Acetylene-air Flame Acceleration in Rough Channels

Grigory Yu. Bivol, Sergey V. Golovastov, Victor V. Golub
Joint Institute for High Temperatures of Russian Academy of Science
125412, Moscow, Russia

1 Introduction

The conditions for flame acceleration and detonation initiation in the narrow channels are of great interest both for practical application and for ensuring explosion safety. As the flame accelerates and the detonation propagates in a narrow channel, the boundary layers and channel walls begin to play an important role [1]. Due to the strong influence of the boundary layer, the roughness of the walls or obstructions in the channel can lead to acceleration of the flame and its transition to detonation. Sandpaper on the channel wall was shown to greatly enhance flame acceleration and transition to detonation in the hydrogen-oxygen mixture [2]. A different type of roughness in the form of small pyramid elements was also used for flame acceleration and detonation formation [3]. The size of the roughness elements has a big impact on flame dynamics. Numerical simulations showed that increase in the roughness size led to faster flame acceleration and faster transition to detonation [4,5]. When detonation propagated in the narrow channels, velocity deficit or galloping detonation modes were often registered. [6,7]. Detonation velocity deficit can also be caused by the channel roughness. Placing helical spiral in the channel led to narrowing of the detonation limits and up to 50% velocity deficit [8].

The experiments were carried out in a channel 7 by 7 mm in size, which corresponds to the size of a detonation cell in the acetylene-air mixture. [9]. The aim of the work was to determine the effect of a rough coating on the walls of the narrow channel on the dynamics of the flame. As a combustible mixture, mixtures of acetylene with air were used at various ratios of fuel and oxidizer (ER – equivalence ratio).

2 Experimental Setup

The experimental setup consisted of a 200 mm long initiation section with an inner diameter of 20 mm and a 1200 mm long diagnostic section with a 7 by 7 mm cross-section. The diagnostic section had plexiglas walls for the flame visualization. Ignition was carried out using a spark gap at the closed left end of the detonation section. The right end of the diagnostic section was open to atmosphere. A combustible mixture was prepared in a 3-liter vessel. Acetylene-air mixture with ER from 0.8 to 1.4 was used. The maximum pressure of the mixture in the vessel was 420 KPa. The mixture was stirred for at least 1 hour using a fan inside the vessel. Each experiment was repeated at least 3 times.

Two types of sandpaper were used to cover one or two walls of the channel. Large grain sandpaper had a thickness of 1.0–1.1 mm and a grain size of 500 µm, small grain sandpaper had a thickness of 0.6 mm and with a grain size of 100 µm. Visualization of the flame was carried out using Phantom VEO 710 high-speed camera. The pressure was measured using four PCB pressure sensors located at a distance of 200, 400, 600, and 800 mm from the beginning of the diagnostic section.

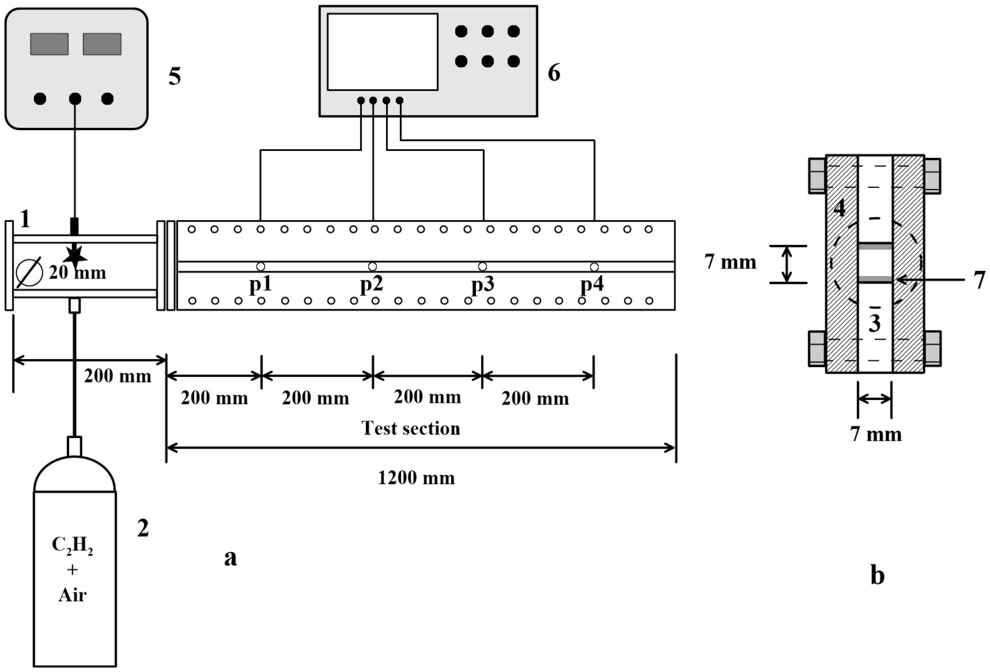


Figure 1: Side view (a) and cross-section of the experimental setup: 1 – spark gap, 2 – supply of combustible mixture, 3 –steel plates, 4 – plexiglass windows, 5 – ignition system, 6 – oscilloscope, 7 – sandpaper.

3 Results and Discussion

Figure 2 shows typical streak images of flame propagation in a stoichiometric mixture of acetylene with air in a channel with one wall covered with large grain sandpaper. Recording of the flame was carried out with a frame rate of 200,000 frames per second. The high-speed camera made it possible to visualize the flame luminance in the spectral range of 350–1050 nm. Flame velocity was also confirmed using IR camera Infratec ImageIR. The spectral range of the IR camera was 1.5-5.7 µm. Based on high-speed images sequences, graphs of the evolution of the flame velocity were plotted, shown in Figure 3.

Figure 3 shows evolution of the flame velocity in a stoichiometric mixture of acetylene with air. Also on the graph are the Chapman-Jouguet detonation velocity ($V_{C\text{-}J}$) and isobaric sound speed (a) [10].

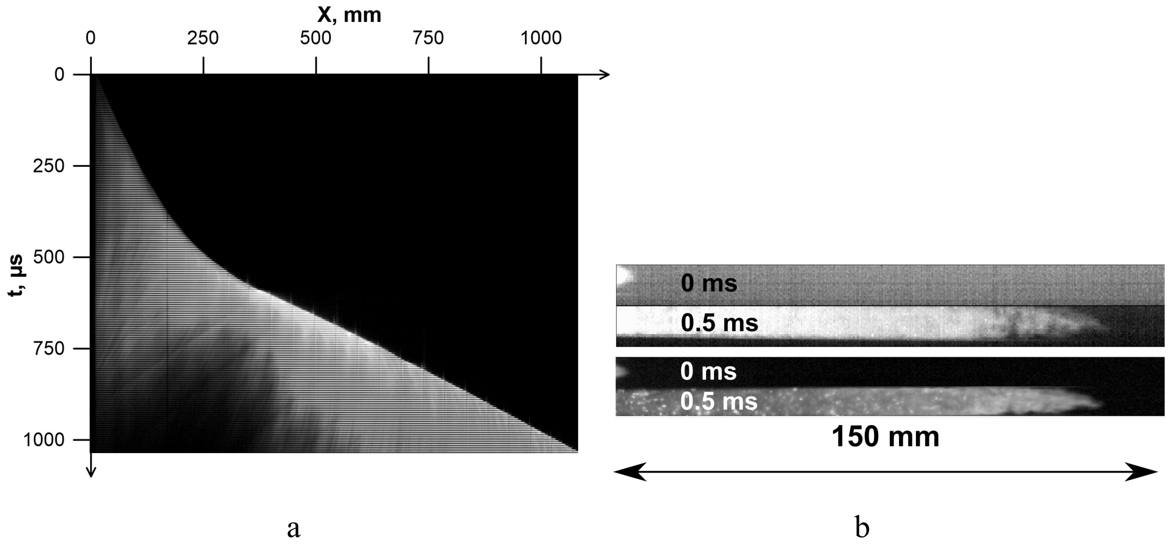


Figure 2: Image sequence of flame propagation in a stoichiometric mixture in the channel with one wall covered with large grain sandpaper (a) and comparison (b) between images obtained in the IR spectral range (top) and in the visible spectral range (bottom).

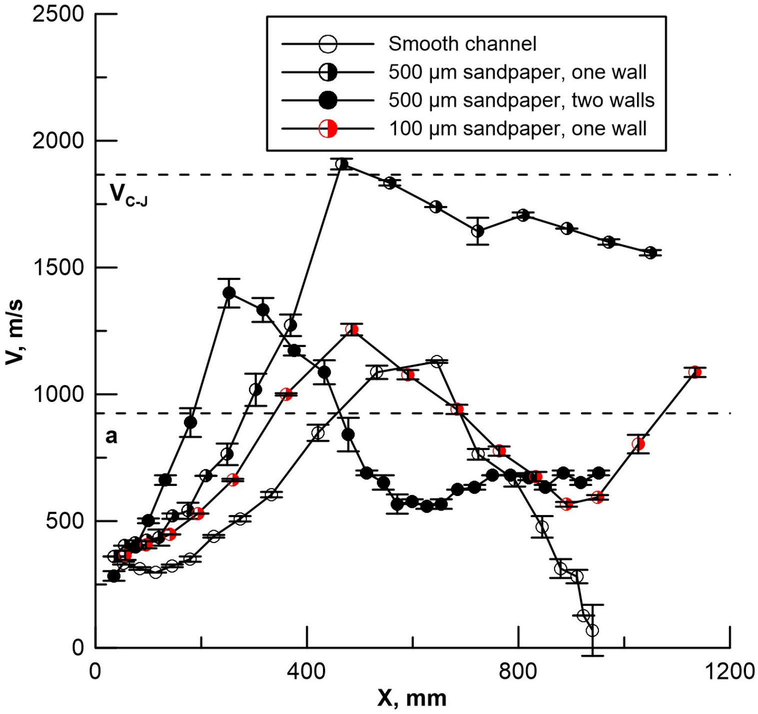
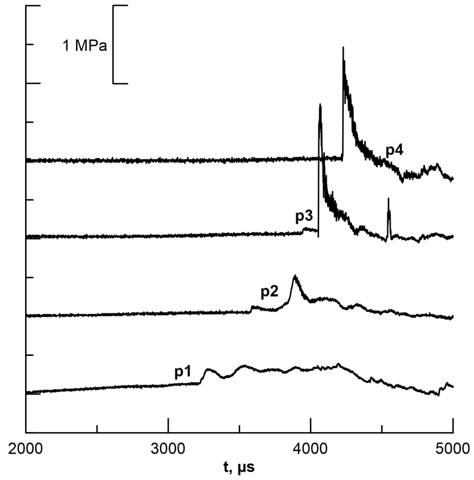
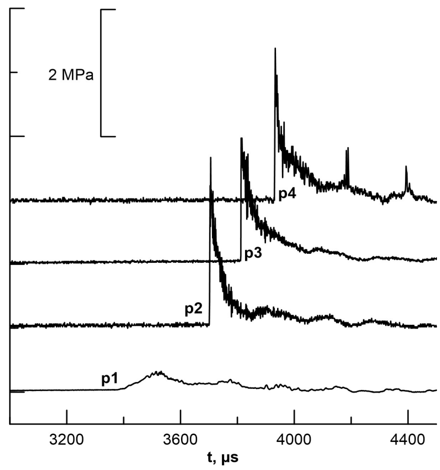


Figure 3: Dependence of the flame speed on the distance in a stoichiometric mixture of acetylene with air in an empty channel, a channel with one covered wall and with two covered walls. Large grain and small grain sandpaper was used

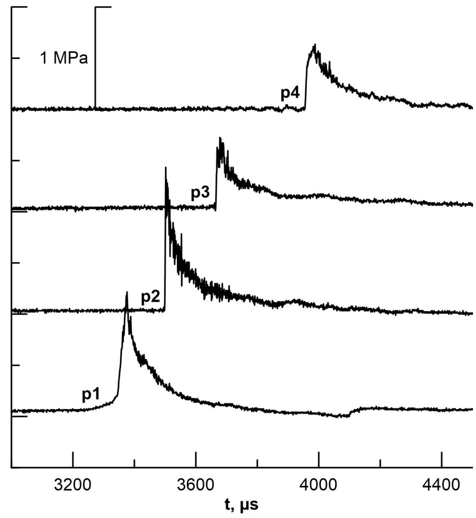
In a smooth channel, the flame reached the velocity of 1200 m/s, followed by rapid slowing down. The final flame velocity in the smooth channel was around 100 m/s. When covering one channel wall with large grain sandpaper, the flame reached Chapman-Jouguet detonation velocity at the distance of 400 mm from the beginning of the diagnostic channel. After the initial acceleration, the flame velocity slowly decreased to 1600 m/s. When covering two channel walls with large grain sandpaper, the flame velocity increase to 1400 m/s was also recorded at the distance of 200 mm. Then the flame decelerated to 600 m/s at the distance of 600 mm and continued to propagate at this velocity to the end of the channel. When covering one channel wall with small grain sandpaper, the flame reached its maximum velocity of 1250 m/s at the distance of 500 mm. The flame then decelerated to 600 m/s and accelerated again over 1000 m/s by the end of the channel. Higher roughness led to more significant acceleration of the flame front. Flame velocity reached the detonation values when using large grain sandpaper. During supersonic flame propagation, this may be due to the combined effect of wall roughness and an increase in the turbulent boundary layer, but turbulence plays the most significant role.



(a)



(b)



(c)

Figure 4: Pressure readings for flame propagation in stoichiometric acetylene-air mixture: a – smooth channel, b – channel with one covered wall, c – channel with two covered walls.

Pressure readings for flame propagation in stoichiometric acetylene-air mixture are shown in Figure 4. In the smooth channel gradual pressure increase was recorded for pressure sensors 1 and 2 which were located at the distance of 200 and 400 mm from the beginning of the diagnostic section. Shock wave with a pressure of 1.5 MPa was recorded on the sensors 3 and 4. In the channel with one wall covered in sandpaper the shock wave with a pressure of 2 MPa was recorded starting from pressure sensor 2. In the channel with two covered walls shock wave was also recorded starting from pressure sensor 2, but the pressure dropped to 0.7 MPa on pressure sensor 4. Flame velocity drop in the smooth channel happened after pressure sensor 4 and did not affect the shock wave pressure.

In the tested acetylene-air mixtures with ER from 0.8 to 1.4 the highest flame velocity was recorded in the channel with one covered wall. For ER = 1 and 1.4 the flame reached Chapman-Jouguet detonation velocity. The lowest flame velocity was recorded in the smooth channel. For example in the mixture with ER = 0.8 the highest flame velocity was 400 m/s, in the channels with one or two covered walls the highest flame velocity was 1500 m/s and 800 m/s, respectively. When two walls of the channel were covered with sandpaper, the flame velocity was higher, than in the smooth channel, but lower, than in the channel with only one covered wall. In the channel with two covered walls the highest flame velocity was around 0.75–0.85 of the detonation velocity for mixtures with ER=0.9–1.4.

In all the studied mixtures, at the initial stage, the flame velocity was higher in the case of two covered channel walls compared to the channel with one covered wall. Since the flame velocity at the beginning of the diagnostic section was higher than the speed of sound in the combustible mixture, a shock wave propagated in front of the flame. Reflection of the shock wave from a large number of small obstacles in the form of sandpaper led to the interaction of shock waves with the flame and its further acceleration. In this case, the presence of two channel walls with roughness led to a larger number of reflected waves and a higher flame velocity.

Doubling the roughness or increasing the size resulted in detonation. But further increase in the size of the roughness on the two walls led to the supersonic combustion, and the maximum velocity was already reached by 250 mm, but detonation was not achieved due to large losses on the channel walls

On the other hand, the presence of roughness on the wall led to an increase in the boundary layer thickness and losses in it [11]. Since losses in the boundary layer are one of the reasons for the detonation velocity deficit [12], covering two walls of the channel with sandpaper can lead to an increase in the boundary layer thickness and losses in them so that stable detonation cannot propagate in such a channel. Therefore, in the channel with two covered walls, we observed the propagation of supersonic combustion at velocities lower than the Chapman-Jouguet detonation velocity.

4 Conclusions

Scenarios of flame acceleration in a smooth narrow channel and the channel with one or two channel walls covered with two types of sandpaper were experimentally obtained in the mixture of acetylene with air. It was discovered that covering one wall of the channel greatly facilitated flame acceleration and led to detonation formation in stoichiometric and rich mixtures. However, covering the second wall with sandpaper did not lead to further flame acceleration and the highest flame velocity in the channel with two covered walls was lower than in the channel with one covered wall and did not reach the Chapman-Jouguet detonation velocity. The grain size of the sandpaper was shown to greatly affect flame propagation, since in the case of covering one wall with the small grain sandpaper the flame did not reach detonation velocity.

5 Acknowledgements

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References

[1] Ballossier Y, Virot F, Melguizo-Gavilanes J. (2021). Flame propagation and acceleration in narrow channels: sensitivity to facility specific parameters. Shock Waves. 31: 307.

[2] Maeda S, Fujisawa M, Ienaga S, Hirahara K, Obara T. (2019). Effect of sandpaper-like small wall roughness on deflagration-to-detonation transition in a hydrogen–oxygen mixture. Proc. Combust. Inst. 37:3609.

[3] Maeda S, Irokawa M, Taneichi D, Obara T: (2022). Flame acceleration process and detonation transition in a channel with roughness elements on a wall. Proc. Combust. Inst.

[4] Houim RW, Oran E. (2017). Effect of surface roughness on deflagration-to-detonation transition in submilimeter channels. In Proc. 26th Int. Colloq. Dynam. Explos. React. Syst.

[5] Dziemiska E, Hara Y, Morishita M. (2017). Roughness Influence on Flame and Detonation Propagation. In Proc. 26th Int. Colloq. Dynam. Explos. React. Syst.

[6] Cao W, Ng H, Lee J. (2020). Near-limit detonations of methane–oxygen mixtures in long narrow tubes. Shock Waves. 30:713.

[7] Golovastov SV, Bivol GY, Golub VV. (2021). An experimental study of detonation propagation and re-initiation for acetylene–air mixtures in a narrow channel. Shock Waves. 31:49.

[8] Liu Y, Lee JH, Tan H, Ng HD. (2021). Investigation of near-limit detonation propagation in a tube with helical spiral. Fuel. 286:119384.]

[9] Knystautas R. (1984). Measurement of cell size in hydrocarbon-air mixtures and predictions of critical tube diameter, critical initiation energy and detonability limits. Progr. Astronaut. Aero. 94:23.

[10] Peraldi O, Knystautas R, Lee JH. (1988). Criteria for transition to detonation in tubes. In Symposium (International) on Combustion. 21:1629.

[11] Ding S, Huang K, Han Y, Valiev D. (2021). Numerical study of the influence of wall roughness on laminar boundary layer flashback. Phys. Rev. Fluids. 6:023201.

[12] Fay JA. (1959). Two-dimensional gaseous detonations: Velocity deficit. Phys. Fluids. 2:283-289.