Influence of Copper Foam on the Flame Front Dynamics of a Hydrogen-Air Mixture in an Open Channel

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1 Introduction

The problem of explosion safety of gases is extremely urgent. This is especially important at the present time with the development of hydrogen energy. To prevent the propagation of the flame front, methods are being developed based on the chemical suppression of the combustion reaction and on the removal of heat [1,2], which in some cases is more efficient and does not require the use of complex reagents. The most effective method of heat removal is carried out by using perforated plates or porous media, which are characterized by a high effective contact surface with the gas medium [3-5].

An important criterion in these problems is the value of the thermal conductivity of the rigid skeleton. If the intensity of heat removal is insufficient, the porous media or perforated plate can act as turbulators for the flow of the unburned mixture and the flame front, leading to a significant acceleration of the flame front [6]. Generally, most of the work on determining the effect of a porous foam is carried out in a semi-open channel [3,7], in a closed channel [8,9], in a closed channel with a membrane/valve [5,10], with a plexiglass plate [11] or with two removable plugs [12].

In this work, the effect of open-pore copper foam on the dynamics of the flame front in an open channel and semi-open channel is studied. Experiments were carried out with hydrogen-air mixtures. To reduce the effect of pressure increase, one or both ends of the tube were open. The influence of the unburned mixture flow on the dynamics of the flame front was studied. In order to implement the displacement of the unburned mixture, the porous partition was placed in a section with expansion, and the initiation was carried out in a tube of a smaller cross section. Experiments were carried out in an open channel, as well as in a semi-open channel in order to change the effect of displacement of the unburned mixture due to the expansion of combustion products. The influence of the pores quantity (number of pores per inch, ppi) and the length of the copper foam on the dynamics of the flame front were determined for several equivalence ratios of the combustible mixtures.

2 Experimental Installation

The schematic of the experimental setup is shown in Fig. 1. The open channel consisted of two sections. The first section was a cylindrical tube with a spark gap and a tube for supplying a pre-prepared mixture of hydrogen with air, and a ball valve. The inner diameter of the tube and ball valve is 20 mm. The position of the spark gap is shown in Fig. 1. The cylindrical tube was connected to the second section which was a diagnostic section of the rectangular cross-section. Such a section was used to make it possible to apply the shadow method of registering the propagation of the flame front. The cross-sectional dimensions of the free channel with expansion were 20*40 mm. Thus, the cross-sectional area of the channel increased by a factor of 2.5. In this case, the distance between the glass walls was 20 mm. Porous elements made of copper foam were installed in the diagnostic section so that the distance from the front edge of the element to the beginning of the section was 60 mm. The porous element length was varied from 10 mm to 90 mm. Numbers of pores per inch (ppi) were 7 and 20.

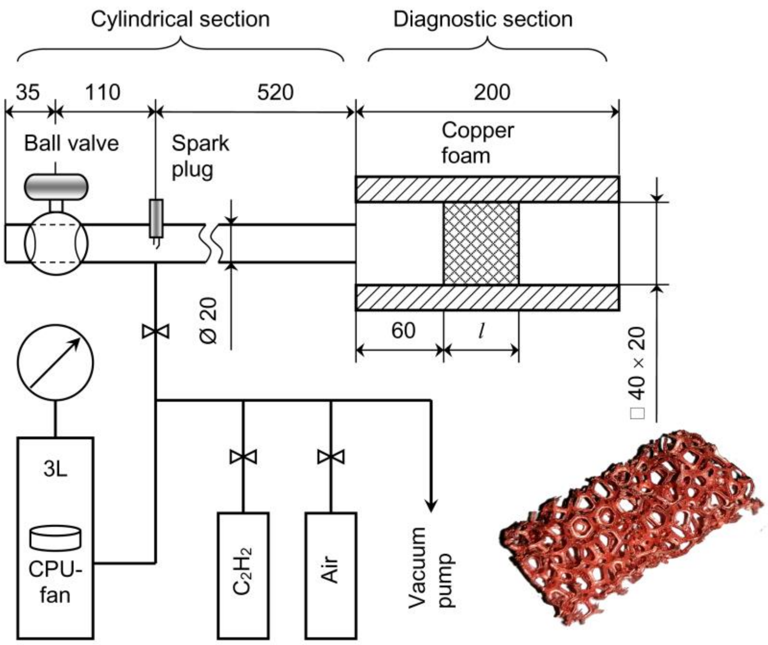

Figure 1: Schematic of experimental setup.

A mixture of hydrogen with air was prepared in a 3L cylinder by partial pressures using an calibrated manometer. The maximum pressure in the vessel was 0.7 MPa; the mixture was mixed using a CPU-fan installed inside the cylinder. At first, the four times volume of the mixture (about 2 L) was blown through the channels with the ball valve closed. After that, the ball valve was opened and the combustible mixture (about 1 L) was again fed into the channel. After filling the channel, the combustible mixture was ignited by a 0.1 J spark plug.

The flame front was recorded using high-speed camera Phantom VEO 710 (Phantom 710) and an IAB-451 Schlieren device with a Foucault knife. The dimensions of the glass windows made it possible to register a segment with a length of 150 mm. Continuous illumination was carried out using an xenon lamp (lamp) with a power of 35 watts. The registration frequency was 300–60 000 fps, the exposure time was 3 µs, the frame size was 1280×168 or 1280×80 pixels. An Infratec ImageIR infrared camera was used to record the combustion zone inside porous copper. The exposure duration was set to 27 µs, and the number of frames per second was 670 at a resolution of 671×312.

3 Experimental data

Figure 2 shows shadow and IR photographs of the interaction of the flame front for compositions $\phi = 0.3$ with a copper foam with 7 ppi and length of 60 mm in open channel. As can be seen from Fig. 2, the flame front in front of the foam has a wrinkled finger-like shape. The interaction of the flame front with the copper foam led to the more intense formation of perturbations at the flame front after passing it.

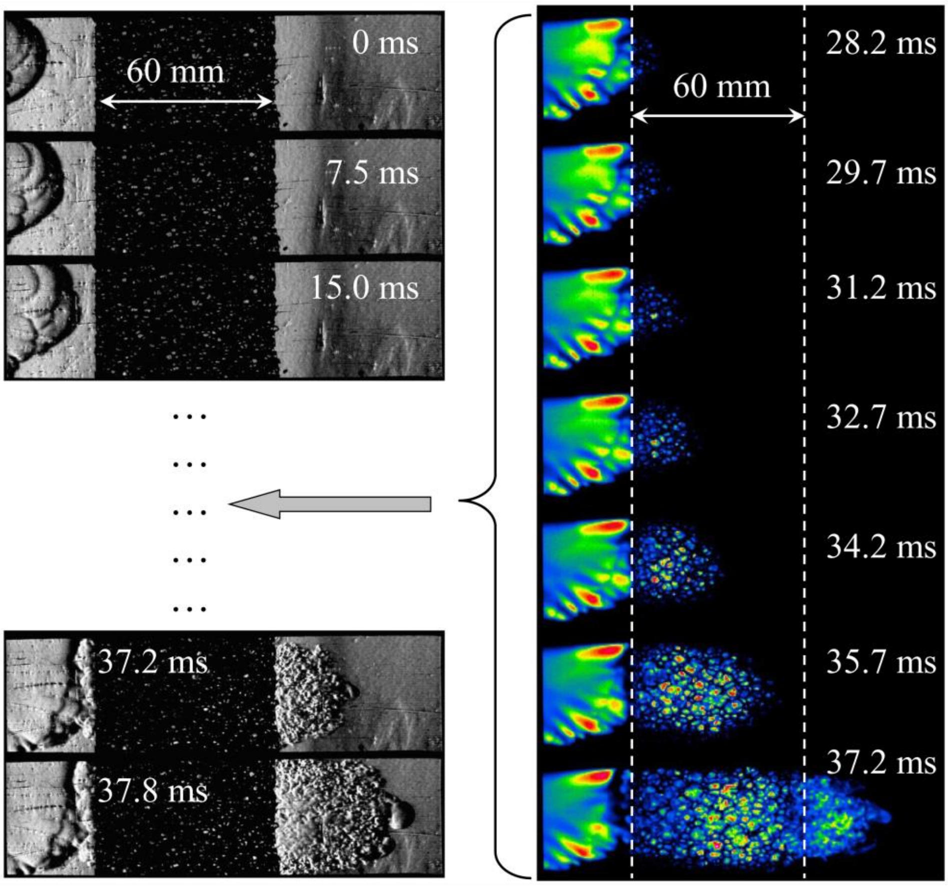

Figure 2: Sequential schlieren and IR images of the flame front in hydrogen-air mixture when passing through the copper foam, 7 ppi, length 60 mm. $\phi = 0.3$. The first image is taken as the zero time moment.

The evolutions of the flame front velocity along the diagnostic section, calculated from the difference in the positions of this front in two adjacent photographs, are shown in Fig. 3. Data are presented for open and semi-open channels, as well as for an empty channel without foam. The flame front velocity u_1 in hydrogen-air mixture with $\phi = 0.3$ before the foam varied in all cases from 1 m/s to 3 m/s (7 ppi), from 0.5 m/s to 2 m/s (20 ppi). An increase in the length from 10 to 60 mm for 7 ppi foam led to an increase in flame front velocity u_2 after passing through the foam from 3 m/s to 15 m/s (7 ppi) and from 3 m/s to 12 m/s (20 ppi). An increase in the length from 60 mm to 90 mm led to flame acceleration for 7 ppi and quenching for 20 ppi. After the flame front went through the foam, its velocity decreased to initial meanings.

Figure 4 shows the ratio of the velocity u_2 after passing through the porous foam to the velocity u_2^* before the foam, taking into account the expansion of the combustion products and the increase in the flame front velocity in the empty channel. The multiple scatter of values at a length of 90 mm is due to the formation and development of secondary ignition sources inside the copper foam, which do not depend on the initial flame front propagation in front of the foam. Considering foam lengths up to 60 mm (up to 90 mm in a lean mixture $\phi = 0.3$), it is worth noting that the dependence of the flame front velocity increases mainly linearly with increasing the length of the porous element.

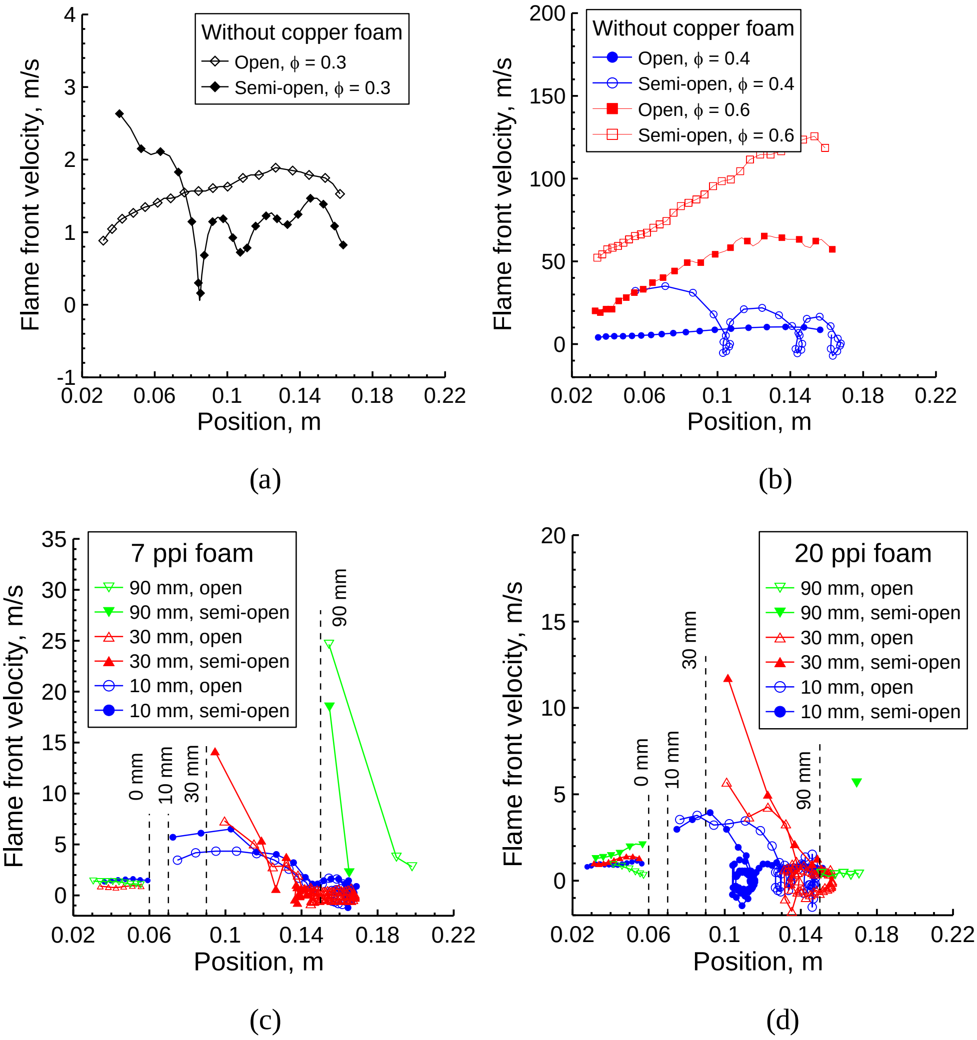

Figure 3: Flame front velocity in hydrogen-air mixture in diagnostic section (a) without porous copper, $\phi = 0.3$, (b) without porous copper, $\phi = 0.4$, 0.6, (c) with 7 ppi copper foam, $\phi = 0.3$, (d) with 20 ppi copper foam $\phi = 0.3$. The distance is given from the beginning of the diagnostic section.

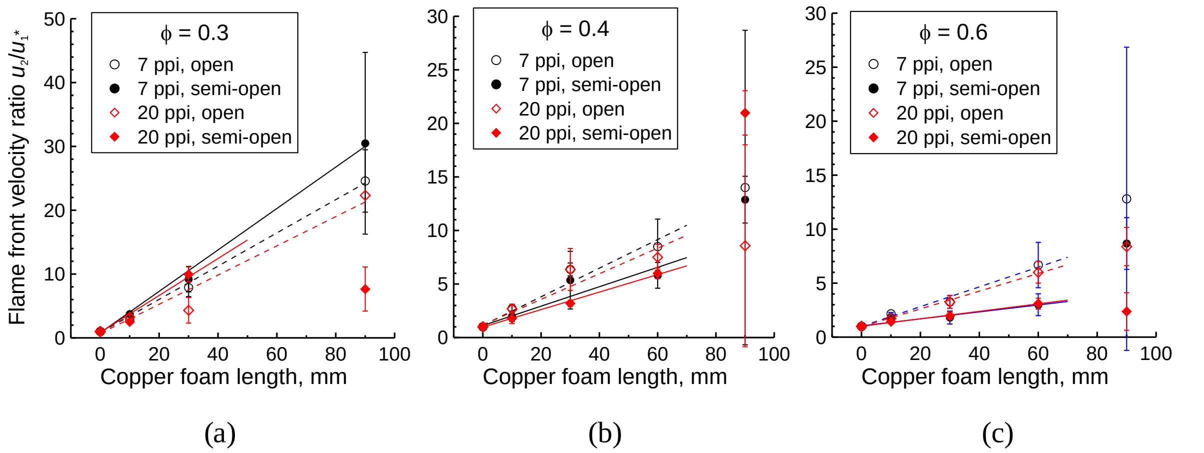

Figure 4: Flame front velocity ratios u_2/u_2^* for hydrogen-air mixture with (a) $\phi = 0.3$, (b) $\phi = 0.4$ and (c) $\phi = 0.6$.

The effectiveness K_{ppi} of the foam influence on the acceleration of the flame front can be determined as the slope of the linear dependence of the normalized velocity ratio u_2/u_2^* on the foam length l:

$$\frac{u_2}{u_2^*} \approx 1 + K_{\text{ppi}} l \,.$$

Figure 5 shows the coefficient values. The maximum efficiency K_{ppi} = 0.22-0.32 mm^{-1} was achieved for the lean mixture with ϕ = 0.3 and the minimum efficiency K_{ppi} = 0.03-0.10 mm^{-}1 for ϕ = 0.6. The values of the coefficients are the same for one number of pores per inch.

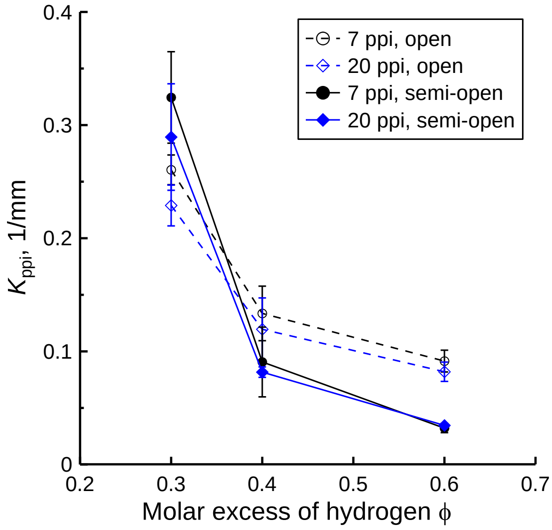

Figure 5: Dependence of effectiveness K_{ppi}, on molar excess ϕ of hydrogen. Solid lines/filled symbols – semi-open channel; dashed lines/empty symbols – open channel.

As can be seen from Fig. 3, in hydrogen-air mixtures ϕ = 0.4, 0.6, the flame front velocity in an empty open channel increases when propagating along the channel axis, and also for ϕ = 0.6 in a half-open channel. This acceleration is caused by the influence of combustion products, the thermal expansion of which increases from 3.7 for ϕ = 0.3 to 5.6 for ϕ = 0.6. In addition, the estimation of the Reynolds numbers Re of the unburned mixture flow for a semi-open channel according to the relations [14] makes it possible to establish the values Re = 900–1000 for the mixture ϕ = 0.3 and Re = 2000–10000 for mixtures ϕ = 0.4, 0.6. Thus, the direct influence of the porous foam on autoturbulence and flame front acceleration, compared with other factors, will be more effective for mixtures characterized by a low thermal expansion ratio of combustion products and a laminar flow of the unburned mixture. In this case, the integral contribution of the porous foam to the autoturbulence is determined by the duration of the flame front propagation through the foam: ~l/u_1, the maximum value is typical for lean mixtures. Similar discussion can be applied to open channels, in which the velocity of the unburned mixture is much lower than the velocity of the flame front, because the combustion products flow in the opposite direction from the propagation of the flame front.

4 Summary

The propagation of the flame front in an open and semi-open channel with the copper foam was studied. The placement of copper foam with 7 ppi and 20 ppi led to the acceleration of the flame front. The relative acceleration of the front during the passage of the foam is linear. The contribution to the acceleration can be due to the turbulization of the combustion zone inside the porous foam. The dependence of the efficiency K_{ppi} on the molar excess ϕ of hydrogen was obtained.

5 Acknowledgements

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