FLAME COLOUR ANALYSIS FOR THE DROPLET COMBUSTION OF WATER-IN-DIESEL EMULSIONS

Zheng L.* (1)
Faik A. (1) (2)
Zhang Y. (1)

*Author for correspondence

(1) Department of Mechanical Engineering,
The University of Sheffield, UK
(2) Mechanical Engineering Department
Al-Mustansiryah University, Baghdad, Iraq

(*) E-mail: lzheng2@sheffield.ac.uk

ABSTRACT

The flame properties surrounding a small size fuel droplet are difficult to investigate due to the infinitesimal size, weak chemiluminescence and relatively fast combustion process. The present work focuses mainly on the flame colour detection and analysis of the combustion of an isolated fuel droplet. The tested fuels are diesel and its water emulsions at different mixing concentrations. High speed colour imaging and digital image processing have been applied for tracking droplet ignition, secondary atomization, and flame chemiluminescence. Side ignition of the droplet reduced interferences in visualizing flame spread during ignition and propagation. Flame propagation starts from the heating side all around the droplet, before the development of the more dominant yellow sooty flame. Flame chemiluminescence during the overall droplet lifetime has been evaluated using the digital flame colour discrimination (DFSC) approach of analysis. This analysis has been used for demonstrating the effect of emulsifying diesel by water in enhancing its combustion characteristics. Droplet secondary atomization and sub-droplet generation has also been tracked and analysed. The chemiluminescence of the flame surrounding each individual sub-droplet has been analysed using the same DFSC scheme. From the analysis, it is shown that the sub-droplets burn in a premixed like mode, especially at a later stage, rather than the diffusive mode of the original droplet.

INTRODUCTION

A large portion of the global energy requirements comes from burning liquid hydrocarbons in the form of sprays of small size droplets. Therefore, a thorough understanding of the basic physical processes related to spray and droplet combustion is essential not only in energy production, but also in propulsion, reducing combustion-generated pollution, and fire hazard control when handling liquid fuels [1].

Conversely, the flame is the zone where fuel and oxidizer meet and react, and it is the point of the highest temperature in combustion. Therefore, understanding the flame and its structure is a prerequisite for combustion explanation. Flame structure has been the subject of a variety of research works in droplet combustion [2-6]. However, more efforts have to be applied on the chemiluminescence and the luminosity of the flame surrounding fuel droplet. Flame luminosity is one of the easily observable main features, and each flame has its own spectrum of luminosity that can be used to characterize the combustion process. This luminosity is attributed to the spectra emitted from the electronically excited radicals CH^* and C_2^*, in addition to soot continuous spectrum [7].

On the other hand, water-in-diesel (W/D) emulsion is one of the methods used for enhancing the combustion efficiency of diesel fuel [8]. Due to the difference in boiling point and other physical properties between diesel and water, W/D emulsions may exhibit some physical phenomena prior to (or during) combustion, which is significantly effective in fuel atomization by accelerating the secondary breakup of the droplets within the fuel spray [9]. This breakup leads to the formation of smaller size droplets or sub-droplets that will evaporate and burn individually, which in turn will enhance the overall combustion efficiency of the total spray. Therefore, flame chemiluminescence analysis of droplet and sub-droplet combustion of water-in-diesel emulsions has been carried out in the present work in addition to pure diesel droplet. This analysis has been performed by colour processing of the acquired flame images using the *Digital Flame Colour Discrimination* (DFCD) scheme developed by [10-12] for extracting the time resolved CH^* and C_2^* emissions for the fuel droplets.

NOMENCLATURE

W/D	[-]	*Water-in-diesel*
*CH**	[-]	*Electronically excited state of CH radical*
C_2*	[-]	*Electronically excited state of* C_2 *radical*
*OH**	[-]	*Electronically excited state of* OH_2 *radical*
HSV	[-]	*Hue, Saturation, Value*

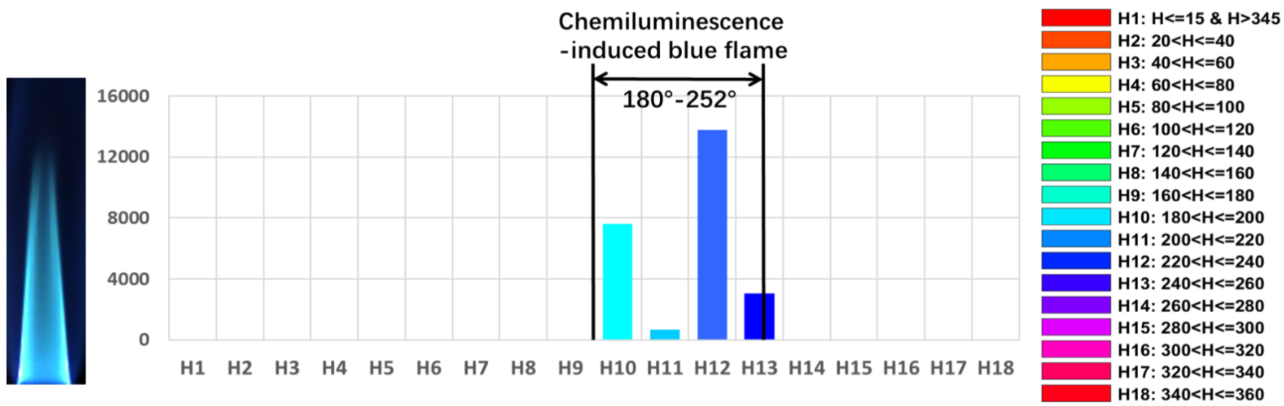

Figure 1 An example of premixed blue flame and their colour distribution on the Hue domain.

FLAME COLOUR PROCESSING METHODOLOGY

Combustion can be recognized by the visualization of the resulting flame. Therefore, flame colour can be used for describing the nature of combustion. The manner a chemical reaction is reflected in the emission of light during combustion is called flame chemiluminescence, which is attributed to the presence of OH^*, CH^*, and C_2^* radical emissions in the ultraviolet (UV), and visible (VIS) spectrum [7]. These radicals appear in the soot-induced flame region as well, which can be detected by the use of optical filters. However, in the bright yellowish flame region, the strong presence of carbon particles impedes the monitoring of OH^* and C_2^* radical emissions. The sensors of the CMOS camera can respond to the VIS spectrum, while the spectrum of OH^* emission corresponds to 310 nm. This means that, at the condition of inadequate luminosity and short exposure time, CH^* and C_2^* can be experimentally identified and can engage in the camera depending chemiluminescence research [13].

The chemiluminescence-induced flame is always visualized as a bluish flame, the signal of which is very weak to be captured by the colour digital camera. Therefore, the post processing, digital flame colour discrimination (DFSC) approach, is indispensable for a better flame visualization. Huang and Zhang have predicted that premixed flame signals are most likely distributed in the hue value band range from 180° to 252° in the HSV colour model space [10, 11]. After converting the RGB image captured by the digital colour camera, into HSV mode, the flaming region should be selectively enhanced to about 20-30 times. This enhancement is for extracting the distinctive details of the flame. Figure 1 illustrates the response of a premixed flame with an equivalence ratio of 1.37 on the hue domain. From the hue bar chart, approximately all the signals of the flame are distributed in the Hue region of H10 to H13 as claim by Huang.

EXPERIMETNAL WORK

EMULSION PREPARATION

Water-in-diesel (W/D) emulsions have been prepared prior to experiments according to the method followed and described by [12, 13]. Where an emulsifier (Polysorbate 80: HLB=15) has been added and stirred with the diesel to be emulsified, then the required water quantity is added gradually to the mixture. A 20000 rpm electric blender has been used for mixing the liquids for more than five minutes until a homogeneous milky white liquid is produced. 10%, 20%, and 30% water content by volume of W/D emulsions have been prepared and tested throughout this work in addition to the base diesel fuel. The W/D emulsions have been stored in containers during the tests, where no visible changes have been observed throughout the testing period.

EXPERIMENTAL SETUP

The schematic drawing of the experimental setup is shown in figure 2. A micro-fine syringe with hypodermic (0.33*12.7mm) needle has been used to generate and suspend the fuel droplet on a 75 µm cross-shaped silicon carbide (SiC) fibre mesh under room conditions. An optical setup consists of a Photron-SA4 high speed colour camera with Sigma zoom 24-70mm f/2.8 EX DG macro lens. The whole setup was self-illuminated by the resulting flame.

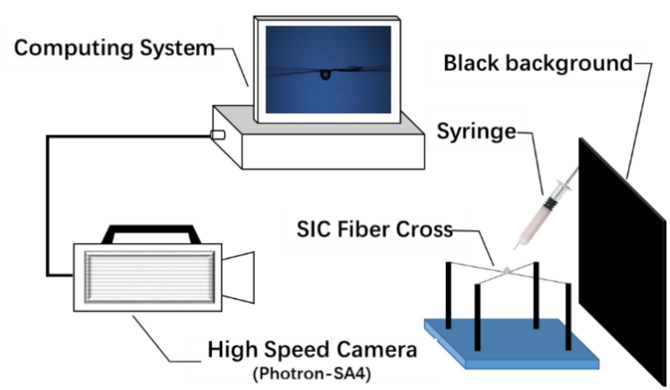

Figure 2 Experimental Setup.

To avoid the redundant noise signals affecting the weak signal detection, the experiments have been carried out in a completely dark room in addition to using black background behind the droplet. Using self-illumination is unusual in droplet combustion investigations. However, it has been used in the present work since the main objective is to study flame characteristics of the droplet combustion. Therefore, using direct or backlit lighting will affect the signal obtained from the flame. Additionally, flame propagation during droplet ignition cannot be visualized with the interference of the external light source. Consequently, no external light source has been used in the present work, and instead light emission from the flame resulting during droplet combustion has been utilized.

The droplet is ignited by a pilot butane flame produced by a micro lighter, and the images are recorded for the period of time between droplet ignition and flame extinction. The tests have been carried out on pure diesel, 10% W/D, 20% W/D, and 30% W/D emulsions. Each test has been repeated three times, with the droplet initial diameter being fixed at 2±0.2 mm. The acquired images have been stored in (TIFF) format and processed by specifically written algorithms using Matlab.

RESULTS AND DISCUSSION
IGNITION STAGE

Figure 3 shows a sequence of blue flame spread during the ignition of 10% water-in-diesel (W/D10) emulsion droplet. The upper row represents the original images recorded at the ignition stage with a shutter speed of 1/1000ss. These images show that from 1/1000ss to 9/1000s, no clearly visible flame can be discerned by bare eyes. While a small part of the yellowish diffusion region appeared in the 11/1000ss to 13/1000 s. This is due to the blue flame signal is quite weak compared to the orange soot emission. Therefore, 25 times selective digital image enhancement and 5 times overall light enfacement have been carried out. To avoid the blind magnification of all the pixels, the weak blue pixels have to be identified first through image processing [14]. The resulting corresponding images are shown in figure 3 (b). From which, flame initiation during ignition can be observed properly. During ignition, the blue flame initiates at the side of the ignition source, then propagates gradually towards the other side of the droplet. With the flame enclosing the droplet, the yellow diffusion flame appears and grows at the top. After ignition, the initially premixed fuel-vapour/air layer is consumed and the evaporation rate is accelerated. Because there is no sufficient time for the vapour to mix well with air, diffusion flame dominates the remaining lifetime of droplet combustion. The blue layer is then shown to surround the lower part of the droplet behind the evaporation zone because fresh air is drawn at this location due to the thermal buoyance cause by the droplet combustion.

Figure 4 shows the average duration of pure blue flame ignition process for droplet combustion of pure diesel, 10%, 20% and 30% water-in-diesel emulsions. This duration is the time delay from the first appearance of the blue flame to the observation of the yellow flame. The figure illustrates that emulsifying diesel by water leads to the increase of the premixed flaming period more than eight times from around five milliseconds to above forty milliseconds in the 10% emulsion and sixty milliseconds in the 30% emulsion. This may be due to the fact that the higher water concentration reduces the resulting combustion temperature. As a result, more time is required to generate soot.

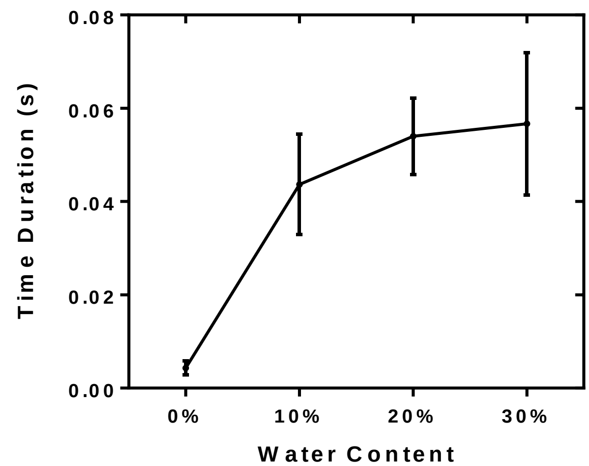

Figure 4 The time interval between the first appearance of blue flame and yellow flame.

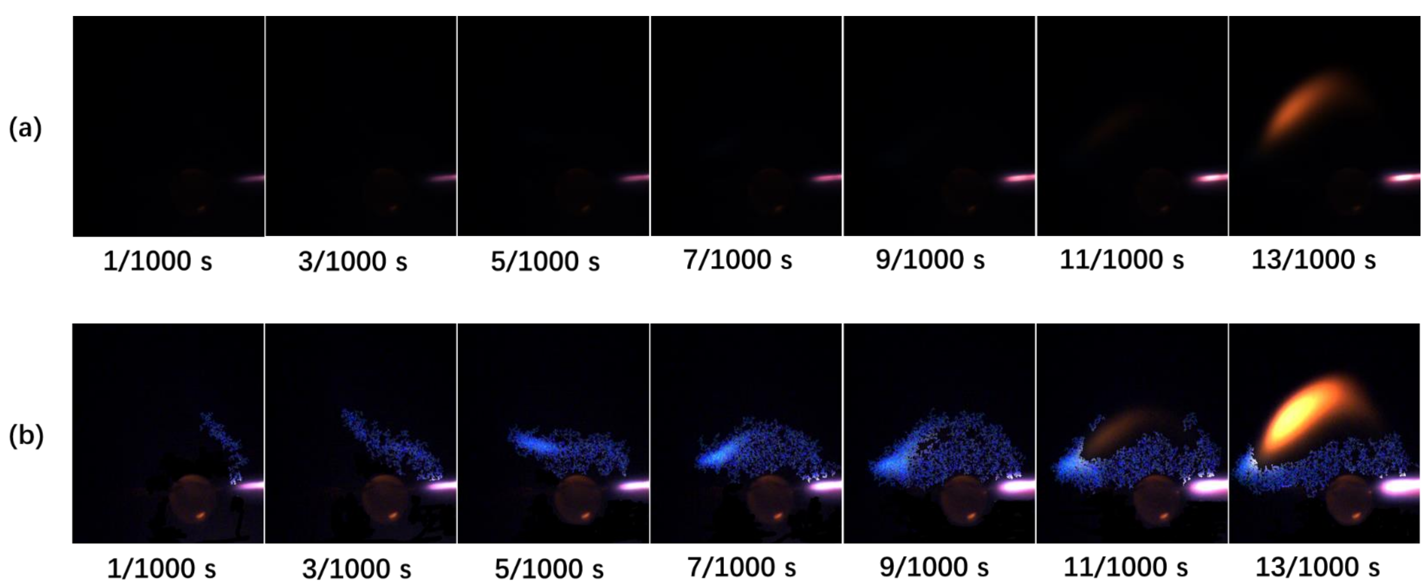

Figure 3 (a) Original images at shutter speed of 1/1000s at the ignition stage; **(b)** The corresponding selectively enhanced images.

BURNING AND EXTINGUISHING STAGES

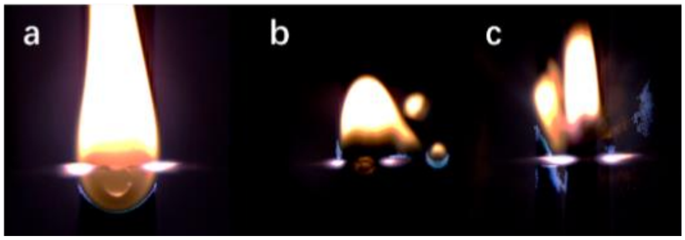

Figure 1 The difficult to visualise blue flame shown in a droplet burning after selectively enhancement: **(a)** steady burning, **(b)** secondary atomization, and **(c)** micro-explosion.

It is stated that under normal gravity conditions, the flame can be separated into three zones, which were described from outside to inside as faint violet zone, blue zone and yellowish dark zone [14]. For droplet combustion, two distinctive flame zones have been identified as shown in Figure 5. These distinctive zones are: a dim blue layer surrounding the outmost bottom of the droplet, and a bright yellow layer that covers the innermost of the droplet, which is also known as the soot-induced flame. However, the heated unburnt carbon particles dominate in this part of the flame. Therefore, its chemical composition cannot be found easily without the use of optical filters. Hence, the chemiluminescence analysis in the present work is based on the blue layers demanded the bottom of the flame shown in figure 5 (a). Additionally, the irregular blue flame generated from the combustion of the sub-droplets generated by droplet secondary atomization in figure 5 (b), and those generated by the droplet micro - explosion shown in figure 5 (c) have been analysed.

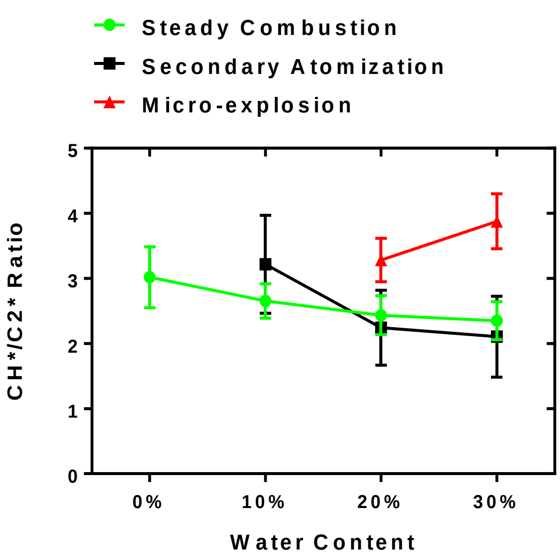

Figure 2 The CH^*/C_2^* ratio for the cases shown in Fig. 5.

Figure 6 shows the average CH^*/C_2^* ratio for the three cases mentioned above, namely, droplet steady combustion, secondary atomization, and micro-explosion. The calculations are based on the blue/green colour intensity ratio of the flame images. For both the steady combustion and droplet secondary atomization cases, the CH^*/C_2^* ratio experienced a decrease with increasing water content in the fuel. This can be attributed to the enhanced mixing resulted by water addition to diesel as previously suggested. This enhancement is stemmed mainly by the difference in volatility and boiling temperature between diesel and water leading to the more volatile component is transferred to the surface of the droplet while the less volatile one flows towards the centre of the droplet. Moreover, decreasing the flame temperature may decrease the CH^*/C_2^* ratio. Since adding water to diesel leads to decreasing flame temperature, due to decreasing the heating value of the fuel. Conversely, the CH^*/C_2^* ratio has shown to increase by increasing water content in the fuel during the droplet micro-explosion.

ECONDARY ATOMIZATION AND SUB-DROPLET EMISSION

Secondary atomization is the process of droplet disintegration into smaller sub-droplets. These sub-droplets are either continuing to burn separately or combine together to form a cloud of droplets. Secondary atomization is important in enhancing combustion efficiency by increasing fuel air mixing. In the present work, droplet secondary atomization has been investigated by studying flame chemiluminescence during this process.

Figure 7 illustrates the change in CH*/C2* ratio distribution of 10% and 20% water-in-diesel emulsions respectively during droplet secondary atomization. Below each ratio graph is the enhanced image from which the ratio has been evaluated. The sequence of images is selected to start on the initial appearance of blue layer around the sub-droplet and terminates with the sub-droplet vanishing and flame extinction. Camera shutter speed has been set to 1/1000 s. The overall process counts around five milliseconds. The blue region colour is selected and enhanced 30 times to manifest a proper visual view.

In figure 7 (a), the ratio ranges from 0 to 9 and displays the colour from dark blue to yellow, while in figure 7 (b), the range is from 0 to 10. The average CH*/C2* ratio is shown below each image as the symbol (R). As shown in the images at the bottom rows of figure 7, the flame surrounding each of the sub-droplets begins yellow in colour then rapidly turns to blue, indicating complete evaporation of the sub-droplet. After the post image processing, the same CH*/C2* ratio methodology described previously has been applied onto the blue flame generated by the sub-droplet. The burning process and flame propagation are represented in the upper line of Figure 7 (a and b). The highest CH*/C2* ratio is most likely distributed at the upwind side of the sub-droplet, where more yellow and green colour located. This is due to the relatively high transportation speed of the sub-droplet that leads to enhanced mixing between the fuel and the surrounding air. Sub-droplet complete consumption takes place with an entirely blue flame and a uniformly distributed CH*/C2* ratio. During flame extinction of both the 10% and 20% emulsions, the CH*/C2* ratio suddenly jumps to more than 30% compared with those of the previous intervals. Moreover, the CH*/C2* ratio for the 20%

water-in-diesel emulsion is shown to be lower than that of the corresponding 10% emulsion. This is the same finding of figure 6 of the original droplet.

CONCLUSIONS

In the present work, an experimental investigation of the flame characteristics during droplet combustion using high speed colour imaging is carried out. From the studies, the following conclusions have been drawn:

- Self-illumination imaging of droplet combustion can provide a good visualization of flame propagation during droplet ignition if combined with advanced digital image processing.
- The average period of premixed combustion during droplet ignition is increased by emulsifying diesel with water and this increase is proportional to the water content in the emulsion.
- The average CH^*/C_2^* ratio is shown to decrease with the increase of water content in the fuel mixture.
- The highest CH^*/C_2^* ratio is most likely distributed at the upwind side of the sub-droplet, where more yellow and green colour located. This is due to the relatively high transportation speed of the sub-droplet and the direct interfacing with the air that leads to enhanced mixing between the fuel and the surrounding air generating lean premixed region.
- The CH*/C2* ratio behaviour of the sub-droplet showed similar trends to those corresponding CH*/C2* values of the original droplet.

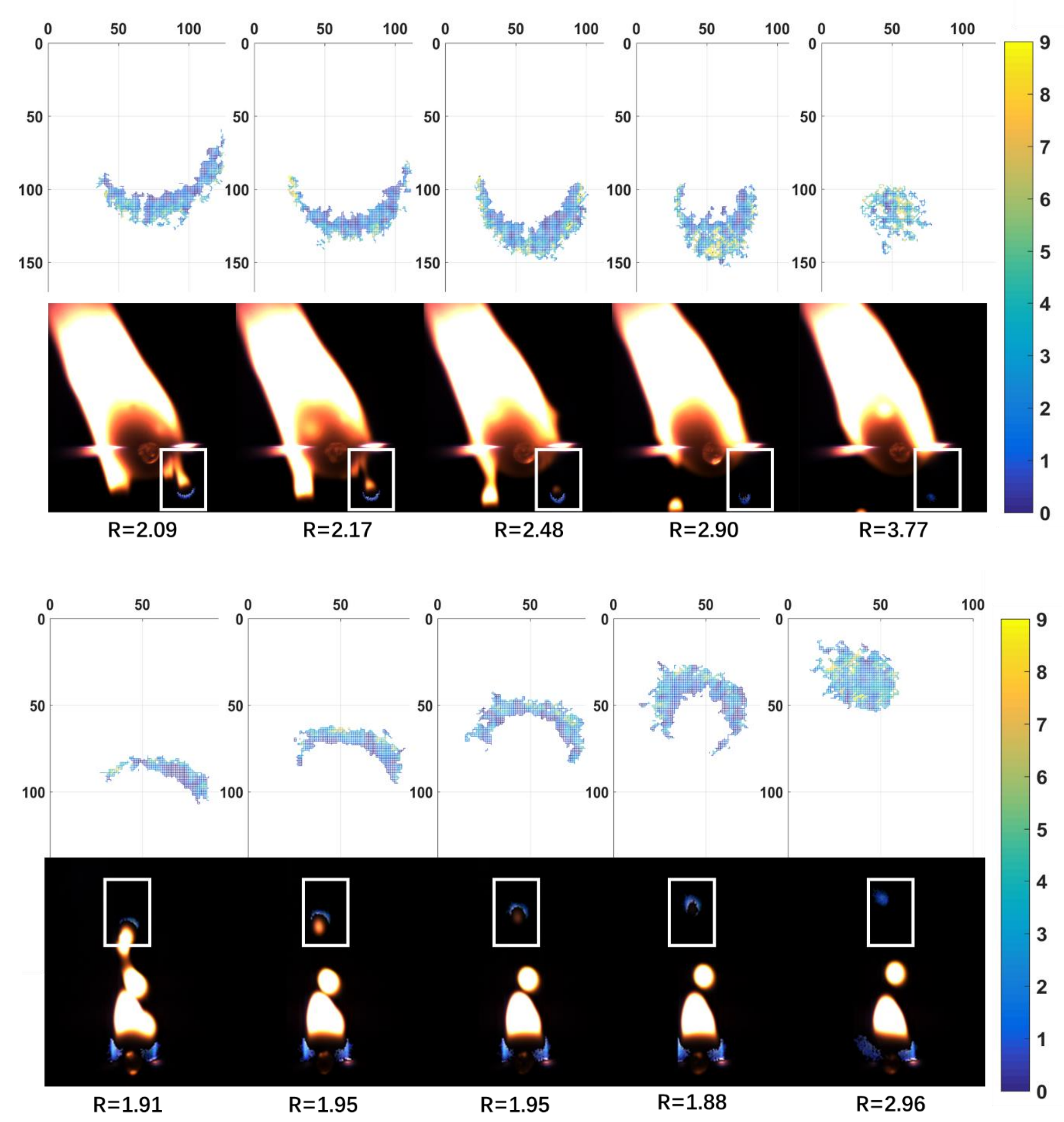

Figure 3 The sequence distribution of CH*/C2* ratio of secondary from the case **(a)** of 10% and the case **(b)** of 20% water emulsion.

ACKNOWLEDGMENTS

The research is partly benefited from the EPSRC projects: EP/K036750/1 and EP/G063044/1. Additionally, the second author is obliged to the scholarship awarded by the Higher Committee for Education Development (HCED) in Iraq.

REFERENCES

[1]. Williams, F. A., "Fiber Supported Droplet Combustion (FSDC)", NASA Lewis Research Center, 1997.

[2]. Reichenbach, R., D. Squires, Penner, S. S., "Flame propagation in liquid-fuel droplet arrays." *Symposium (International) on Combustion*. Vol. 8(1), 1961, pp. 1068-1073.

[3]. Gollahalli, S. R., Brzustowski, T. A., "Experimental studies on the flame structure in the wake of a burning droplet." *Symposium (International) on Combustion*, 14(1), 1973, pp. 1333–1344.

[4]. Mikami, M., Niwa, M., Kato, H., Sato, J., & Kono, M., "Clarification of the flame structure of droplet burning based on temperature measurement in microgravity." *Symposium (International) on Combustion,* Vol. 25(1), 1994, pp. 439-446.

[5]. Dwyer, H. A., B. D. Shaw, Niazmand, H., "Droplet/flame interactions including surface tension influences." *Symposium (International) on Combustion*, vol. 27(2), 1998, pp. 1951-1957.

[6]. Liu, Y. C., Avedisian, C. T., "A comparison of the spherical flame characteristics of sub-millimeter droplets of binary mixtures of n-heptane/iso-octane and n-heptane/toluene with a commercial unleaded gasoline." *Combustion and Flame,* 159(2), 2012, pp. 770-783.

[7]. Gaydon, A. G., *The Spectroscopy of Flames*, 2nd Edition. Chapman and Hall, 1974.

[8]. Kadota, T., and H. Yamasaki. "Recent advances in the combustion of water fuel emulsion." *Progress in energy and combustion science,* 28(5), 2002, pp. 385-404.

[9]. Shinjo, J., Xia, J., Ganippa, L. C., Megaritis, A., "Physics of puffing and microexplosion of emulsion fuel droplets." *Physics of Fluids,* 26(10), 2014, pp. 103302.

[10]. Huang, H. W., Zhang, Y., "Flame colour characterization in the visible and infrared spectrum using a digital camera and image processing." *Measurement Science and Technology,* 19(8), 2008, pp. 085406.

[11]. Huang, H. W., Zhang, Y., "Dynamic application of digital image and colour processing in characterizing flame radiation features." *Measurement Science and Technology,* 21(8), 2010. pp. 085202.

[12]. Mishra D. P., Patyal A., and Padhwal M., "Effects of gellant concentration on the burning and flame structure of organic gel propellant droplets," Fuel, vol. 90, no. 5, pp. 1805–1810, 2011.

[13]. Aldred, J. W., Patel, J. C., Williams, A., "The Mechanism of Combustion of Droplets and Spheres of Liquid n-Heptane." *Combustion and Flame*, Vol. 17(2), 1971, pp. 139-148.

[14]. Huang HW, Zhang Y. Digital colour image processing based measurement of premixed CH4 + air and C2H4 + air flame chemiluminescence. Fuel 2011;90:48–53.