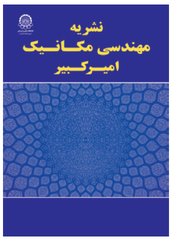

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Experimental Study of Premixed Methane-Air Flame Propagation in a Closed Duct with Porous Obstacle

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ABSTRACT: The propagation and shape of methane-air premix flame in an enclosure with dimensions of 50 × 11 × 8 cm and the effect of the porous obstacle with a porosity percentage of 95 with 20 cavities per square inch in the flow path has been studied in a laboratory. The study of flame behavior has been done with high speed camera photography. The pressure variations inside the enclosure are recorded with the help of a pressure sensor and converter located on top of the enclosure. The range of pressure variations has been adapted to the reference samples and has been validated. The location of the porous obstacle has been tested for four different distances of 5, 10, 15 and 20 cm from the spark plug. The results for the four porous obstacle states indicate that the turbulence created in the flow field can change the location of formation of the tulip flame, as well as its formation time. For a distance of 20 cm the porous obstacle from the spark location, the turbulence of the flow field is at its maximum within 4 different distances, and the flame front is formed with a fundamental difference similar to the flame of the classic tulip flame.o, the greatest amount of pressure in the inner span of the wing and near the edge of the wing attack is observed.

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1- Introduction

The propagation of flames in closed tubes has been the subject of combustion research since the late 1800s (Mallard and Le Chatelier, 1883). Because of the lack of energy, as well as greenhouse gas emissions, improving the thermal efficiency of combustion engines and reducing greenhouse gas emissions is a significant issue in combustion research and development of combustion engines. Gaining an understanding of the dynamics of premixed flame propagation in confined spaces is of great importance considering both gas explosion dynamics and the burning processes of typical internal combustion engines explanation [1]. Generally, the propagation of a premixed flame in a closed duct is a complex issue compared to flame propagation in an unconfined space, which can generate different structures, including curved, flat, cusped and cellular fronts in the early stage. The flame propagation is affected by many factors including special installations, flame, acoustic, and hydrodynamic instabilities [2]. The thermal expansion of the combustion products plays a vital role in the initial acceleration of the flame and the flame is unstable due to the intrinsic hydrodynamic instability that results from thermal expansion [3]. One of the curious phenomena is the tulip flame which is characterized by a shape concaved from the unburned mixture to the burnt gas. Ellis first reported the inversion images of premixed flame surfaces in 1928, after which this particular flame shape was named the “tulip” flame by Salamandra. The onset of tulip flame is the significant characteristics of the flame front deformation and the transition from laminar to highly turbulent combustion. Four stages can be distinguished in the tulip flame propagation according to Clanet and Searby [4], i.e. spherical/hemispherical flame, finger-shaped flame, flame with its skirt touching the tube side walls, and tulip flame and Bychkov et al. [1] developed an analytical theory of flame acceleration and the stages of the tulip flame formation. Chen et al. [6] studied the effect of porosity on the closed duct walls for a methane-air mixture. He showed that porous material on the wall affects the transverse waves, reducing the inversion of the flame front and delaying the onset of the tulip flame. The most important issue in the further development of combustion science is better understanding and adequate modeling of turbulent combustion. Therefore, in current work, an experimental framework designed to demonstrate the effects of creating turbulence in the formation of tulip flame in a closed duct. Also, the flame behavior of methane-air stoichiometric mixture in the closed duct in three conditions: unobstructed enclosure, the presence of the porous obstacles and presence of the block obstacles in the path of combustion flow are considered. Moreover, the effect of the presence of porous obstacles and their interaction on the flame formation and turbulence are considered.

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2- Methodology

The experimental setup as shown in Fig. 1, is mainly consisted of a constant volume combustion chamber with dimensions of 11×8×50 cm, a high-speed camera (Dimax-s), a pressure transducer (ADAM 6017), a gas mixing device and a high-voltage ignition system. The experiments are carried out at an initial temperature of 25 °C and a mixture initial pressure of 1 bar.

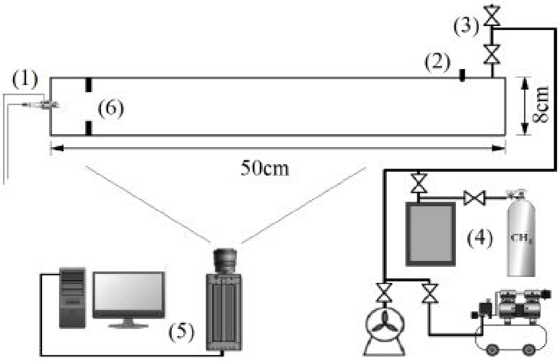

Fig. 1. Schematic diagram of the experimental apparatus including (1) spark plug, (2) pressure transducer, (3) charge and discharge valves, (4) gas mixing equipment, (5) high-speed camera and (6) obstacles

The combustion chamber is a horizontal rectangular duct made of 304 stainless steel with a thickness of 15 mm. Inside surfaces are completely polished using sandpaper with a roughness of 400-grit. The side view of the chamber has been made of transparent Plexiglas with a thickness of 20 mm to record the flame propagation. The spark plug, which is ignited by a high-voltage transformer, is located in the center of the first chamber. The Dimax-s's high-speed camera with color capture capability and 4500 Frames Per Second (fps) is used to capture the flame growth. In order to improve image quality, flame photography is performed in a dark room. Due to the combustion rate and the quality of the images, the high-speed camera is set on 1000 fps in this experiment. The pressure rise inside the enclosure is measured through the WIKA pressure transducer model S-10 and is recorded on the local computer using the ADAM data recorder model 6017. The obstacles are made of nickel and have a porosity of 95% with 20 pores per square inch. Dimensions of each porous obstacle are 0.5×2×11 cm. The effect of these obstacles is investigated in four different distances from the spark plug (case 1, 2, 3, 4), i.e. 5, 10, 15 and 20 cm. Preparation of methane-air stoichiometric mixture is performed using partial pressure method.

3- Results and Discussion

3- 1- Flame behavior in the closed duct without an obstacle

Fig. 2 shows the images taken from the process of propagating the flame in front of methane-air stoichiometry. The results of the formation of classical tulip flame, which include the formation of spherical flame, fingers, flat state and tulip formation, and in terms of the shape and sequence of the flame growth stages, are very similar to the results of [4-6], and according to the results of Matalon and Metzner [5], the flame front was flattened in the middle of the channel.

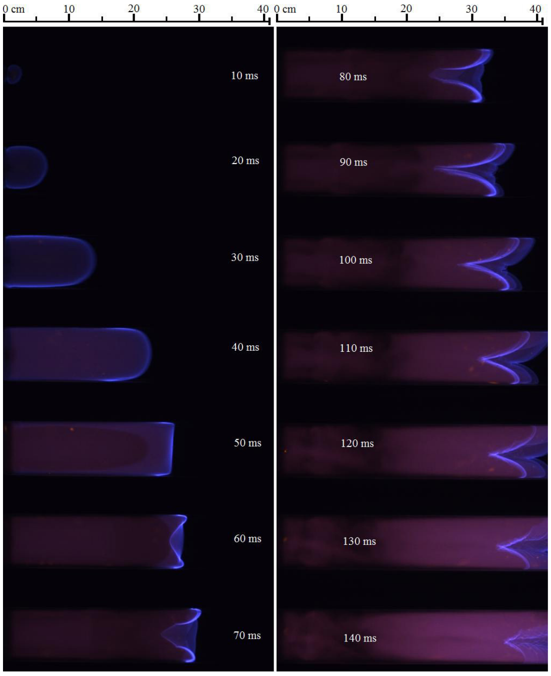

Fig. 2. High-speed images of premixed methane–air flame front in the closed duct at a pressure of 1 bar.

3- 2- Flame behavior in the closed duct with the porous obstacles

Fig. 3 shows the flame propagation images in case 3. As can be seen, the appearance of the flame front is slightly different, and the degree of turbulence in the flow field, as well as the boundary layer near the wall, is greater than the two previous cases.

Fig. 4 shows the location of the flame front as a function of time for five different cases (0, 1, 2, 3, and 4). According to the diagram, the process of flattening the flame front, the velocity of the flame front approaches zero, which is shown in the curve of the flame position variation as a slope of zero in the curve.

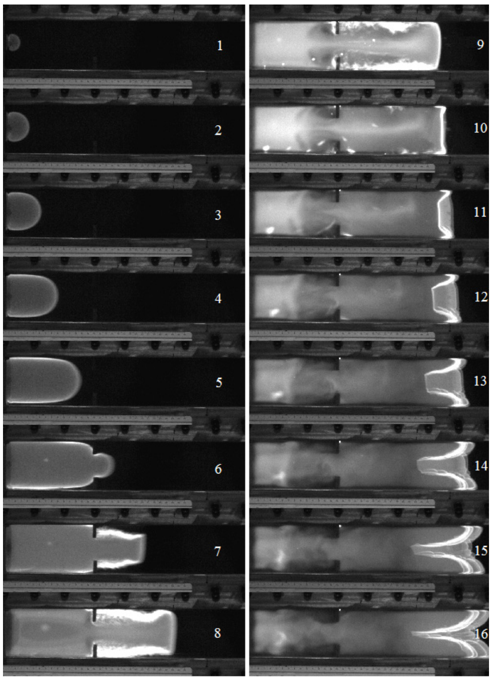

Fig. 3. The flame front images with the porous obstacles at a distance of 15 cm from the spark plug (the time interval between consecutive images is 5 ms).

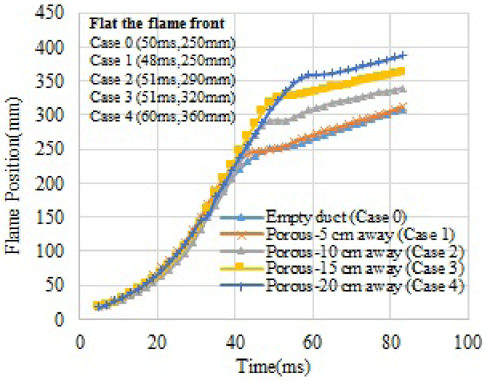

Fig. 4. The position of the flame front as a function of time for five different cases.

Considering this, the formation of a flat flame front as an introduction to the formation of tulip flame, in an unobstructed enclosure at a distance of 25 cm (50 ms), case 1 at a distance of 25 cm (48 ms), for case 2 at a distance 29 cm (51 ms), for the case 3 at 32 cm distance (51 ms), and for case 4, at 36 cm distance (60 ms), starts from the spark plug.

4- Conclusions

The results of the effect of the porous obstacles on the combustion flow field and the pattern of flame propagation in the closed duct have clearly been shown. The results of the experiments show that:

The obstruction formed in the flow path is important from two points: first, the decrease of the Reynolds flame causes an increase in the burning rate and acceleration of the flame front; secondly, obstruction increases the Reynolds flow and turbulence, which results in an increase in the surface of the flame front helps and increases burning rate.

The maximum pressure of the chamber with the presence of the porous obstacles in four cases (1, 2, 3, 4) was reduced by 6, 9, 3 and 11 percent, respectively, compared to the absence of the obstacle.

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