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EXPERIMENTAL INVESTIGATION OF THE IGNITION PROCESS OF A METHANE DIFFUSION IMPINGING FLAME

Qian Wang[a]*, C.Y. Zhao[a], Yang Zhang[b]
*Author for correspondence
[a] School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai, 200240, China
[b] Department of Mechanical Engineering, University of Sheffield, Mappin Street, Sheffield, S1 3JD, UK
Email: qianw2006@gmail.com

ABSTRACT

The ignition process is of great importance both in fundamental combustion research and industrial applications. In this study, the flame structure and propagation characteristics of a methane diffusion impinging flame were investigated experimentally. Both high speed schlieren and stereo imaging techniques were applied to visualise the hot gas and visible flame evolution from ignition to flame establishment. It was found that the visible flame at the initial stage of ignition is highly three dimensional (3D) in space. The digital 3D reconstruction methods based on stereo images were applied to obtain the real flame structures. It can be seen from the 3D results that a long flame was formed tortously at first; after the flame reached the impinging plate, a round and wavy flame structure was observed; finally a flat round flame with a slender conical bottom was established. Moreover, the weak blue flame at the very beginning of ignition has been enhanced selectively for a more clear visualisation. It is found that the blue flame was in a ring-like shape locating at the top of the flame front. The diameter of the ring is increasing with time after it reaches the solid disc. After 120 ms over ignition initiation, the blue flame is vanishing gradually and the dominated flame is in yellow-redish color only.

INTRODUCTION

Jet diffusion flame is one of the most widely applied combustion mode 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 local flame structure is of great help to gain physical insights into the combustion process. The modern high speed camera offers an effective tool to get time-resolved flame images. However, the real flame structure is irregular and cannot be well understood only by 2D images. One aim of this article is to investigate the global 3D flame structure and dynamics by 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 without the need of synchronization between recording instruments. The camera calibration and digital reconstruction algorithms established by Zhang [11] are applied to obtain the real flame structures. Moreover, the high-speed schlieren imaging technique is used to visualize the hot gas evolution during the ignition process. It is believed that the results may give improved phenomenological insight into the nature of the impinging flame and also provide definitive experimental data for comparison with detailed modelling results.

EXPERIMENTAL SETUP

The schematic layout of the experimental apparatus and the burner structure 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 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 controller 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 arrangement configuration was employed to observe both the non-reacting and reacting flows during the ignition process. The schlieren system consists of a 500W Xenon lamp source and two $\lambda/10$ parabolic mirrors which were 0.3048 m (12 in.) in diameter with focal length of 3.048 m (10 feet). 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.

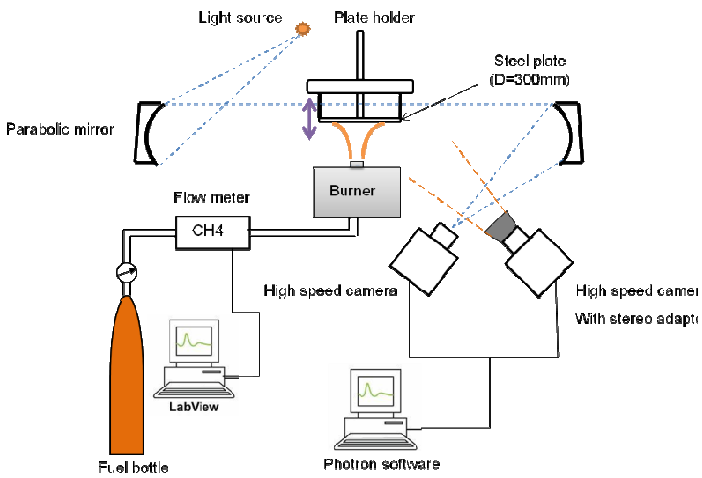

Fig. 1 Schematic of experiment setup

For colour 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 [12]. 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, which induces an exit velocity of 5 m/s and Reynolds number of 1280, was considered. 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. The time-resolved color and schlieren imaging sequences are 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

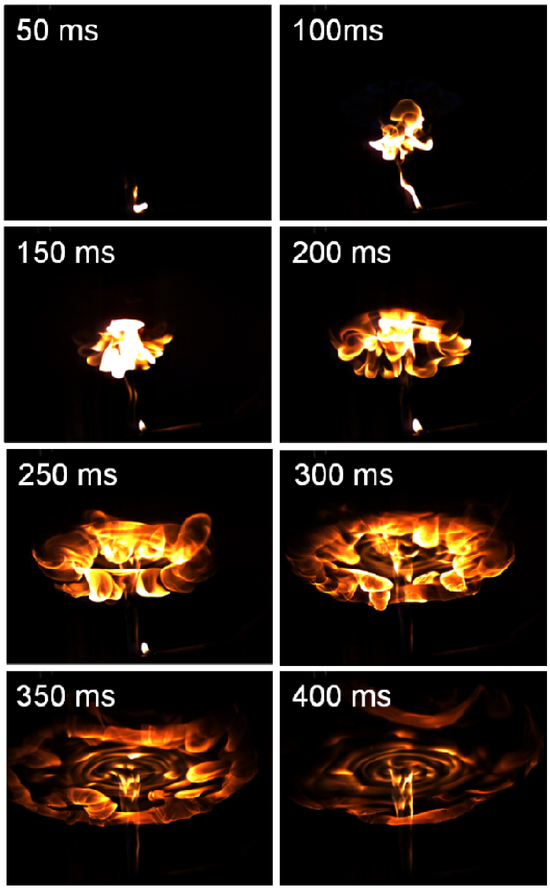

Fig. 2 Time-resolved color images of the methane diffusion impinging flame

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. The flame reaches the solid wall after 10 ms; then the flame begins to expand from the plate centre outwardly. A round disc diffusion flame is formed finally after 40 ms. It can be seen from the colour images that the flame structure at initial stage is irregular. Very bright white flame can be observed, which means there exists intensive chemical reactions. After 20 ms from ignition, a round disc flame begins to form, with curling structures. The disc flame becomes more flat while expanding outwardly.

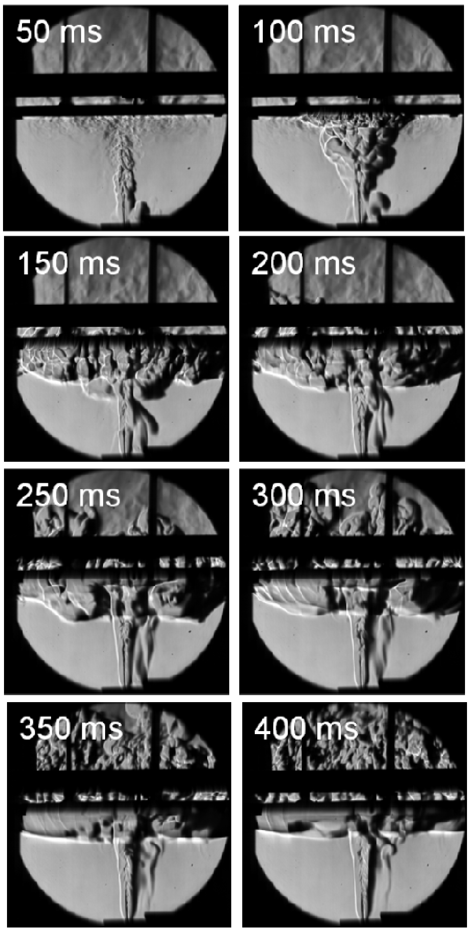

Fig. 3 Time-resolved schlieren images of the methane diffusion impinging flame

With the help of a stereo adapter, two images at different angles can be captured in one frame on the camera screen. A sample pair of stereo flame image at 250 ms after ignition is shown in Fig. 4. The 3D flame structure is then reconstructed through the well-developed image processing procedures. The results at 100 ms, 200 ms, 300 ms and 400 ms after ignition at different view angles are shown in Fig. 5. It can be seen that the flame at 100 ms is tortuous in space. At 200 ms, wavy-like flame structures can be observed on the disc flame. At 300 ms and 400 ms, the amplitude of the wavy structure becomes lower, while the disc flame diameter increases.

Fig. 4 Stereo image pair of the flame at 250 ms after ignition

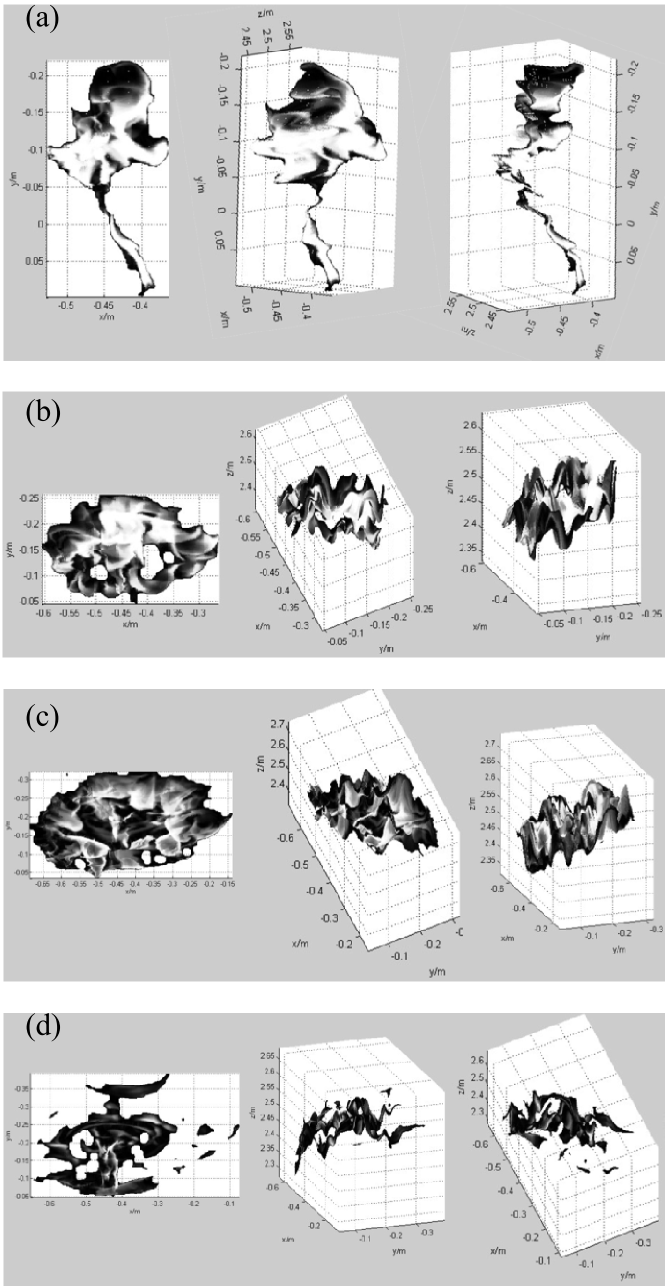

Fig. 5 3D flame structures at different time instance after ignition (a) 100 ms (b) 200 ms (c) 300 ms (d) 400 ms

Previous studies by Huang and Zhang [13] found that there is weak blue flame at the initial stage of ignition process, which is from the radical CH* and C2* chemiluminescence emissions in the short wavelength portion of the visible spectrum. However, this kind of blue flame is hard to be observed directly from the high speed colour images, as shown in Fig. 2. 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, as shown in Fig. 6. It can be seen that the blue flame formed at the flame front area and expanded outwardly after reaching the solid plate. After 120 ms, the blue flame is vanishing gradually and the flame is yellow-reddish dominated.

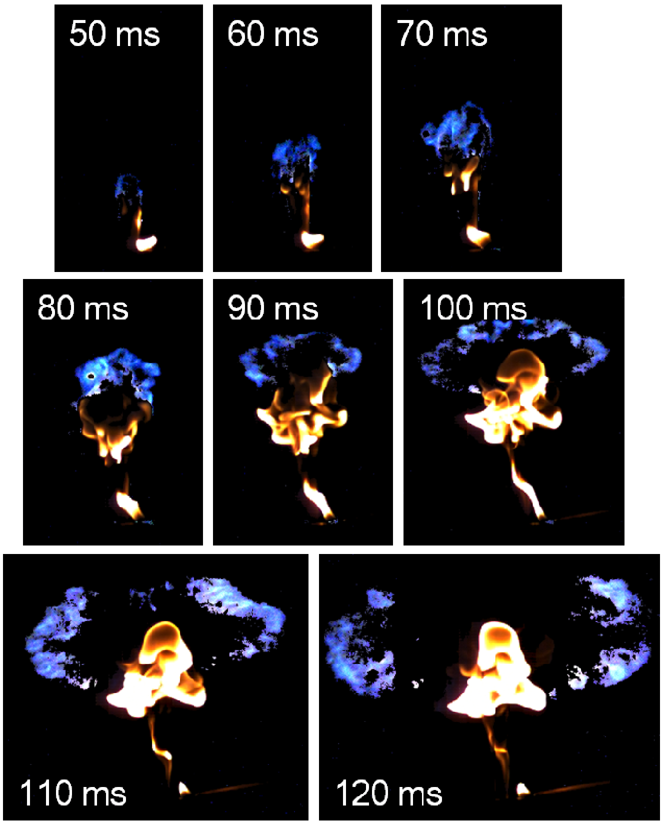

Fig. 6 Enhanced blue flame at the initial stage of ignition

CONCLUSION

The ignition process of a methane diffusion impinging flame has been investigated via high speed color/schlieren imaging, color enhancement and digital 3D reconstruction methods. A T-shape cross section of the fuel/air mixture can be observed before ignition. When the ignition initiated, the flame begins to propagate from nozzle exit upwardly. The flame at initial stage is irregular and tortuous in space. After reaching the solid wall, the flame expands from the central area of the disc outwardly. A wavy flame structure can be observed in the disc flame. The flame becomes more flat while it is expanding in radial direction. 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 and is in a shape of round ring. The blue flame begins to expand outwardly after reaching the solid disc and is vanishing gradually after 120 ms. The detailed experimental investigation of the flame structure is of great importance in understanding the ignition phenomena and may be used for validation of numerical simulations in future.

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REFERENCES

[1] Dong LL, Cheung CS, Leung CW. Heat transfer from an impinging premixed butane/air slot flame jet. *International Journal of Heat and Mass Transfer*, Vol. 45, 2002, pp: 979–992.
[2] Kwok LC. Heat transfer characteristics of slot and round premixed impinging flame jets. *Experimental Heat Transfer*, Vol. 16, 2003, pp: 111–137.
[3] Agrawal GK, Chakraborty S, Som SK. Heat transfer characteristics of premixed flame impinging upwards to plane surfaces inclined with the flame jet axis. *International Journal of Heat and Mass Transfer*, Vol. 53, 2010, pp: 1899–1907.
[4] Zhao Z, Wong TT, Leung CW. Impinging premixed butane/air circular laminar flame jet – influence of impingement plate on heat transfer characteristics. *International Journal of Heat and Mass Transfer*, Vol. 47, 2004, pp: 5021–5031.
[5] Hou S-S, Ko Y-C. Effects of heating height on flame appearance, temperature field and efficiency of an impinging laminar jet flame used in domestic gas stoves. *Energy Conversion and Management*, Vol. 45, 2004, pp: 1583–1595.
[6] Baukal CE, Gebhart B. Heat transfer from oxygen-enhanced natural gas flames impinging normal to a plane surface. *Experimental Thermal and Fluid Science*, Vol. 16, 1998, pp: 247–259.
[7] Chander S, Ray A. Flame impingement heat transfer: a review. *Energy Conversion and Management*, Vol. 46, 2005, pp: 2803–2837.
[8] Viskanta R. Heat transfer to impinging isothermal gas and flame jets. *Experimental Thermal and Fluid Science*, Vol. 6, 1993, pp: 111–134.
[9] Zhang Y, Bray KNC. Characterization of impinging jet flames. *Combustion and Flame*, Vol. 116, 1999, pp: 671–674.
[10] Foat T, Yap KP, Zhang Y. The visualization and mapping of turbulent premixed impinging flames. *Combustion and Flame*, Vol. 125, 2001, pp: 839–51.
[11] Zhang Z. A flexible new technique for camera calibration. *Pattern Analysis and Machine Intelligence I.E.E.E.*, Vol. 22, 2000, pp: 1330–1334.
[12] Ng WB, Zhang Y. Stereoscopic imaging and reconstruction of the 3D geometry of flame surfaces. *Experiments in Fluids*, Vol. 34, 2003, pp: 484–493.
[13] Huang HW, Zhang Y. Flame colour characterization in the visible and infrared spectrum using a digital camera and image processing. *Measurement Science and Technology*, Vol. 19, 2008, paper: 085406.