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Time-resolved 3D Investigation of the Ignition Process of a Methane Diffusion Impinging Flame

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ABSTRACT

The ignition process of a methane diffusion impinging flame was investigated experimentally, using high speed schlieren/stereo imaging and image processing techniques. Two types of flame can be identified during the ignition process: premixed like flame with weak blue colour and diffusion flame with yellow-reddish colour. The 3D structure of blue flame after enhancement and yellow flame has been reconstructed and analysed seperately. The ratio between green and blue colour intensity is used to provide indications of the global fuel/air mixture state of the blue flame, which is found to correlate well with the flow conditions and flame propagation characteristics.

Keywords: Impinging flame; Ignition; High speed imaging; Schlieren; 3D reconstruction.

INTRODUCTION

Jet diffusion flame is one of the most widely applied combustion modes in industrial applications. Flame impinging on solid wall is unavoidable in confined combustion systems, such as internal combustion engine, gas turbine, etc. The fire disaster caused by gas leakage in a confined space is also a typical diffusion impinging flame. Thus the impinging flames have been intensively studied for a variety of applications. Most of the impinging studies focused on the effects of heat transfer characteristics with physical burner and plate geometries [1-3], equivalence ratio and Reynolds number [4], thermal efficiency [5,6] and plate materials [4]. Review papers have been published regarding impinging flame heat transfer [7] and its applications [8]. It is found that different combustion modes of impinging flames can be established under identical nozzle flow conditions only by changing the initial ignition locations [9, 10]. However, the aforementioned research mainly focused on the flame-to-wall heat transfer characteristics; the investigation of real flame structure and propagation dynamics during ignition process is rarely reported yet.

The ignition process is a fundamental research topic in combustion science. The investigation on the combustion transition from a non-reacting (forced ignition) or a slow reacting state (auto ignition) to a fully burning state is important for many technological applications, such as the relighting of an aviation gas turbine, the spark-ignition engine and diesel engine. The process from ignition to flame establishment is a complex phenomenon involving complicated flow conditions and chemical reactions. The modern high speed camera offers an effective tool to get time-resolved flame images. The digital colour images encode the captured visible radiation into three discrete signal ranges with sensitivity peaking in the R, G and B portion of the visible electromagnetic spectrum. In this form, digital colour cameras can be considered as a device that offers limited multi-spectral discrimination in addition to its spatial functionality. Based on this, a Digital Flame Colour Discrimination (DFCD) combustion quantification scheme has been established by Huang et al. [11]. The DFCD approach has already been successfully applied in the characterisation of diffusion and premixed hydrocarbon flames, providing the trends of spectroscopic-derived CH* and C_2* emission distributions over a range of equivalence ratios [12], and the local fuel/air mixture states [13]. Previous study found that the characteristic flame colour fidelity induced by known visible intermediate radicals such as the CH* and C_2* are confined to discrete ranges of occurrences in both the *RGB* and the *H* of the *HSV* colour space. The blue and green emissions (in the RGB colour space) were found to model well with the CH* and C_2* chemiluminescence intensities, respectively [12]. The blue and green intensity can be integrated in one image to denote the CH* and C_2* chemiluminescence emissions, which can be captured simultaneously onto the same detector [15]. The CH*/C_2* ratio has been shown to have a linear response to equivalence ratio for premixed propane and methane flames [15-16].

The local flame structure is of great help to gain physical insights into the combustion process. However, the real flame structure is irregular and cannot be well understood only by 2D images. One aim of this study is to investigate the global 3D flame structure and dynamics using high-speed stereo imaging techniques. Stereoscopic or 3D photography works because the human brain is able to recreate the illusion of depth with two images at slightly different directions. Once the stereo image pairs are available, they can be visualized in 3D optically using a pair of 3D glasses. This method is widely used in 3D TV and films. It has also been proven to be very useful for the visualization of flame dynamics both in laboratory and industrial combustors. Modern industry and research uses stereoscopic technology to detect and record 3D information from specific optical setups. Based on the projective geometry theory, the optical parameters of the 3D system can be obtained through calibration processes. The 3D coordinates can then be reconstructed based on the optical parameter and corresponding points extracted from the stereo image pairs. Once the 3D flame structure is reconstructed digitally, it can be visualized on a computer screen by using advanced functions such as rotation, which will enable a much more clear view than a 2D image. In this study, a stereo adapter is attached to the front of a high-speed camera lens to record the stereo image pairs of a methane impinging flame. The stereo adapter consists of four delicate flat mirrors and is able to form two images at slightly different angles on the camera focus plane. In this stereo system, only one camera is required, which is easy and flexible to be implemented without the need of synchronization between recording instruments. The camera calibration and digital reconstruction algorithms established by Zhang [17] are applied to obtain the real flame structures.

In this study, the ignition process of methane diffusion impinging flames has been investigated using high speed colour/stereo imaging, image processing and 3D reconstruction techniques. Moreover, the high-speed schlieren imaging technique is used to visualize the hot gas evolution during the ignition process. The results aim to gain phenomenological insight into the nature of the impinging flame and also provide definitive experimental data for future modelling validation.

EXPERIMENTAL SETUP

The schematic layout of the experimental apparatus is shown in Fig. 1. The burner allows the flow of fuel through a centre nozzle (4.57 mm in diameter) to impinge onto a steel plate (300 mm in diameter, 10 mm in thickness) held at a distance of 150 mm from the nozzle exit by a steel holding frame. The device for holding the plate consists of a steel frame with an upper ring with 0.9 m in diameter, which has three small arms attached in order to hold the plate securely with minimal disturbance to the flow. The plate can be traversed vertically using a knife edge system which is accurate to 1 mm and the design ensures that the plate is held horizontally without wobbling. In this investigation, methane was fed into the burner through a set of dedicated flow controllers and manual valves before reaching the nozzle exit. The flow controller was electronically controlled using the Labview 10.0 software.

For the acquisition of schlieren images, a z-type schlieren mirror configuration was employed to observe both the non-reacting and reacting flows during the ignition process. The schlieren system consists of a 500 W Xenon lamp source and two $\lambda/10$

parabolic mirrors which were 0.3048 m (12 in.) in diameter and 3.048 m (10 feet) in focal length. A high-speed monochromic imaging camera (Photron SA3) was used to capture the schlieren images of the flame from a direction perpendicular to the plate.

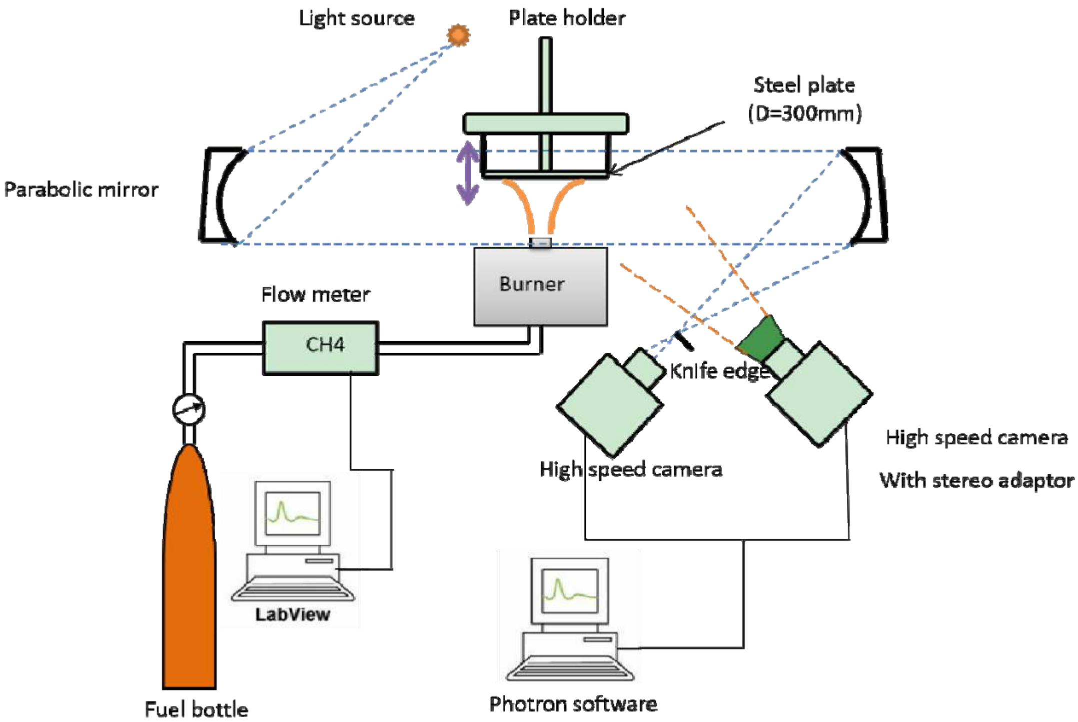


Fig.1 Schematic experimental setup.

For stereo reconstruction, a different high speed digital colour camera was utilised (Photron SA4) and positioned at a tilted angle to the plate to capture the flame establishment process from the instance of ignition. An Asahi Pentax 52 mm stereo adapter was attached to the front of a Sigma EXDG 24–70 mm, f2.8 zoom lens to capture a pair of images at two slightly different viewing angles. The adapter consists of four delicate reflection mirrors; more details about its specification can be found in [18]. For data acquisition, the two high speed cameras were synchronized in a master and slave mode to capture both the schlieren and colour stereo images simultaneously. The frame rates of the two cameras were both set at 500 fps, at the maximum system resolution of 1024 by 1024 pixels. The shutter speed for colour imaging is 1/500 s, while for schlieren is 1/500,000 s.

RESULTS AND DISCUSSION

In this study, a methane diffusion flame with fuel flow rate fixed at 4.2 l/min was considered, which induces an exit velocity of 5 m/s and Reynolds number of 1280. The igniter to initiate the burning is an out-of-shelf product used for home cooking, which has a long handle and uses butane as fuel. The igniter is placed at the nozzle exit, under which a plate flame will be finally formed at the fully-burning state. A T-shape cross section of the fuel/air mixture can be observed before ignition.

Previous studies by Huang and Zhang [13] found that there is weak blue flame at the initial stage during ignition process, which is from the radical CH* and C2*chemiluminescence emissions. However, this kind of blue flame is hard to be observed directly from the original high speed colour images. Based on the previous investigations, suitable ranges of Hue (H), for signifying the different flame colour appearance, have been identified using varying hydrocarbon fuel compositions [11, 12 and 19]. With post-processing of the colour signals, the soot induced (yellow-reddish) and radical chemiluminescence-induced (green-bluish) flame can be separated accordingly. The weak blue flame can then be enhanced on purpose to be visualized easily. In this study, the blue-enhancement has been applied on the images at initial stage of the ignition. The time-resolved processed colour images and schlieren images have been shown in Fig. 2 and Fig.3 respectively. The time origin is defined from the schlieren image when the flame from the igniter reached the fuel/air mixture. It can be observed from the schlieren images that the fuel/air mixture formed a T-shape cross section before ignition due to the blockage of the solid wall. After the ignition initiation, the flame propagates upwardly from the nozzle exit. Two types of flame can be observed from colour images: blue flame showing premixed flame characteristics due to fuel/air mixing and yellow-reddish flame showing diffusion flame characteristics. Regarding the flame propagation characteristics observed through time-dependent colour and schlieren images, the blue flame development can be divided into three stages roughly: (I) upward propagation stage (0-70ms), (II) transition stage (70-90 ms) and (III) radial propagation stage (90-120 ms). In stage I, the blue flame is formed at the flame front area after ignition and propagates upwardly. In stage II, it can be seen from schlieren images that the flame front begins to impinge onto the solid plate. In stage III, the flame expands outwardly in a ring-shape along the solid plate. After 120 ms, the blue flame is vanishing gradually and the flame is yellow-reddish dominated.

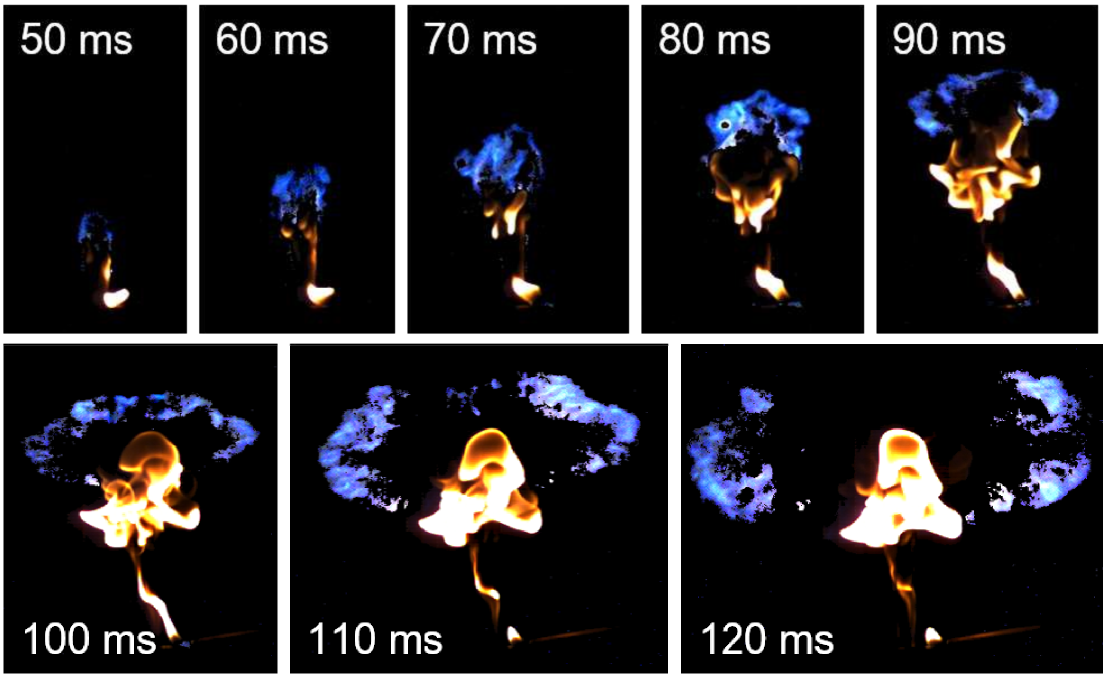


Fig. 2 Colour image sequence with selectively enhanced weak blue flame.

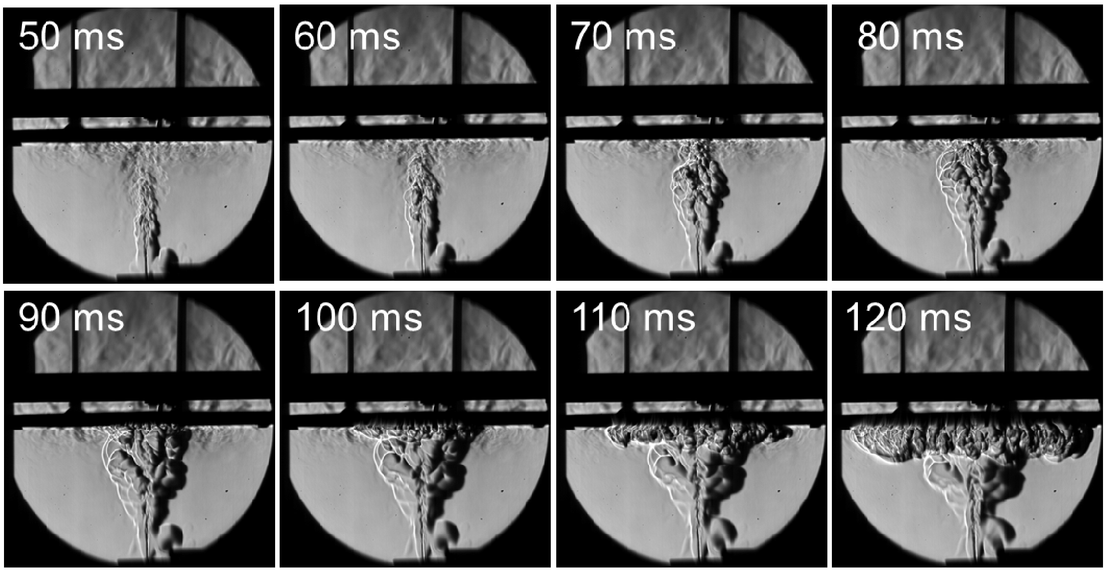


Fig. 3 Schlieren image sequence at the initial stage of ignition.

Using a stereo adapter, two images at different angles can be captured in one frame on the camera screen. The 3D flame structure is then reconstructed through the well-developed image processing procedures. With the help of blue flame enhancement, the 3D reconstruction algorithm can be applied to resolve the real structure of the blue flame. In order to show the blue flame clearly, the blue and yellow flame in the same image is separated using DFCD technique and the reconstruction is only conducted on blue flames. A sample pair of stereo images of blue-enhanced flame at 90 ms is shown in Fig. 4. The reconstructed blue flame structures are shown in Fig.5, with the same view angle in 3D coordinates. It can be seen that the blue flame with a hollow core is formed at 50 ms. The flame propagates into the core area and expands gradually from 60 ms to 70 ms. After the flame reaching the plate, the hollow blue flame in a ring shape is formed again from 80 ms. The diameter of the flame ring is increasing with time. By rotating the 3D structure at different view angles, some irregular up and down structure in the ring flame can be observed, which is hard to be recognised only using 2D images.

Fig. 4 Stereo enhanced blue flame image pair at 90 ms.

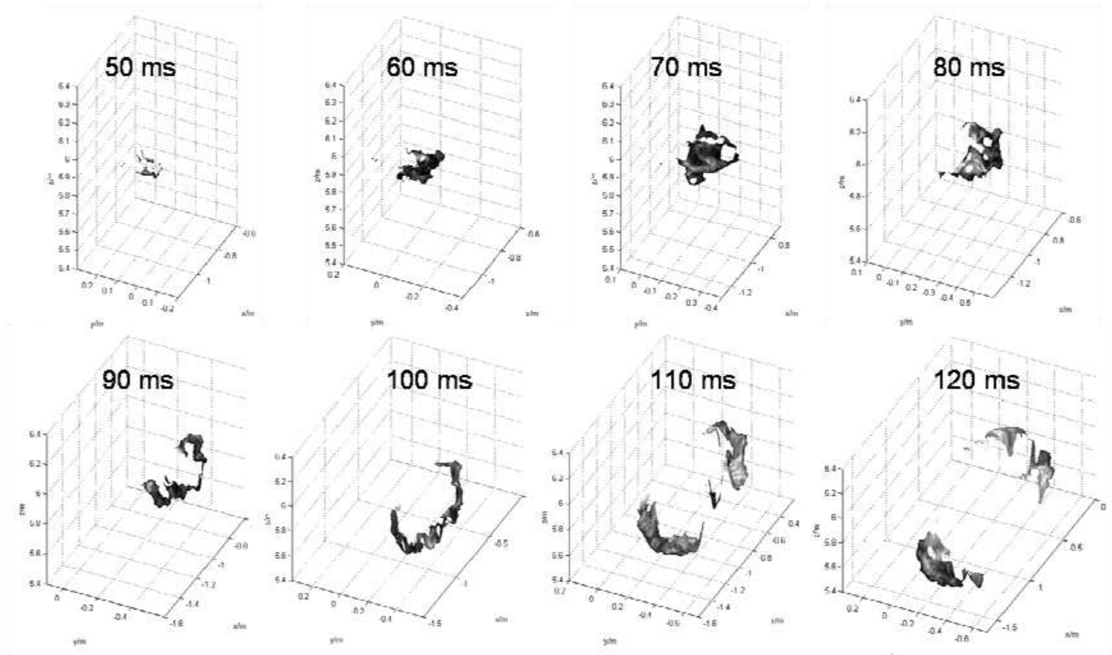


Fig. 5 3D structure of the enhanced blue flames at different time instances.

The integration of blue and green colour intensity indicates the 1D detection of CH* and C2*chemiluminescence emissions, which is plotted in Fig.6 with the variation with time. It is seen that the changing trends of blue and green colour intensities are similar, while blue colour intensity is higher than green. The variations of blue and green colour intensities show different trends in the three stages of blue flame propagation. In stage I, the flame is propagating upwardly with time and the blue flame intensity is increasing with time. In stage II, the impinging effect results in a decreasing of the flame intensity. In stage III, the flame is propagating outwardly in a ring shape. The flame intensity is increasing at first because of increasing of the ring radius. A maximum value appears at 112 ms, after which the blue flame intensity is decreasing with time because the accumulated combustible fuel/air mixtures is consumed up.

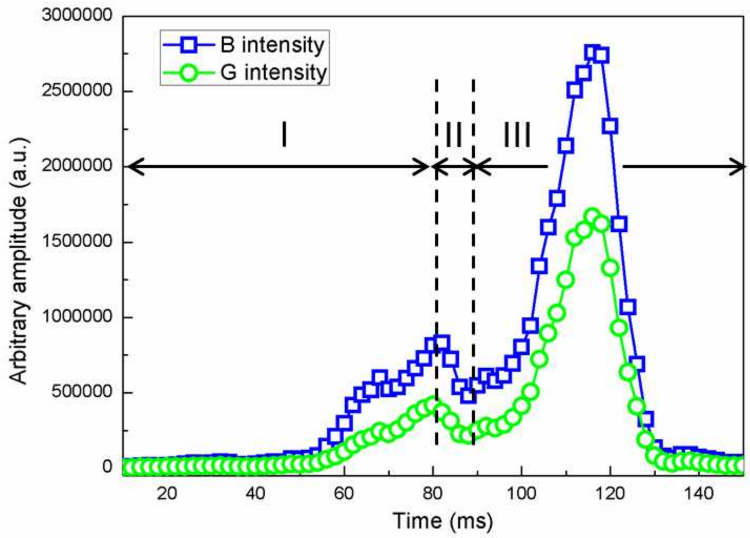
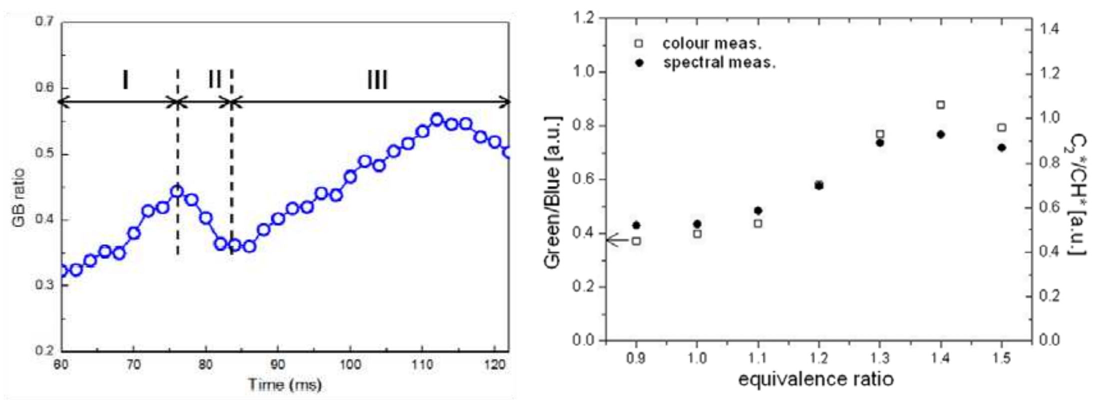


Fig. 6 Total blue and green pixel intensity of blue flames changing with time.

The C_2*/CH* ratio of two radical chemiluminescence intensities have been previously used to provide indications of the global fuel/air mixture state of a premixed flame [16, 17], which can be estimated by the blue and green colour intensity ratio (GB ratio) at the local pixels. The characteristic mean value of the GB ratio in one image is calculated based on the Gaussian distribution algorithm, as shown in Fig.7a. Since the GB ratio is a kind of mean value of the whole image, only the images with large blue and green intensity values from 60 ms to 122 ms have been analyzed. The GB ratio variation at different equivalence ratios between 0.9 and 1.5 of premixed methane flames have been obtained by Migliorini et. al [14], which shows a good match with the spectral measurements, as shown in Fig.7b. It can be seen that the GB ratio is increasing with the equivalence ratio on the whole, only with a slight decreasing when the equivalence ratio is increased from 1.4 to 1.5. Since the GB ratios in Fig.7a are lower than 0.6, which can be considered to be increasing with the equivalence ratio. It can be seen from Fig.7a that the GB ratio variation can also be divided into three stages, which corresponds with the three stages of blue flame propagation roughly. During stage I, the flame is propagating upward and the GB ratio is decreasing, which means the average equivalence ratio of the blue flames is increasing. In a non-premixed fuel jet flow, the equivalence ratio of the fuel/air mixtures varies from 0 to infinity from outside to the jet centre. It can be seen from the flame in 3D space shown in Fig.5 that, the flame is propagating from outside to jet centre gradually in stage I. Thus the equivalence ratio will increase. In stage II, the equivalence ratio is decreasing with time. That is because the impinging effect enhances the fuel/air mixing and a leaner fuel/air mixture is formed at the plate centre area. In stage III, the ring flame is formed and the average equivalence ratio is increasing with time before 110 ms. The main reason is that the flow velocity along the plate is decreasing away from the plate centre. As a result, the air entrainment into the fuel is poor. Thus fuel/air mixture will remain fuel rich. After 110 ms, the equivalence ratio begins to decrease again. That is because the fuel amount is decreasing around the edge of the plate; thus the mixtures become leaner again.



(a) (b)

Fig. 7 (a) The GB ratio variation of blue flame with time; (b) The GB ratio variation at different equivalence ratios of methane premixed flames [15].

The blue flame only appears in the initial stage after ignition, which vanishes gradually after the premixed fuel/air mixture is consumed up. Then the diffusion yellow-reddish flame is dominated until the steady-state diffusion impinging flame is established. The yellow-reddish flame is investigated in a longer time scale than the blue flames. The time-resolved colour and schlieren imaging sequences are shown in Fig.8 and Fig.9 respectively. It can be seen that the flame structure at initial stage is irregular. Very bright white flame can be observed, which means there exists intensive chemical reactions. After 150 ms from ignition, a round disc flame begins to form, with curling structures. These vortex rings are formed parallel to the plate and develop downstream in the radial direction. A round disc diffusion flame is formed finally after 400 ms. Two regions can be recognized from the flame and schlieren images: the primary jet region before the jet flow touches the impinging wall and the wall jet region. In the wall jet region, the impinging flow progresses into a radial wall-jet formation as a consequence of the jet deflection; and a boundary layer appears as the flow develops in the radial direction after the impingement. The thickness of the boundary layer is decreasing with time due to the consumption of accumulated fuel before ignition; the disc flame can be observed to be more flat while expanding outwardly. No obvious vortex ring of the jet in the stream-wise direction is formed under buoyancy driven forces at the beginning of flame establishment. However, a regular vortex shedding phenomena can be observed in the jet region in a steady sate impinging flame as described in [20].

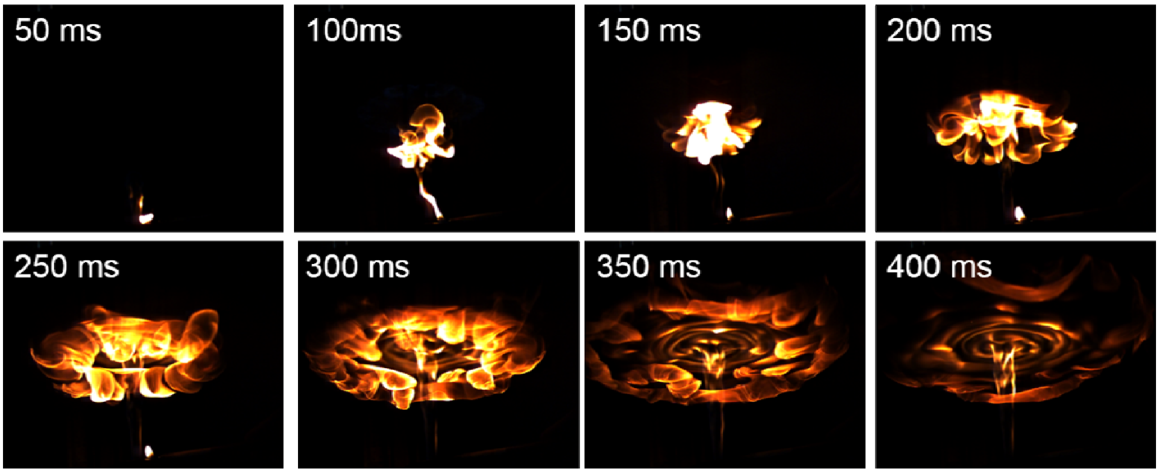


Fig. 8 Time-resolved colour images of the methane diffusion impinging flame.

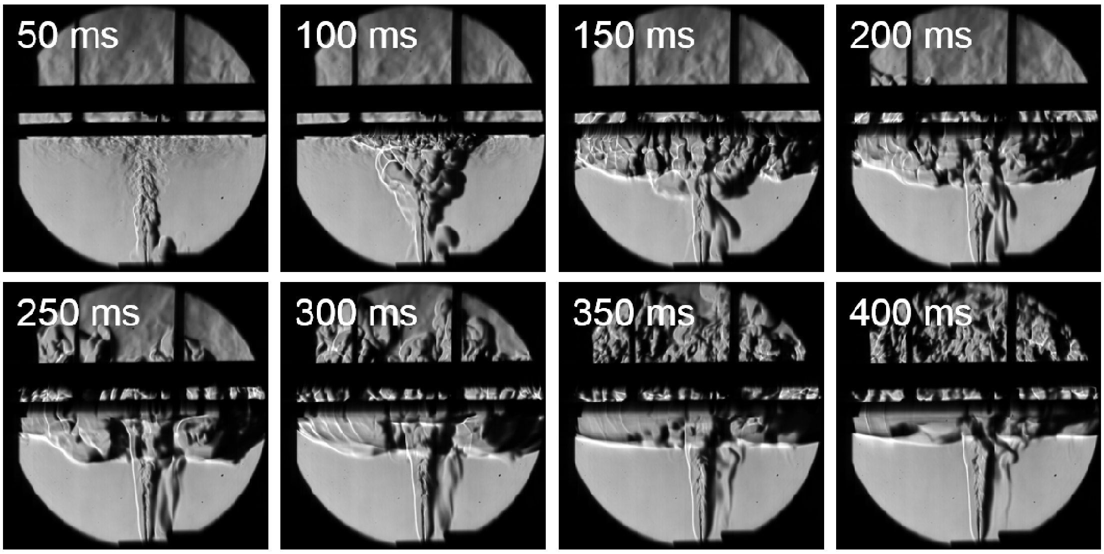


Fig. 9 Time-resolved schlieren images of the methane diffusion impinging flames.

In order to resolve flame evolution in space, the 3D structure of the yellow diffusion flames have been reconstructed based on stereo imaging and 3D reconstruction algorithms. The results at seven time steps from 100 ms to 400 ms after ignition are shown in Fig. 10. It can be seen that the flame at 100 ms is tortuous in space. At 150 ms, the flame becomes flatter due to the impinging effect onto the solid wall. At 200 ms, wavy-like flame structures can be observed on the disc flame. After that, the amplitude of the wavy structure becomes lower with time, while the disc flame diameter increases.

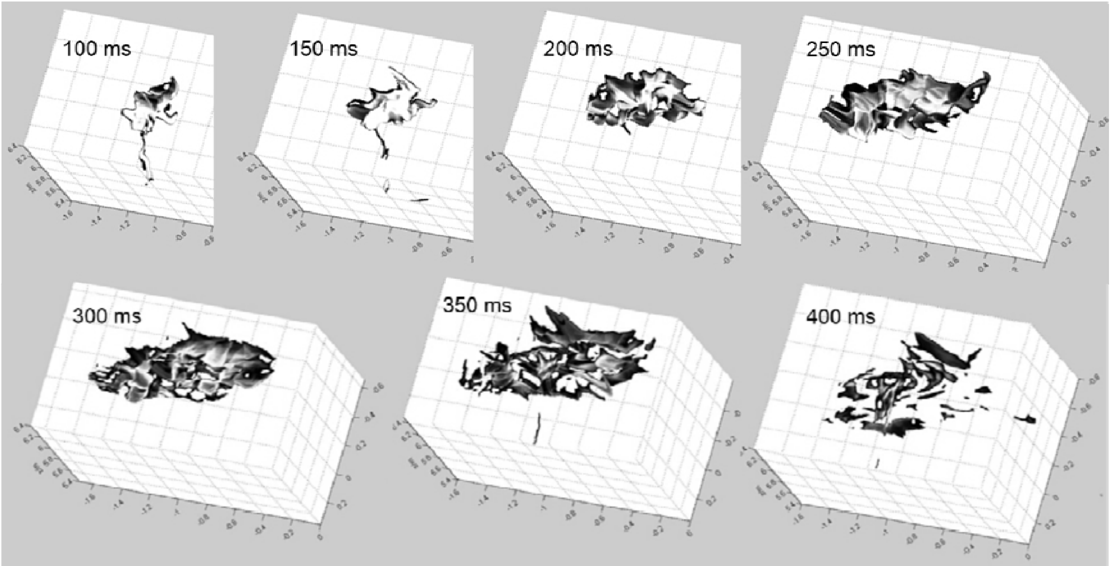


Fig. 10 3D flame structure at different time instance after ignition.

CONCLUSION

The ignition process of a methane diffusion impinging flame has been investigated using high speed colour/schlieren imaging, colour enhancement and digital 3D reconstruction methods. The 3D structure of premixed blue flame and diffusion yellow flame has been reconstructed separately. A T-shape cross section of the fuel/air mixture can be observed before ignition. The weak blue flame at the initial ignition stage has been purposely enhanced for a more clear visualization. It is found that the blue flame appears at the flame front during the upward propagation process and it is in a shape of round ring after reaching the plate. It can be observed from 3D results that the blue flame starts from the outside of the jet and is progressing into the jet centre area while it is moving upward; then the blue flame begins to expand outwardly in a ring shape after reaching the solid disc. The blue flame is vanishing after 120 ms and the flame is then yellow colour dominated. The ratio between green and blue colour intensity of blue flames, which is a good indication of the average equivalence ratio, has been calculated and analysed. The results show that the GB ratio variation matched the expected flow condition change well. It is observed from 3D results that the yellow diffusion flame at initial stage is irregular and tortuous in space. After reaching the solid wall, a wavy flame structure can be observed in the disc flame, which becomes flatter while it is expanding in radial direction. The steady-state impinging diffusion flame is established after about 400 ms. The detailed experimental investigation of the flame structure is of great importance in understanding the ignition phenomena and provide experimental data for the validation of future numerical simulations.

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