Experimental Study upon the Influence of Single-Layer Wire Mesh on Premixed Methane-Air Flame Behavior and Pressure Dynamics in a Closed Duct

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ABSTRACT

An experimental study on the influence of single-layer wire mesh on premixed methane-air flame behavior and pressure dynamics in a closed duct is conducted. Premixed methane-air mixture with equivalence ratio $\Phi = 1$ is used in our experiments. Seven different kinds of wire mesh are chosen. High-speed schlieren photography system is applied to capture flame behaviors. Two pressure transducers are used to record the pressure-time history. It is found that the flame propagates through the wire mesh in the cases of 12 and 20 mesh, but quenches in the case of 30 mesh. For the cases of 40, 60, 80, and 100 mesh, the flame presents salient quenching tendency but finally propagates through the suppression zone with wire mesh being destroyed, which fully demonstrates that the anti-destructive performance of wire mesh should be also considered in particular. Moreover, it is found that the single-layer wire mesh can directly influence the flame behavior. The single-layer wire mesh makes the tulip flame formation time advanced and makes the flame front inversion extent weaker compared with the case of no wire mesh. In addition, it is found that the single-layer wire mesh has no suppression effect on flame tip speed in the upstream duct, but delays the flame propagation in the suppression zone. Besides, the single-layer wire mesh can effectively suppress the maximum pressure, and the suppression effect increases as the increase of mesh of wire mesh. Finally, all of the potential mechanisms of the influence of single-layer wire mesh on premixed methane-air flame behavior, flame tip speed, and pressure are analyzed in this paper.

KEYWORDS: Premixed methane-air flame, single-layer wire mesh, pressure, suppression.

INTRODUCTION

Methane has become one of the most promising clean energy all over the world because of fossil energy depletion and serious environmental pollution. Gaining an understanding of its combustion and explosion characteristics is essentially meaningful both for safety and engineering applications.

Research into premixed flame propagating in ducts has a history of more than one hundred years. A variety of studies on premixed flame propagation behavior and dynamics have been reported [1-6]. Meanwhile, a lot of scholars begin to study the suppression of premixed flame propagation and explosion using different kinds of inhibitors [7-11]. Metal wire mesh has become one of the most common flame arrest structures used in ducts due to its advantages of small volume, light weight, and good quenching performance. In 1980s, Jin Tianjian and Guangxing [12] conducted some experimental studies on the quenching performance of metal wire mesh and found that the quenching performance was unrelated to the material of wire mesh and axial angles of wires. Wang et al. [13] studied the influence of layer and distance between each wire mesh on quenching performance. Yu et al. [14] studied the explosion suppression of premixed acetylene-air flame,

Proceedings of the Ninth International Seminar on Fire and Explosion Hazards (ISFEH9), pp. 173-183
Edited by Snegirev A., Liu N.A., Tamanini F., Bradley D., Molkov V., and Chaumeix N.
Published by St. Petersburg Polytechnic University Press
ISBN: 978-5-7422-6496-5 DOI: 10.18720/spbpu/2/k19-30

some empirical formulas about the relationship between the critical values of flame quenching and geometrical parameters of wire mesh were proposed. Zalosh [15] found that the expanded metal mesh and polymer foams with appropriate pore and sufficient surface area can suppress the deflagrations of gas-air mixtures. Besides, the detailed requirements for expanded metal mesh and polymer foams used for explosion suppression in military aircraft fuel tanks were proposed in his study. Golovastov et al. [16] conducted an experimental study on the processes of decay of a detonation wave in a hydrogen–air mixture during propagation along a porous surface. They chose polyurethane with porosities of 95.9 and 98.9%, as well as a steel wool with a porosity of 99.0% and a polyurethane foam with polypropylene tape of 50 μm thickness as the porous coatings, and the dynamics of the flame front and shock waves were discussed. Jin et al. [17] studied the suppression effect of multi-layer wire mesh on premixed hydrogen-air flame propagation in a closed duct. And it was found that the multi-layer wire mesh could effectively suppress the maximum flame tip speed, maximum pressure, and maximum sound waves. Cui et al. [18] conducted a series of experimental studies on the double-suppression effect of a multi-layer wire mesh structure on methane-air mixture explosions and found the number of layers and meshes had a significant influence on suppression effect.

Overall, although a variety of studies upon the suppression effect of metal wire mesh have been reported, almost no one focused on the influence of single-layer wire mesh on premixed methane-air flame propagation in ducts. Besides, most of these previous studies only focused on the pressure waves but ignored the flame characteristics. So, it is quite desirable to study the influence of single-layer wire mesh on flame shape changes, flame front dynamics, and pressure dynamics simultaneously.

EXPERIMENTAL SETUP AND PROCEDURES

The experimental setup is presented in Fig. 1. It is very similar to our past work and the details can be seen in reference [17]. Premixed methane-air mixture at equivalence ratio Φ = 1 (with methane concentration of about 9.5%) is used in the experiments. Seven different kinds of stainless still wire mesh are chosen, as shown in Fig. 2. They are mounted in the suppression zone using some spacers. The geometry parameters are shown in Table 1. The initial pressure is 101.325 kPa, and the initial temperature is 298 K. Repeated experiments (three times) are conducted to ensure the reproducibility of the results is good.

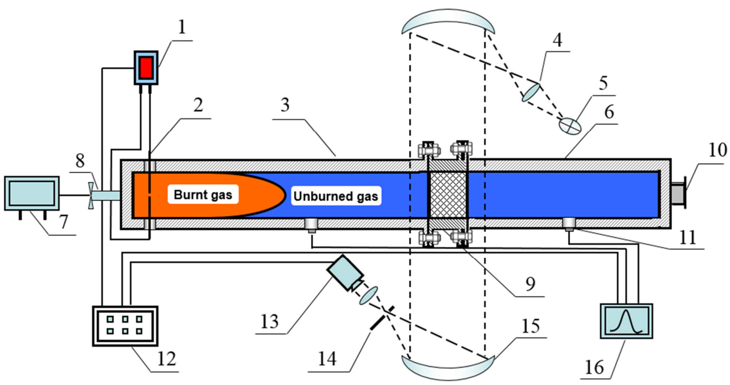


Fig. 1. Sketch of experimental setup: (1) spark igniter, (2) ignition electrode, (3) upstream duct, (4) focusing lens, (5) point light source, (6) downstream duct, (7) gas mixing device, (8) insulation valve, (9) suppression zone, (10) discharge vent, (11) pressure transducer, (12) synchronization controller, (13) high speed video camera, (14) knife edge, (15) schlieren mirror, (16) data recorder [17].

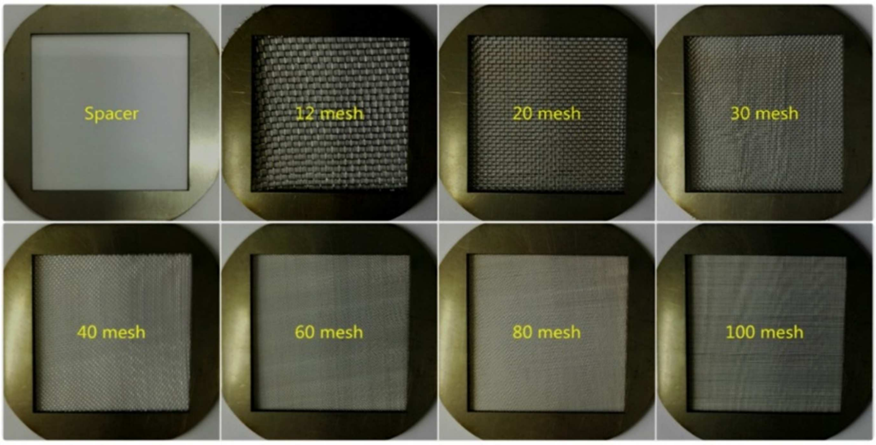


Fig. 2. Images of spacer and wire mesh.

Table 1. Geometrical parameters of stainless still wire mesh

No	Mesh (the number of mesh within one inch of length)	Line diameter (mm)
1	12 mesh	0.390
2	20 mesh	0.345
3	30 mesh	0.210
4	40 mesh	0.096
5	60 mesh	0.077
6	80 mesh	0.072
7	100 mesh	0.070

RESULTS AND DISCUSSION

Influence of single-layer wire mesh on flame shape changes

Fig. 3 presents the high-speed schlieren images of premixed methane-air flame propagation in the closed duct. It should be noted that the first line is the flame shape changes in the case of no wire mesh. Obviously, the flame propagates freely in the empty duct, and four classical kinetic stages (spherical flame, finger-like flame, flame skirt touching sidewalls, tulip flame) proposed by Clanet and Searby [1] are obtained during the flame propagating in the upstream duct. As the flame moves through the suppression zone, tulip flame disappears gradually, but the flame inversion shape is still vaguely visible. Meanwhile, the flame front becomes wrinkled but no longer smooth.

A quite similar flame evolution procedure are found in the cases of adding wire mesh of 12 and 20 mesh, the flame propagates through the wire mesh. And the flame front becomes more wrinkled in the downstream duct but still presents an inversion shape. For the case of adding wire mesh of 30 mesh, the flame quenches in the suppression zone, and it is not captured in the downstream duct. While, for the cases of adding wire mesh of 40, 60, 80, and 100 mesh, the flame also presents salient quenching tendency, but finally propagates through wire mesh just before quenching with wire mesh being destroyed. Due to the effect of wire mesh on strengthening the disturbance flow of gases in unburned field, it is found that the flame front becomes more wrinkled in the downstream duct in these cases compared with the case of no wire mesh.

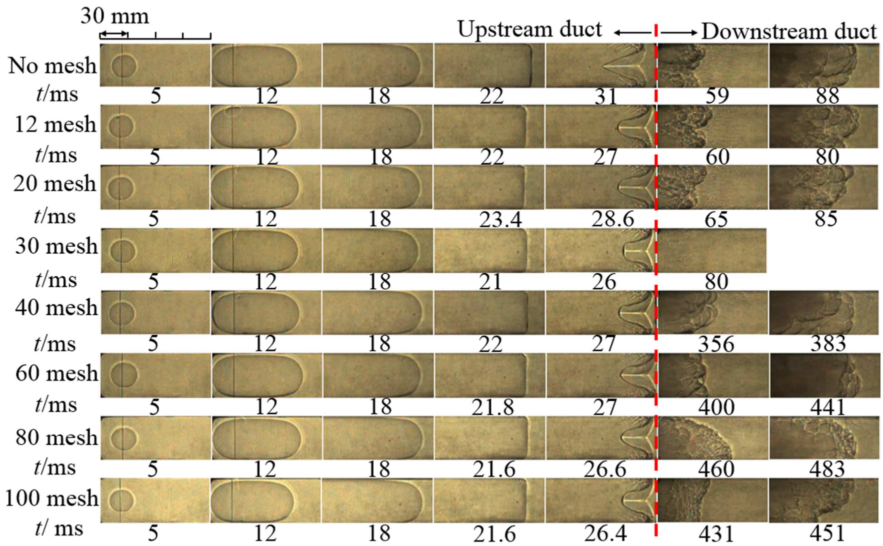


Fig. 3. High-speed schlieren images of flame shape changes.

View from all of images, the flame has a quite similar shape changes in the early stages. But some major difference appears later. First, the single-layer wire mesh makes the tulip flame formation time advanced and makes the flame front inversion extent weaker compared with the case of no wire mesh. Both of the two phenomena will be analyzed in detail later. Second, the presence of single-layer wire mesh makes the flame front more wrinkled and random in the downstream duct, and this effect is strengthened as the mesh of single-layer wire mesh increases.

Influence of single-layer wire mesh on flame front dynamics

Fig. 4 shows the flame tip speed as a function of flame tip location, and the calculation method of flame tip speed can refer to our previous work [17]. The ignition time and ignition site is defined as the initial time and initial site, respectively. And the flame tip location refers to the distance between flame front and ignition site. For the case of no wire mesh, the flame tip speed increases sharply in a very short time due to the effect of spark igniter. Then, the flame propagates freely, and flame tip speed increases exponentially because of the rapid increase of flame surface areas. The acceleration stops until the flame skirt touching the sidewalls, and the flame tip speed reaches its maximum value in the location of about 170 mm. Then, a drastic flame deceleration procedure is presented due to the decrease of flame surface areas caused by the flame skirt sweeping along the sidewalls. The flame deceleration stops until tulip flame forms, which increases the flame surface areas to a certain extent. Subsequently, the flame propagates with slight oscillations at a quite slow speed.

For the cases of adding single-layer wire mesh, the flame tip speed coincides very well with the case of no wire mesh in the upstream duct. As presented in Fig. 4, the maximum flame tip speed appears at about 170 mm for all cases. Fig. 5 illustrates the maximum flame tip speed in different cases, and “0 mesh” represents the case of no wire mesh. It is found that the maximum flame tip speed is almost constant as the mesh of single-layer wire mesh increases, and the value is about 23.3 m/s.

Then, the flame tip acceleration rate in different cases are calculated and compared, as presented in Fig. 6. Also, the flame tip acceleration rate in the cases of adding single-layer wire mesh coincides very well with the case of no wire mesh in the early stages. Besides, the maximum flame tip acceleration rate appears just after ignition, which also maintains at a constant value (about 3.33×103 m/s^{-2}) as the mesh of single-layer wire mesh increases, as shown in Fig. 7. All of these results above seem to indicate that the single-layer wire mesh has almost no suppression effect on flame tip speed in the upstream duct. However, some difference appears right in the location of the suppression zone, as shown in Fig. 4. It is evident that the flame tip speed decreases sharply as the mesh of wire mesh increases. Especially in the cases of adding wire mesh of 40, 60, 80, and 100 mesh, the flame tip speed has become a tiny value, which demonstrates that the single-layer wire mesh has a salient suppression effect on the flame tip speed in the suppression zone.

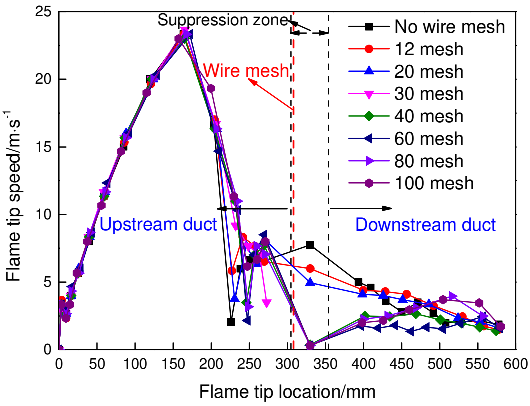


Fig. 4. Flame tip speed versus flame tip location.

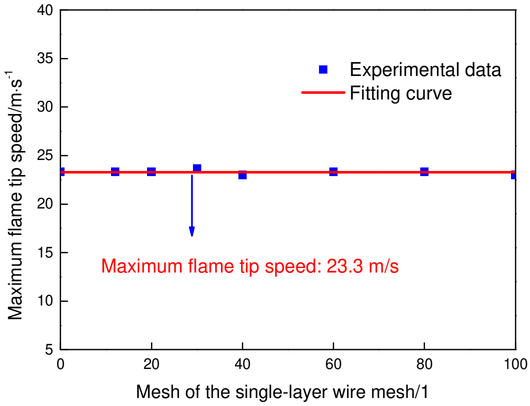


Fig. 5. Maximum flame tip speed as a function of mesh of wire mesh.

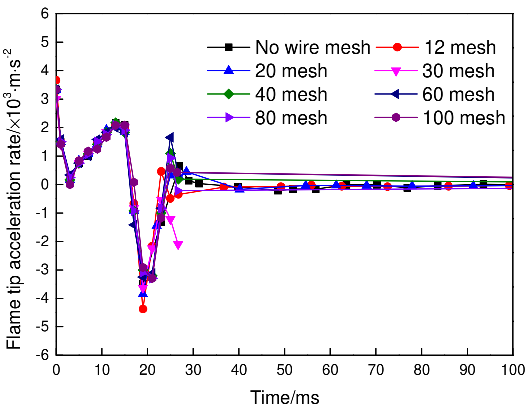


Fig. 6. Flame tip acceleration rate versus time.

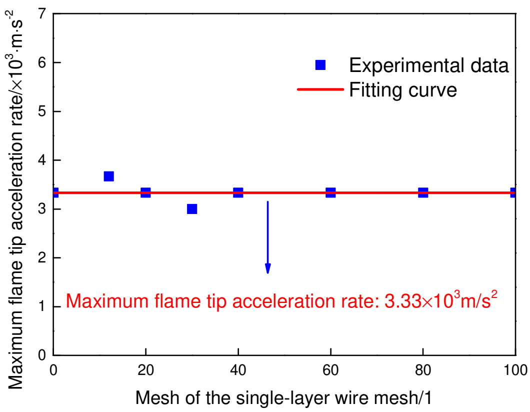


Fig. 7. Maximum flame tip acceleration rate as a function of mesh.

Figure 8 presents the time for flame propagating through the suppression zone in different cases. For the case of 30 mesh, the flame quenches due to the effect of wire mesh, so the time for flame propagating through the suppression zone is regarded as an infinity value, which is not plotted here. It is evident that the time for flame propagating through the suppression zone increases as the mesh increases. In addition, it is found that the time value increases sharply from the cases of 20 mesh to 40 mesh, and becomes much larger than the cases of no wire mesh, 12 mesh, and 20 mesh. The result directly indicates that the suppression effect of the single-layer wire mesh on the flame tip speed in the suppression zone is strengthened as the mesh of wire mesh increases. For the cases of adding single-layer wire mesh of 40, 60, 80, and 100 mesh, although the wire mesh is destroyed, but it can also effectively delay the flame propagation procedure and attenuate the flame tip speed in the suppression zone.

After the flame propagates through the suppression zone, the flame tip speed also becomes a tiny value and shows slight oscillations, which is quite similar to the case of no wire mesh. Meanwhile, in the cases of adding wire mesh of 40, 60, 80, and 100 mesh (with single-layer wire mesh being destroyed), it is found the flame tip speed has a slight increasing tendency in the downstream duct. This phenomenon may be attributed to a second combustion procedure occurred in the downstream duct after the wire mesh being destroyed just before the flame being quenched.

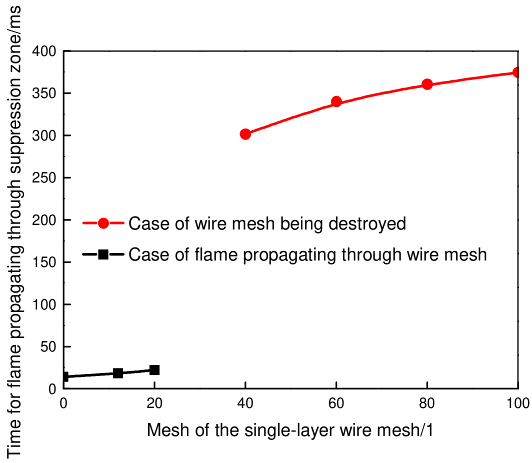


Fig. 8. Time needed for flame propagating through the suppression zone.

Influence of single-layer wire mesh on pressure dynamics

The pressure-time curves are presented in Fig. 9. For the case of no wire mesh, pressure increases rapidly due to the great increase of flame tip speed at early stages. As flame skirt touches sidewalls, the pressure rise rate presents a slight decreasing tendency, which is closely related to flame deceleration. However, the pressure still increases continuously. And the sudden decrease of pressure at about 150 ms is caused by the open of the discharge vent. For the cases of adding wire mesh of 12 mesh and 20 mesh, the pressure curves are very close to the case of no wire mesh, and only the maximum pressure values are a little smaller than the result of no wire mesh. For the case of 30 mesh, the pressure curve coincides well with the case of no wire mesh in the early stages. However, the pressure decreases sharply and becomes saliently smaller than the case of no wire mesh at about 40 ms. Also, for the cases of 40, 60, 80, and 100 mesh, the pressure curves present a quite similar procedure before wire mesh being destroyed. However, the pressure increases again after the flame propagating through the destroyed wire mesh, and the maximum pressure reaches almost the same level compared with the values before wire mesh being destroyed. If the duct is longer enough, the pressure will increase continuously, and the risk will be increased at the same time, which should be avoided in practical engineering applications.

In order to gain a further study on the suppression effect of single-layer wire mesh on pressure during premixed flame propagation, the maximum pressure as a function of mesh is illustrated in Fig. 10. It is evident that the maximum pressure decreases as the mesh of wire mesh increases, especially from the case of 20 mesh to 30 mesh, the maximum pressure decreases rapidly, which indicates that the suppression effect of single-layer wire mesh on pressure in the case of flame quenching is more effective than that in the case of flame propagating through the wire mesh. For the case of adding wire mesh of 100 mesh, the maximum pressure reaches its minimum value, 0.070 MPa. And the attenuated percentage reaches about 56.6%. This phenomenon could be explained by two aspects. First, the wire mesh could directly absorb the pressure waves and reduce the pressure. Second, the wire mesh could suppress the combustion procedure and make the flame tip speed in the suppression zone decrease, which leads to the decrease of pressure. These two effects finally make the maximum pressure inside the duct be attenuated effectively.

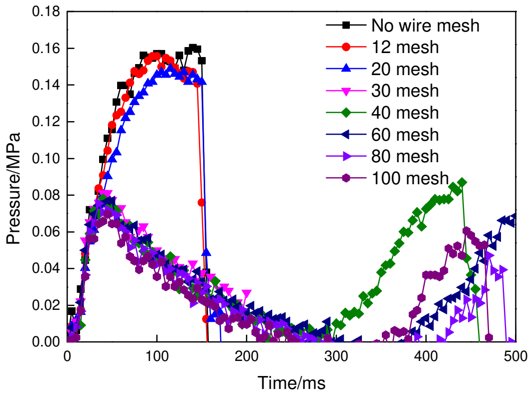


Fig. 9. Time history of pressure in the upstream duct.

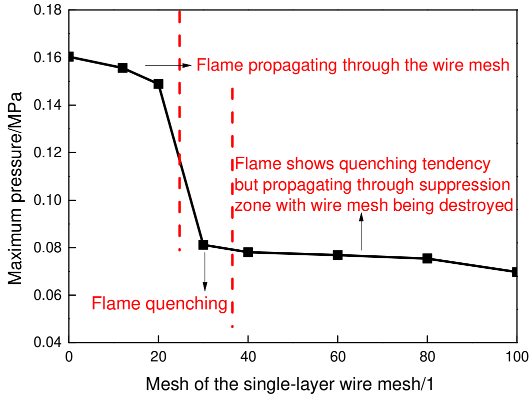


Fig. 10. Maximum pressure as a function of mesh.

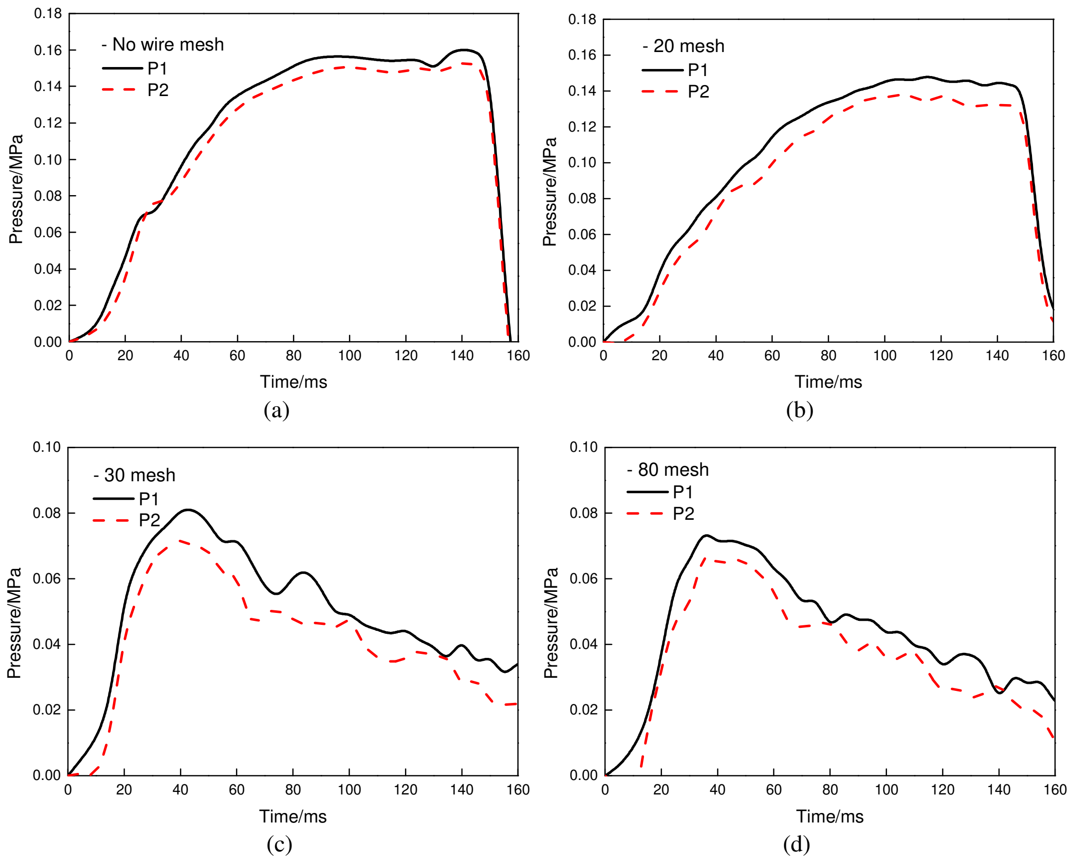


Fig. 11. Comparison of pressure in the upstream duct and downstream duct in the cases of (a) no wire mesh and adding single-layer wire mesh of (b) 20 mesh, (c) 30 mesh, and (d) 80 mesh.

Figure 11 illustrates the comparisons of pressure-time curves recorded in upstream duct and downstream duct clearly. P1 and P2 are defined as the pressure in the upstream duct and downstream duct, respectively. The cases of adding wire mesh of 20, 30, and 80 mesh are chosen here to represent the cases of flame propagating through wire mesh, flame quenching, and flame showing quenching tendency but finally propagating through the suppression zone with wire mesh being destroyed, respectively. For the case of no wire mesh, it is found that P2 coincides very well with P1. However, for the cases of adding wire mesh, no matter the flame quenching or propagating through wire mesh, it is found P2 is always a little smaller than P1. This result fully indicates that the single-layer wire mesh mounted in the suppression zone has a slight influence on increasing the resistance of gases flow inside the duct, which makes the pressure in the downstream duct a little smaller than that in the upstream duct.

Analysis of flame tip speed, pressure and tulip flame formation

Based on the analysis above, it is concluded that the single-layer wire mesh has no suppression effect on the flame tip speed in the upstream duct, but it can attenuate the pressure inside the duct effectively. According to the previous study [4], the flame tip speed is described as:

$$v = v_c + v_f \, . \tag{1}$$

Where v is the flame tip speed, v_c is the combustion speed of the mixture, and v_f is the gas flow speed in unburned field. Usually, v_c is determined by the laminar burning velocity, while v_f is closely related to the resistance of gases flow inside the duct and compressing on unburned field. With respect to laminar burning velocity, the relationship between laminar burning velocity, pressure, and temperature is described as [19]:

$$\frac{S_L}{S_{L_0}} = \left(\frac{T}{T_0}\right)^m \left(\frac{P}{P_0}\right)^n \tag{2}$$

Where S_L is the laminar burning velocity at pressure P and temperature T, S_{L0} is the laminar burning velocity at initial pressure P_0 and initial temperature T_0, m is the temperature index, and n is the pressure index. Premixed flame propagation is usually a rather short process. In this study, the total time for flame propagating in the upstream duct is about 30 ms, and for most of the time, the flame is not in contact with the sidewalls during this period. Considering the smaller heat transfer coefficient of the gas mixture, it can be approximately assumed as an adiabatic process. According to the adiabatic compression law [20], the relationship between temperature and pressure can be expressed as [21]:

$$\frac{T}{T_0} = \left(\frac{P}{P_0}\right)^{(\gamma-1)/\gamma} \tag{3}$$

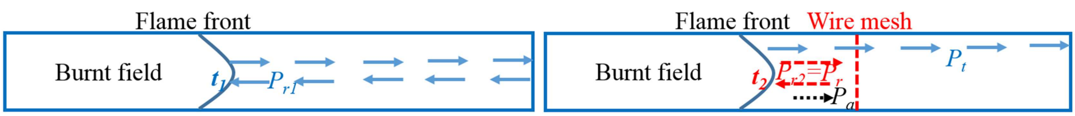
Where $\gamma = c_p / c_v$, c_p is the specific heat of constant pressure, and c_v is the specific heat of constant volume. In addition, the pressure and temperature change simultaneously in the flame propagation procedure, as such, the laminar burning velocity is described as [22]:

$$S_L = S_{L_0} \left(\frac{P}{P_0}\right)^{\varepsilon} . \tag{4}$$

Where $\varepsilon = m_0 + n_0 - m_0 / \gamma$, is the overall thermo kinetic index. According to previous studies [4, 23], for methane, ε is smaller than zero. Thus, the laminar burning velocity will increase with the decrease of pressure.

For the cases of adding wire mesh, it has been proved that the single-layer wire mesh has the ability to increase the resistance of gases flow inside the duct and attenuate the pressure, which makes v_f decrease. Of course, the attenuated pressure will lead to the increase of laminar burning velocity, which makes v_c increase at the same time. Consequently, the single-layer wire mesh cannot suppress the flame tip speed in the upstream duct because the decrease of the gas flow speed is balanced by the increase of the combustion speed. While, once the flame touches the wire mesh, the great heat losses caused by the wire mesh will effectively suppress the combustion procedure and leads to the flame deceleration. Meanwhile, the pressure will be attenuated simultaneously due to the coupling effect of single-layer wire mesh on absorbing pressure waves and suppressing combustion procedure in the suppression zone.

As presented in Fig. 3, it is found that the single-layer wire mesh make the tulip flame formation time advanced. And also, the single-layer wire mesh make the flame front inversion extent weaker compared with the case of no wire mesh. According to the previous studies [24, 25], tulip flame formation is closely related to the interactions between flame front and pressure waves. Pressure waves propagate forth and back in the closed duct, and once the flame meets pressure waves which propagate in the opposite direction, an inversion will be produced in the flame front, and tulip flame will form due to the coupling effect of pressure waves, flame front, and sidewalls. The propagation procedure of pressure waves is schematically shown in Fig. 12. In the case of no wire mesh, the pressure waves will propagate to the right end of the combustion duct and reflect back to interact with the flame front. We define the time when the pressure waves first contact the flame front as t_1, and the pressure value is defined as P_{r1}. However, in the cases of adding wire mesh, the pressure waves will be separated into three parts when touching wire mesh. The first part, which is defined as P_t, propagates through the wire mesh and propagates to the downstream duct continuously. The second part, which is defined as P_r, is reflected by the wire mesh to interact first with flame front. The third part, which is defined as P_a, is absorbed by the wire mesh directly. In these cases, we define the time when the pressure waves first contact the flame front as t_2, and the pressure value is defined as P_{r2}. Obviously, due to the presence of wire mesh, $t_2 < t_1$, which means the interactions between flame front and pressure waves in the cases of adding wire mesh occur earlier compared with the case of no wire mesh. Meanwhile, $P_{r2} = P_r < P_{r1}$ (as shown in Fig. 9 in the manuscript), which means the intensity of the interactions between flame front and pressure waves in the cases of adding wire mesh become weaker compared with the case of no wire mesh. Hence, tulip flame formation time becomes advanced and flame front inversion extent presents weaker in the cases of adding wire mesh compared with the case of no wire mesh.



(a) (b)

Fig. 12. Sketch of pressure waves propagation in the case of (a) no wire mesh and (b) adding wire mesh.

CONCLUSIONS

An experimental study on the influence of single-layer wire mesh on premixed methane-air flame behavior and pressure dynamics in a closed duct is conducted. The following conclusions are obtained from this study:

(1) The premixed methane-air flame propagates through the single-layer wire mesh in the case of adding wire mesh of 12 and 20 mesh, but quenches in the case of 30 mesh. For the cases of 40, 60,

80, and 100 mesh, the flame shows a salient quenching tendency but finally propagates through the suppression zone with single-layer wire mesh being destroyed.

(2) The quenching performance of single-layer wire mesh does not increase as mesh density increases, because the anti-destructive performance is also quite important in practical applications. Once the wire mesh is destroyed, the flame will present a second combustion and acceleration. If the duct is longer enough, the risk will be increased sharply, which should be avoid in particular in engineering applications.

(3) The single-layer wire mesh makes the tulip flame formation time advanced and makes the extent of flame front inversion weaker compared with the case of no wire mesh.

(4) The single-layer wire mesh has no suppression effect on the flame tip speed in the upstream duct, but delays the flame propagation procedure in the suppression zone, and this effect is strengthened as the mesh of single-layer wire mesh increases.

(5) The single-layer wire mesh has a salient suppression effect on maximum pressure during flame propagating in the closed duct, and the suppression effect increases as the mesh of single-layer wire mesh increases.

ACKNOWLEDGEMENTS

This work is supported by the National Natural Science Foundation of China (Project No. 51706220) and the National Key Research and Development Plan (No.2016YFC0800100). The authors are also thankful for the support provided by and the Research Grants Council of the Hong Kong Special Administrative Region, China (Project No. 9042354, CityU 11261216).

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