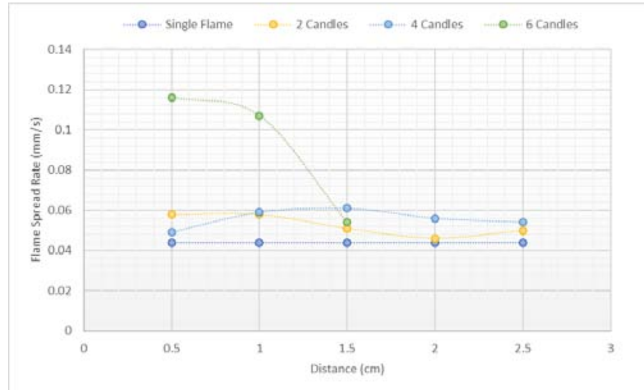


Fig. 6: Variation of flame spread ratewith repect to separation distance (of sources) for even number of candles.

Fig. 6 shows the variation for even configurations. The spread rate was noted to be increased for 2,4,6 number of candles but V_f for 6 number of candles is very high, at distance 1cm V_f for 4,2 number of candles is almost same but for 6 number of candles it is still too high but has decreased from that it was at 0.5cm. At 1.5cm V_f is highest for 4 number of candles and the values for 2,6 number of candles are almost same. At 2cm and 2.5cm trend is almost same with 4 number of candles having highest spread rate. The flame spread rates were **31.82%** ,**11.36%**,**163.64%** for 2,4,6 number of candles respectively at 0.5cm. At 1cm spread rate for 2,4 candles is almost same with **31.82%**,**34.09%** and 6 number of candles having maximum value with **143.18%** increase. At 1.5cm 4 number of candles have maximum value with **38.64%** increment, 6 number of candles with **22.73%** increment, 2 number of candles show **15.91 %** increment having the minimum value. At 2cm values for single flame and 2 number of candles is approximately same with only **4.54%** increment ,4 number of candles showing maximum value with **27.27%** increment. At 2.5cm all values tend to become same as it is the limit of nearby zone with **13.64%**,**22.73%** increase in 2 and 4 number of candles. Increase in Spread rates for 4 number of candles at 2.5cm and 6 number of candles at 1.5cm are same and increase in spread rate of 4 number of candles becomes almost constant from 2 to 2.5cm showing the values **22.27%**and **22.73%** respectively.

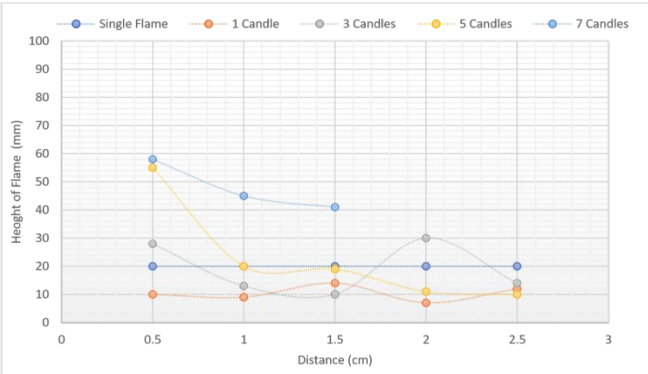


Fig. 7: Flame Height V/S distance of source candles from pilot candle for odd number of candles.

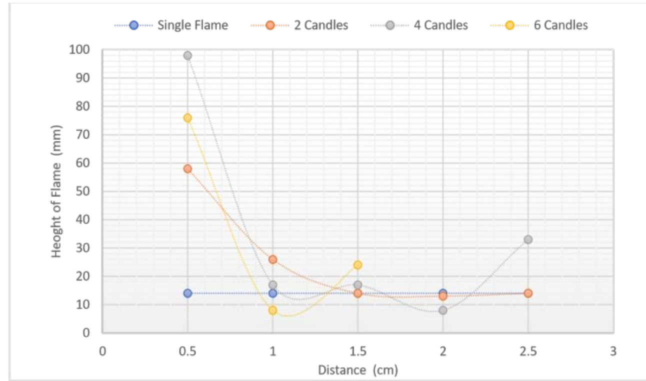


Fig. 8: Flame Height V/S distance of source candles from pilot candle for even number of candles.

Fig. 7 details the Flame Height V/S Distance for odd number of candles, Flame Height vary markedly in range at 0.5cm distance. At 1.0cm height for 5 number of candles is same as for single flame but for 1,3 number of candles it is even smaller than that of single flame, for 7 number of candles height is maximum but has decreased from what it was at 0.5cm. At 1.5cm flame height for 5 number of candles and single flame is still almost same, Height for 1,3 number of candles is lower than single flame but now flame height of 1 candle is more than that of 3 number of candles. At 2cm interestingly, Flame height for 3 number of candles is highest, 1 and 5 number of candles flame heights are lower than single flame height with 1 candle having lowest value. At 2.5cm height of all cases tends to become same as 2.5cm is the end of nearby zone hence after this flickering behaviour is less prone to happen. Changes of **-50%**,**40%**,**175%**,**190%** for 1,3,5,7 number of candles respectively, flame height for 7 number of candles is almost twice as big as that of single flame. At 1cm flame height of 5 number of candles is same as that of single flame, and heights of 1,3 number of candles decreases by **55%**,**35%** except for 7 number of candles which is still **125%** high from single flame. At 1.5cm flame height of 5 number of candles is still almost same and is just **5%** less. Now minimum height is for 3 number of candles rather than for 1 number of candles as seen in previous case and the values are **-50%**, **-30%** respectively, 7 number of candles still has maximum height and is almost double than that of single flame with value of **105%**. At 2cm an interesting phenomenon is seen when 3 number candles flame height becomes maximum and is **50%** of that of single flame, with minimum value by 1 candle showing **65%** decrease and **45%** decrease in 5 number of candles. At 2.5cm all the values tend to become same with the values **40%**,**30%**,**50%** less than that of the single flame for 1,3,5 number of candles respectively.

Fig. 8 shows Flame Height V/S Distance for even number of candles, Flame height is more than the flame height of single flame for other cases and is interestingly maximum for 4 number of candles. At 1cm flame height is maximum for 2 candles, interestingly flame height of 6 candles is even lower than single flame height. At 1.5cm flame height for 2 candles and single flame is almost same but for 4 number of candles it is slightly more and maximum for 6 number of candles. At 2cm flame height for 2,4 number of candles is less than single flame and the value is lowest for 4 number of candles. At 2.5cm Flame height for 4 number of candles is maximum and 2 number of candles has the same value as that of single flame. The Flame Height values are **314.28%**, **600%**, **442.86%** for 2,4,6 number of candles, which is a large increment in flame height and 4 number of candles show more increment than 6 number of candles at 0.5cm, which is thrice as large as single flame. At 1cm, 2 number of candles show maximum increase in height with **85.71%** increment, followed by 4 number of candles with **21.43%** increment and 6 number of candles interestingly has minimum value with **42.86%** decrease in height. At 1.5cm, 2 number of candles has the same flame height as that of single flame and 4 number of candles show no change in height with same value of **21.43%** increment and 6 number of candles show sudden increase in its flame height with **71.42%** increment. From 2cm to 2.5cm, 2 number of candles flame height is almost constant and has almost same value as that of single flame with **7.14%** decrement, **0%** at 2cm and 2.5cm respectively. 4 number of candles show minimum value at 2cm with **42.86%** decrement and maximum at 2.5cm with **135.71%** increment. Within 1cm, 4 number of candles show drastic change in its value.

The heat transfer which should be same for all cases as predicted, becomes uneven with different set of conditions carried out in this paper for even and odd number of sources. So, we get varying spread rates which are different for different configurations and are really difficult to predict. Wherever spread rate is more, more heat is transferred to the unburnt region from burnt region and that is because of the energy added to it by external heat source (candles). So, different configurations of candles at different distances and different levels of energy or may take some energy from the pilot candle. This net algebraic sum of energy is forward heat transfer to the unburnt fuel and this forward heat transfer is directly proportional to the flame spread rate.

4. CONCLUSION

In this experimental setup Spread rates with different number of candles and different configurations at different distances has been studied. The effect of different configuration and number of sources present around a pilot flame decide its behaviour in that environment and can change it drastically. Number of sources placed at different distances and in different configurations(s) can change the behaviour of any flame within the reach of that flame, distance should be appropriate to allow heat transfer. As similar configurations are seen in combustion chambers, hence the orientation and proper designing of combustion chamber is very important. The different burners placed at different positions show different behaviour. This can also affect the efficiency of any Combustion chamber. As according to 2012 data analysis 30.14 thousand barrels of Aviation fuel are consumed per day, which costs lots of money, by selecting the proper design of the combustion chamber we can reduce the spread rate in short can reduce the fuel consumption per annum on large scale. For that one should know the behaviour of flames and fuel consumption rate with different number of candles having different orientations and one such attempt has been made through this paper.

REFERENCES

[1] Chamberlin, D,S., and Rose, A., “The flicker of luminous flames” Ind Eng Chem, 20(10), 1013-1016, 1928.

[2] Toong, T-Y., Salant Richard, F., Stopford John, M., “Mechanisms of combustion instability”. Symposium on Combustion/The Combustion Institute, 1301-1313, 1965.

[3] Gebhart, B., “Instability, transition, and turbulence in buoyancy-induced flows”. Annual Rev. Fluid Mechanics, 1973.

[4] Yuan, T., Durox, D., and Villermaux, E., “An analogue study for flam flickering”.Experiments in Fluids, volume 17, issue 5, pp. 337-349, 1994.

[5] Kermit, C. Smyth., Christopher, R, Shaddix., David, A, Everest., “Aspects of soot dynamics as revealed by measurements of broadband fluorescence and flame luminosity in flickering diffusion flames”. Combustion and Flame, Volume 111, Issue 3, pp. 185-194, 1997.

[6] Waldemar, W., “Flame flicker measurement in industrial conditions”. Proceedings Optoelectronic and Electronic Sensors III, Volume 3730, 1999.

[7] Sato, H., Amagai, K., and Arai, M., “Flickering frequencies of difuusion flames observed under various gravity fields”. Proceedings of combustion institute, volume 28, Issue 2, 2000.

[8] Kato, T., Saeki, K., Nishide, H. and Yamada, T., “Development of CNG fueled engine with lean burn for small size commercial van”. JSAE Reviews, 22, 365-368, 2001.

[9] Yilmaz, N., Donaldson, A, B., Gill, W., Lucero, R, E., “Imaging of Flame Behavior in Flickering Methane/Air Diffusion Flames”. Journal of Visualization, Vol. 12, No. 1, 47-55, 2009.

[10] Tanoue, K., Ogura, Y., Takayanagi, M., Nishimura, T., “Measurement of temperature distribution for theflickering phenomenon around the premixedflame by using laser speckle method”. Journal of visualization, Volume 13, Number 3, 2010.

[11] Guo, H., “Flame and Acoustic Waves Interactions and Flame Control”. PhD dessertation, School of Mechanical, Aerospace and Civil Engineering, University of Manchester, 2011.

[12] Blanchard, M., “Linear and nonlinear dynamics of laminar premixed flames submitted to flow oscillations”. PhD dessertation, École polytechnique, 2015.

[13] A. Hamins, M. Bundy, “Characterization of Candle Flames”,

[14] K. Okamoto, A. Kijima, Y. Umeno, H. Shima, “Synchronization in flickering of three-coupled candle flames”,

[15] Kitahata, H., “Oscillation and synchronization in the combustion of candles”. J. Phys. Chem. A 113, 8164–8168, 2009.

[16] Ghosh, S., Mondal, S., Mondal, T., Mukhopadhyay, A. & Sen, S. “Dynamic characterization of candle flame”. Int. J. Spray Combust. Dyn. 2, 267–284, 2010.

[17] Forrester, D. M., “Arrays of coupled chemical oscillators.” Sci. Rep. 5, 16994, 2015.

[18] Ishida, T. & Harada, S., “Oscillation of the light of flames” (in Japanese). Kagaku to Kyoiku 47, 716–716 1999.

[19] Omata, S., “Entrainment among coupled limit cycle oscillators with frustration.” Physica D 31, 397–409 (1988).

[20] Saxena, G., Prasad, A. & Ramaswamy, R., “Amplitude death: The emergence of stationarity in coupled nonlinear systems.” Phys. Rep. 521, 205–228 (2012).

[21] Liu, W. et al. “Oscillator death induced by amplitude-dependent coupling in repulsively coupled oscillators.” Phys. Rev. E 91, 052902 (2015).

[22] Grant, A. & Jones, J., “Low-frequency diffusion flame oscillations.” Combust. Flame 25, 153–160 (1975).

[23] Maxworthy, T., “The flickering candle: transition to a global oscillation in a thermal plume.” J. Fluid Mech. 390, 297–323 (1999).

[24] J. Buckmaster & N. Peter, “The Infinite candle and its stability-A Paradigm for flickering diffusion”, (1986).