Effect of Obstacle Type on Methane–Air Flame Propagation in a Closed Duct: An Experimental Study

The combustion in a closed environment was the subject of many works in the past century due to its importance and complex nature compared with the combustion in an open environment. Most research works in this field have investigated different types of gas mixtures, the governing boundary conditions and their effect on the flame propagation structure. Additionally, several investigations have been performed on creating disturbance through obstacles in the flow path as well as the process of deflagration to detonation transition. This paper, for the first time, investigates the effect of porous and solid obstacles on the propagation and the structure of premixed methane–air flame in a closed duct with dimensions of 50 × 11 × 8 cm. The blockage created in the duct by obstacles is in such a way that the deflagration process does not occur. The results for the unconstrained duct correctly represent the process of forming the classical tulip flame inside the closed duct. The location of the obstacles is changed in four different distances of 5, 10, 15, and 20 cm from the spark plug, and its effect on combustion characteristics has been evaluated. The results show that the obstacles create fundamental changes in the structure and flame propagation. A significant difference between solid and porous obstacles is that the porous obstacle, in proportion to the solid obstacle, creates less disturbance in the flow field and also does not cause excessive acceleration in the flame propagation. Porous obstacles also reduce the maximum pressure in the chamber during the process, more than the solid obstacles. [DOI: 10.1115/1.4043790]

Keywords: methane–air mixture, closed duct, tulip flame, porous obstacle, solid obstacle

1 Introduction

The flame propagation in closed ducts has been the subject of combustion research since the late 1800s [1]. On one hand, due to the shortage of fossil energy resources and the global warming problems, improving the thermal efficiency of combustion devices and reducing the greenhouse gas emissions are getting a significant attention in the combustion community. The combustion mechanism and the flame structure vary according to different applications. An internal combustion engine [2] is an example for the combustion process in a closed environment. The combustion process, the flame formation, and the growth mechanism depend on different conditions, such as initial temperature, boundary conditions, fuel type, and spark ignition energy. In many applications, an explosion within the cylinder is a destructive phenomenon that can be controlled through the combustion science [3]. On the other hand, methane (CH₄) is considered as one of the most promising alternative fuels because it has shown to have lower pollutant emissions and is very economical compared to conventional fuels. Methane has a high research octane number equal to 110–130 and low carbon/hydrogen ratio, which in turn produces less CO₂ per unit of energy released [4,5].

Shelkin explained the flame acceleration under a no-slip condition on the wall which resulted in the expansion of unburned mixture [6]. Friction on the wall causes nonuniformity of the fluid flow and bends the flame front. This increases the velocity of the flame and accelerates the flame. However, there is a common view that it is impossible to accelerate the flame without turbulence; therefore, an analytical theory of accelerating the flame in an open-end tube under no-slip and adiabatic wall conditions was developed. The theory showed that increasing the flame’s Reynolds number resulted in flame acceleration reduction [7]. In another work, an analytical solution to accelerate the laminar flame, inside a tube for the early stages of flame growth in a long tube, was developed. It was concluded that the acceleration of the flame only depends on the expansion coefficient of the mixture, and the flame’s Reynolds number does not have any influence on the flame’s acceleration [3,8]. Moreover, in later works, a model for accelerating flame propagation in a tube with an obstacle to analyze the process of the deflagration to detonation transition was presented and the results showed that thinner obstacles produce stronger acceleration [9]. Generally, among the combustion processes, combustion in a closed environment is more complex than outdoor combustion. Many studies, in the field of flame propagation, were done in closed environments [3,7–18].

The propagation of the flame depends on many factors, including boundary conditions, Taylor’s instability, hydrodynamic instability [19–21], and the interaction of compression waves with the flame front [14,18,22–28]. The thermal expansion of the burned mixture behind the flame front plays an essential role in accelerating the flame front [3,25,29,30], which makes the flame unstable due to the intrinsic hydrodynamic instability [29,31]. One of the interesting phenomena, in the flame propagation in confined spaces, is the tulip flame structure which is characterized by a shape concaved from the unburned mixture toward the burnt gas [15,29,31]. In 1928, the first image of the inversion flame was presented by Ellis [32]. This phenomenon was later called the tulip flame by Salamandra et al. [33]. The onset of tulip flame is the significant characteristics of the flame front deformation and the transition from laminar to highly turbulent combustion. The process of forming tulip flame phenomenon is divided into four stages: spherical/hemispherical flame, finger-shaped flame, flame with its skirt touching...
the tube side walls, and tulip flame. Besides, the pressure wave and the boundary layer do not significantly affect the formation of tulip flame [29]. One of the topics of interest in this research is the effect of obstacles on flame propagation stages in a closed duct.

The initial deformation of the flame front is a direct result of the hydrodynamic instability, but the actual formation of the tulip flame results from the vortical motion created in the burned gas which is a consequence of the vorticity produced at the flame front. Therefore, when a tulip flame emerges, it forms just after the flame has traveled half of the length of the tube and it does not form in short tubes [17]. It was experimentally observed that the formation of the tulip flame is sensitive to the geometry of combustion vessel, and faster burning mixtures have more small-scale structures than the slow-burning mixtures [15]. It was experimentally proved that the tulip flame phenomenon is due to the flame cooling in the vicinity of the walls where the flame has lost the main part of its surface area [34]. Another significant issue with the presence of an obstacle on the flame propagation path is that the wall added as an obstacle also has the flame cooling effect.

Researchers have focused on the mixture composition, for example, Xiao et al. [23,28,30,35], with the aid of experimental study and numerical simulation on the premixed hydrogen-air flame, showed that the flame propagation has a strong dependence on factors such as initial temperature, initial pressure, heat loss, wall effects, and ignition location. Shen et al. [36] carried out a similar laboratory study for a mixture of hydrogen–air and propene–air and compared the behavior of these two mixtures. Zheng et al. [11] studied the effect of hydrogen content in a premixed methane–hydrogen–air mixture in a combustion chamber. Jin et al. [13] studied the behavior of the methane–air, acetylene–air, and natural gas–air flame front in a similar way. They showed that the nature of the gas mixture has a significant impact on the flame velocity and its shape. The low amounts of ethane and propane in natural gas increase the flame propagation speed, pressure rise, and difference in the flame shape compared to pure methane. Additionally, acetylene has a higher laminar burning speed [37–39] and a higher maximum pressure than methane and propane, which is due to its higher chemical reaction rate. Wen et al. [40] studied the effect of three solid obstacle configurations with varying cross-wise positions of obstacles in an open-ended channel. They showed that the acceleration and the velocity of the flame depend on the configurations of obstacles.

Chen et al. [41], through a numerical and experimental study in a closed duct, showed that tulip flame is a hydrodynamic phenomenon, and the velocity of the flame tip increases with increasing length to diameter ratio. Chen et al. [42], with a laboratory and numerical study, examined a closed duct effect of a thin obstacle on the flow path. They divided the shape of the flame in this state into five stages, i.e., spherical flame, finger-shaped flame, jet flame, mushroom-shaped flame, and bidirectional propagation flame. Chen et al. [12] studied the effect of porosity on the closed duct walls for a methane–air mixture. They showed that a porous material on the wall affects the transverse waves, reducing the inversion of the flame front and delaying the onset of the tulip flame. Wang et al. [43] studied the effect of different types of obstacles in terms of the shape and the blockage ratio in an open-end tube. They showed that the acceleration of the flame depends on the type of obstacles. Chen et al. [10,44] have studied the interactions of methane flames in a closed tube through an experimental and numerical work. They have used a slit obstacle with different numbers of slits and different gap size on the flame propagation path. They have divided the flame propagation process into four stages, i.e., hemispherical flame, finger-shaped flame, jet flame, and bidirectional propagation flame. Additionally, they have shown that the peaks of the flame tip speed and the pressure growth rate are reduced by increasing the number of slits.

The most important issue in the further development of combustion science is understanding and modeling of turbulent combustion. Therefore, in this study, first, an experimental framework was designed to demonstrate the effects of creating disturbance in the formation of tulip flame in a closed duct. Second, the flame behavior of methane–air stoichiometric mixture in a closed duct in three cases of no obstacles, presence of porous obstacles, and presence of solid obstacles is studied. Moreover, the effect of the presence of porous and solid obstacles and their interaction on the flame formation and disturbance is investigated.

2 Experimental Setup
The experimental setup, as shown in Figs. 1(a) and 1(c), mainly consisted of a constant volume combustion chamber with dimensions of 11 x 8 x 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.

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 the image quality, the 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 Advantech’s data acquisition modules (ADAM) data recorder model 6017. To study the effect of porous obstacles on the flame propagation structure, two obstacles are placed symmetrically inside the enclosure at a distance of 5 cm from the spark plug location as shown in Fig. 1(b). The obstacles are made of nickel and have a porosity of 95% with 20 pores per square inch. The dimensions of each porous obstacle are 0.5 x 2 x 11 cm. The effect of these obstacles is investigated in four different distances from the spark plug, i.e., 5, 10, 15, and 20 cm. In order to study the flame behavior with the presence of the solid obstacles as well as to compare with the porous ones, two solid obstacles made of wood with the same size as the porous obstacles are utilized as shown in Fig. 1(d). The effect of these obstacles is investigated in four different distances similar to the porous obstacle.

To prepare a methane–air premixed mixture, a mixing chamber made of a seamless iron pipe with a diameter of 152 mm, thickness of 7 mm, and length of 250 mm is used. The volume of the mixing chamber is 5% larger than the combustion chamber. Preparation of the methane–air stoichiometric mixture is performed using a partial pressure method [20,21,38,45]. The methane gas, with a purity of 99.99%, is then injected into the mixing chamber. Then, the dry air from the compressor, to the relative pressure of 3 bar, is injected into the mixing chamber. Considering the initial pressure of 1 bar in the combustion chamber for carrying out the tests, the prepared mixture is sufficient to perform three experiments. In order to ensure the correct operation of the laboratory setup as well as the optimized photographic system, the test is repeated seven times.

3 Results and Discussion
3.1 Flame Behavior in a Closed Duct Without an Obstacle
Figure 2 shows the images taken from the process of flame propagation of stoichiometric methane–air mixture. The formation of classical tulip flame, which includes the formation of spherical flame, fingers, flat state, and tulip formation in terms of the shape and sequence of the flame growth stages, is very similar to the literature [8,12,24,46]. According to the results of Matalon and Metzener [17], the flame front is flattened in the middle of the channel at a distance of 250 mm from the spark plug. First, the flame is formed in a spherical shape and after collision with the walls of the enclosure, the fingers took place and in the next stage the flame stretched out.
Fig. 1  Experimental apparatus: (a) real view of the experimental apparatus; (b) porous obstacles inside the closed duct; (c) 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; (d) solid obstacles inside the closed duct

Fig. 2  Flame snapshots of premixed methane–air mixture in a closed duct with no obstacles: (a) $t = 10$ ms, (b) $t = 20$ ms, (c) $t = 30$ ms, (d) $t = 40$ ms, (e) $t = 47$ ms, (f) $t = 57$ ms, (g) $t = 67$ ms, (h) $t = 77$ ms, (i) $t = 87$ ms, and (j) $t = 97$ ms
After 47 ms, the flame front is completely flattened and the flame front inversion process begins. During the flame propagation, the tulip flame at the time of 87 ms is completely formed. As seen in Fig. 2, during the flame propagation, the upper edge of the flame front has gone farther than its lower edge, which is consistent with the results of Zheng et al. [11]. According to the results of Dunn-Rankin and Sawyer [15], the reason is the relatively slow reaction of methane-air and the combustion chamber in the present study, which allowed the buoyancy force to change the shape of the flame front. Flame front position and flame velocity with respect to time are shown in Fig. 3. As seen in Fig. 3, at 47 ms (i.e., 250 mm position), the gradient of the flame front position curve is almost zero, which indicates the stop of the flame momentarily and the introduction of the tulip flame. Figure 3 shows that at the beginning of the flame propagation, the velocity of the flame front is 1.33 m/s and it continues to grow until it gets to a maximum of 9 m/s at 30 ms. As the flame propagates, the velocity of the flame decreases to a value close to zero and then the flame inversion occurs. The flame front continues to grow in the form of the tulip flame at an approximate speed of 1.8 m/s.

The Froude number is defined as [47]

\[ Fr = \frac{gW}{U_f^2} \]  

(1)

where \( g \) is the gravity accelerate (\( g = 9.81 \text{ m/s}^2 \)), \( W \) is the depth of the closed duct (\( W = 0.11 \text{ m} \)), and \( U_f \) is the flame velocity (\( U_f = 1.8 \text{ m/s} \)). The Froude number is \( Fr = 0.333 \). The tulip flame formed in the absence of an obstacle is almost symmetrical, and only the upper edge of the flame front is slightly ahead of the lower edge. The calculated amount of Froude number is very well suited to the critical Froude number computed by Jin et al. [13], which has given \( Fr = 0.3 \) for the methane-air mixture.

Figure 4 shows the variations in pressure inside the closed duct in terms of time for the four times the test and their mean values. The mean values of pressure in Fig. 4 are derived from the mean of measured pressure values for four test repetitions which prove the repeatability of the experiments, precision of the instruments, precision of the mixing/charging method and the ignition system. The maximum pressure inside the combustion chamber during the flame propagation is about 4.2 bar, which is very consistent with the work of Dunn-Rankin and Sawyer [15].

3.2 Effect of Obstacles on the Flame Behavior in a Closed Duct

In this section, two types of obstacles are tested. Experiments are performed for porous and solid obstacles for four different distances from the spark plug, i.e., 5, 10, 15, and 20 cm which are corresponding to cases 1, 2, 3, and 4, respectively. The purpose of this section is to compare the differences created between these two different types of obstacles. The photographic results for case 1 with solid and porous obstacles are shown in Fig. 5.

In this case, only the structure of the initial vortex is different. Despite the disturbance created by the proximity of the obstacles to the spark plug location, the obstacles have little effect on the formation of the flame and the formation of the tulip flame. Therefore, the flame front configuration has been similar to the unobstructed closed duct. The flame flattening is formed at 48 ms for solid and 46 ms for a porous obstacle. Eventually, the tulip flame is formed at about 80 ms. Figure 6 shows the flame front location and the average pressure rise inside the closed duct as a function of time for case 1. The formation of the flat flame front, as an indication to the formation of tulip flame, occurred at a distance of 250 mm from the spark plug location for both types of obstacles. The maximum pressure value is occurred at about 200 ms. In this case, obstacles reduce the maximum pressure inside the closed duct compared with no obstacle’s case. The porous obstacle has a stronger effect on reducing pressure. The porous and solid obstacles have reduced the maximum pressure by 6% and 2%, respectively.

Figure 7 shows the flame images in case 2, which appears to have very slight differences with case 1 shown in Fig. 5. The degree of turbulence created in the flow field, especially in the boundary layer near the wall, has a major role in the flame inversion phenomenon. The reason for the increase in the turbulence rate of the combustion flow field in case 2 relative to case 1 is the more preventative distance of the obstacles from the spark plug and hence the collision of the flame front with the obstacles at a faster velocity. The solid obstacle has created more severe turbulence than porous obstacles. The flame flattening is formed at 50 ms for porous and 42 ms for the solid obstacle. Finally, the flame images are shown at 91 and 80 ms, respectively, in the same position near the end of the duct for porous and solid obstacles at which the propagation velocity in the solid obstacle is greater than the porous obstacle.

Figure 8 shows the flame front location and the average pressure rise inside the closed duct as a function of time for case 2. In this case, the flat flame front for the porous and solid obstacles is formed at a distance of 290 mm and 300 mm from the spark plug location, respectively. At the early stages of the flame growth, after crossing the solid obstacle, the acceleration of the flame front and its velocity are greater than the porous obstacle. According to Fig. 8, the presence of the porous obstacle does not accelerate the flame. The porous obstacle retained only the initial acceleration of the flame and set back the formation of a tulip flame in terms of location. The porous and solid obstacles have reduced the maximum pressure by 9% and 0.2%, respectively.
Fig. 5 The flame front images with the obstacles at a distance of 5 cm from the spark plug for case 1. Solid obstacle (case 1): (a) $t = 25$ ms, (b) $t = 30$ ms, (c) $t = 48$ ms, and (d) $t = 86$ ms. Porous obstacle (case 1): (e) $t = 25$ ms, (f) $t = 30$ ms, (g) $t = 46$ ms, and (h) $t = 80$ ms.

Fig. 6 (a) Position of the flame front and (b) measured pressure rise versus time for case 1

Fig. 7 The flame front images with the obstacles at a distance of 10 cm from the spark plug for case 2. Solid obstacle (case 2): (a) $t = 28$ ms, (b) $t = 33$ ms, (c) $t = 42$ ms, and (d) $t = 80$ ms. Porous obstacle (case 2): (e) $t = 28$ ms, (f) $t = 33$ ms, (g) $t = 50$ ms, and (h) $t = 91$ ms.
Figure 9 shows the flame propagation images for case 3. As can be seen, the appearance of the flame front is slightly different. The degree of turbulence in the flow field, as well as the boundary layer near the wall, is greater than the two previous cases. Due to the relatively high turbulence, for the porous obstacle, the flame front has a flat surface in the range of 41–51 ms from 246 mm to 324 mm. Whereas for the solid obstacle, the flame front has a flat surface at a distance of 330 mm and 48 ms, and after that, the inversion process of the flame front occurs. By focusing on the flame image of the porous obstacle, at 48 ms, a return flow is created at the beginning of the duct and generated a vortex. In fact, the porous obstacle allows flow through itself and the return flow passes through it with a little disturbance. However, in the solid obstacle, the return flow collides with it and flow becomes very disturbed and creates strong shocks which can be seen at 45 ms and 48 ms in Fig. 9. The solid obstacle has created more disturbance and has also strengthened the shocks created by the combustion process. Finally, the flame images are shown at 82 and 68 ms, respectively, in the same position near the end of the duct for porous and solid obstacles at which the propagation velocity in the solid obstacle is greater than the porous obstacle.

Figure 10 shows the flame front location and the average pressure rise inside the closed duct as a function of time. In this case, flame position as well as maximum pressure inside the closed duct are similar for solid and porous obstacles. The only difference is that the acceleration of the flame is in the solid obstacle, and it can be attributed to a greater disturbance than the porous obstacle and the porous and solid obstacles have reduced the maximum pressure by 3% and 1%, respectively.

Figure 11 shows the flame propagation images for case 4 which is the case with the most disturbance. The return flow generated by the combustion process in the closed duct passes through the porous obstacle. For the solid obstacle, the flame flattening is formed at 46 ms. The strong compressive wave created by the interaction of the flame with the solid obstacles and the walls of the duct has completely changed the structure of the flame front. The solid obstacles amplify the compressive waves created by the combustion process, which can be seen at 44 ms in Fig. 11. In fact, the
Fig. 10  (a) Position of the flame front and (b) measured pressure rise versus time for case 3

Solid Obstacle (Case 4)                          Porous Obstacle (Case 4)

(a)                                          (f)
(b)                                          (g)
(c)                                          (h)
(d)                                          (i)
(e)                                          (j)

Fig. 11  The flame front images with the obstacles at a distance of 20 cm from the spark plug for case 4. Solid obstacle (case 4):  
(a) $t = 38$ ms,  
(b) $t = 42$ ms,  
(c) $t = 44$ ms,  
(d) $t = 46$ ms, and  
(e) $t = 50$ ms. Porous obstacle (case 4):  
(f) $t = 38$ ms,  
(g) $t = 42$ ms,  
(h) $t = 55$ ms,  
(i) $t = 60$ ms, and  
(j) $t = 80$ ms.

Fig. 12  (a) Position of the flame front and (b) measured pressure rise versus time for case 4
porous obstacle relative to the solid obstacle creates less disturbance in the flow field and the return flow passes slowly through the porous obstacle which can be seen at 55 ms and 60 ms in Fig. 11. Finally, the flame images are shown at 80 and 50 ms, respectively, in the same position near the end of the duct for porous and solid obstacles and the structure of the flame front is completely different. Figure 12 shows the flame front location and the average pressure changes inside the closed duct as a function of time for case 4. In this case, the flat flame front for porous and solid obstacles is formed at a distance of 360 mm and 380 mm from the spark plug location, respectively. At the early stages of the flame growth, after crossing the solid obstacle, the acceleration of the flame front and its velocity are much greater than the porous obstacle and the formation of a tulip flame in terms of location and the burning velocity is much higher than the porous obstacle. According to Fig. 12(a), the presence of the porous obstacle does not accelerate the flame. The porous obstacle retained only the initial acceleration of the flame and set back the formation of a tulip flame in terms of location and time. In the solid obstacle, the maximum pressure inside the closed duct occurred at 100 ms. The porous and solid obstacles have reduced the maximum pressure by 11% and 2%, respectively.

4 Conclusions

The effect of porous and solid obstacles on the propagation of methane–air stoichiometric mixture flame in a closed duct with the help of laboratory equipment and direct imaging of the flame with high-speed camera and the pressure rise inside the closed duct is measured through the pressure transducer. The results of the effect of the obstacles on the combustion flow field and the pattern of flame propagation in the closed duct have been clearly shown. The results of the experiments show that

(1) The disturbance created in the flow field by obstacle plays a fundamental role in the growth pattern of the flame front and the flame velocity. In fact, the disturbance of the flow field increases the burning velocity and accelerates the flame propagation process in the closed duct. At the early stages of the flame growth, after crossing the obstacles, in a solid obstacle, the acceleration of the flame has increased compared to the unobstructed state, but in the porous obstacles, the flame acceleration has not changed much, and only its value has been maintained for a longer time.

(2) There is a fundamental difference between the porous obstacle and the solid obstacle in the interaction of them with the flow field of combustion. The porous and solid obstacles have some differences in the volume of unburned mixture around them. This is clearly seen in case 1 at 25 ms, case 2 at 33 ms, case 3 at 41 ms, and case 4 at 42 ms in Figs. 5, 7, 9, and 11, respectively. This difference in the effect between two different types of obstacles is due to the difference in the obstacle structure and their different effects on the flow field of combustion. A solid obstacle with similar dimensions as the porous obstacle has accelerated the flow due to the higher blockage ratio than the porous obstacle.

(3) The porous obstacle allows flow through itself and the return flow passes through it with a little disturbance. However, in the solid obstacle, the flow hit it and the return flow collides with it. This yielded high disturbance and created stronger shocks than the porous obstacle.

(4) The disturbance created, in both obstacles, is the function of the location of the obstacles. The disturbance in the flow field increases with the increasing distance of the obstacle from the spark location.

(5) The pressure variations inside the closed duct are the same for unobstructed and porous obstacle cases and solid obstacle at cases 1, 2, and 3. The maximum pressure of the closed duct occurs at time around 200 ms. The maximum pressure of the closed duct for case 4 in the solid obstacle occurred at 100 ms. The combustion products are rapidly cooled by heat transfer to the walls of the duct. Due to the large thermal capacity of the stainless steel compared to the gas mixture, the temperature inside the duct is close to the ambient temperature. Due to the passage of time, the burned mixture is cooled rapidly and the pressure inside the closed duct decreases rapidly.

(6) The porous obstacle, in all tested conditions, has a stronger effect in reducing the maximum pressure inside the closed duct. The maximum pressure of the closed duct with the presence of the porous obstacle in four cases (1, 2, 3, 4) is reduced by 6%, 9%, 3%, and 11%, respectively, compared to the absence of the obstacle. The peak pressure reduction with the solid obstacle in four cases (1, 2, 3, 4) is reduced by 2%, 0.2%, 2%, and 1%, respectively. Adding obstacles increases the interior surface of the closed duct by 7%. This can increase the heat transfer surface and can be the reason for the maximum pressure drop inside the closed duct relative to the unobstructed state.

References


112208-8 / Vol. 141, NOVEMBER 2019 Transactions of the ASME


