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Penetration of methane–oxygen flames through flat obstacles with several openings

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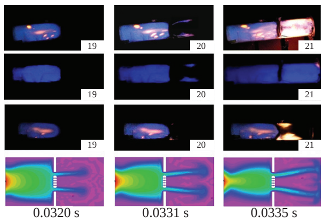
It was established that both the minimum diameter of a central opening through that the flame of a dilute methane–oxygen mixture can penetrate and the minimum pressure of flame penetration decrease with the number of openings.



The influence of obstacles located in the volumes filled with combustible mixtures on flame front (FF) propagation has been investigated.[1,2] If the composition of a gas mixture is far from ignition limits, the FF velocity in the presence of obstacles can increase to supersonic values.[3,4] The most prominent reason for the investigation of these accelerated flames is explosion safety problems.[5] In a breakdown of fire safety, an amount of flammable gas can be released into ambient air. The resulting explosive mixture can endanger the integrity of the vessel, reactor, mine, *etc*. The power of explosion depends on the shape of the confinement and the number of openings in it (doors, windows and air vents). Although the global characteristics of the flame acceleration have been investigated,[1–6] the data basis obtained by locally highly resolved measurement methods, determining process variables like density, temperature, velocity, and species concentration is still very poor. In accordance with a concept of a limit of flame propagation on the diameter of single opening in an obstacle, there is a critical opening diameter below which a flame does not penetrate through the opening. However, we found earlier that a dilute methane–oxygen flame gets through a close-meshed grid, *i.e*., through the obstacle consisting of a large number of openings with very small diameters.[6] The number of openings in an obstacle influences the limit of flame penetration through an obstacle. This matter relevant to explosion safety is not considered in literature.

We found recently that, upon the penetration of FF through obstacles, gas dynamic factors, for example, turbulization of a flame, show a noticeable feedback with combustion kinetics.[6,7] The FF after a single obstacle does not occur in close proximity to an obstacle, and the primary center of ignition is observed far from an obstacle surface (flame jump). The use of a net sphere as an obstacle leads to an increase in the jump length of FF behind an obstacle in comparison with a round opening. Two or more spherical and flat obstacles considerably suppress FF propagation, and the flame jump length after the opening in an obstacle is mostly determined by the time of occurrence of a transition from laminar to turbulent flow rather than the time of ignition delay period. It was experimentally shown that, at penetration of a flame through obstacles, gas dynamic factors, for example, flame turbulization, could determine the kinetics of combustion, for instance, a transition of low-temperature hydrocarbon combustion to a high-temperature mode.[8]

Due to the complexity of branched chain combustion and the geometry of a containment, the propagation of a flame and the resulting warming-up cannot be simulated with suitable accuracy. The compressible reactive Navier–Stokes equations can be simplified and used to model a non-isothermal flow with a low Mach number.[6,9,10] In low speed turbulent combustion applications, the variable-density low Mach number approximation of the Navier–Stokes equations is an adequate basis for simulation. Nevertheless, any comparison of experimentally detected flame front propagation with the result of numerical modeling is only qualitative, *e.g*., on propagation velocity of the boundary of initial and reacting gas and on the shape of this border.

This work was focused on the influence of the number of openings in a flat obstacle on a minimum diameter and minimum pressure of flame penetration through the obstacle.

Flame propagation in the stoichiometric methane–oxygen mixtures diluted with CO_2 and Ar at initial pressures of 100–200 Torr and 298 K in a horizontal cylindrical quartz reactor 70 cm in length and 14 cm in diameter was investigated.[†] The reactor was fixed in two stainless steel gateways at butt-ends supplied with inlets for gas pumping and blousing and a safety shutter, which swung outward when the total pressure in the reactor exceeded 1 atm.[6] A pair of spark ignition electrodes was located near the left butt-end of the reactor.[6] Thin obstacles 140 mm in

† The combustible mixture (15.4% CH_4 + 30.8% O_2 + 46% CO_2 + 7.8% Ar) was prepared; CO_2 was added to enhance the quality of filming by decreasing FF velocity; Ar was added to diminish the discharge threshold. The reactor was filled with the mixture to a necessary pressure. Then, spark initiation was performed (discharge energy, 1.5 J).

The speed filming of ignition dynamics and FF propagation was carried out with a Casio Exilim F1 Pro digital camera (frame frequency, 600 s^{-1}).[6–8] The interference filter of 435 nm (40% filter factor, the half-width of 15 nm) was applied to select the emission of CH ($A^1\Delta$–$X^2\Pi$) at 431 nm.[12] Acoustic oscillations were recorded with a Ritmix sensitive microphone (up to 40 kHz). The audio file was analyzed with the Spectra Plus 5.0 software package. Chemically pure reagents were used.

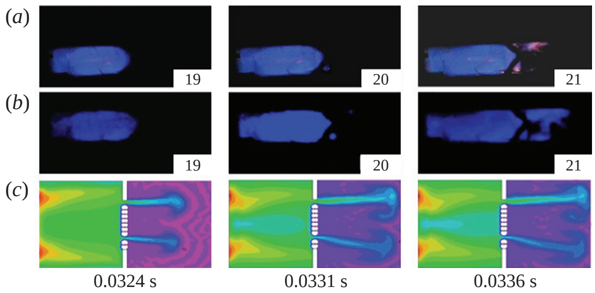


Figure 1 High-speed filming of FF propagation through (*a*) a flat obstacle 14 cm in diameter with two asymmetrically arranged openings 15 mm in diameter (the first is located at 35 mm from the center, and the second, at 55 mm from the center); (*b*) the same obstacle with an interference filter (435 nm) placed in the front of the camera. Initial pressure, 155 Torr; 600 frames s^{-1}. (*c*) Calculation of the process of flame propagation through the obstacle: change in dimensionless concentration of initial substance for $n = 0$ on the mesh (type I of boundary conditions).

diameter with two circular openings 15 mm in diameter and three circular openings 12 mm in diameter were placed vertically at the reactor center (Figures 1–3). In a few experiments, the obstacle with two symmetrical openings (Figure 2) was equipped with two reservoirs where iron nanopowder was placed. Iron nanoparticles obtained by a chemical metallurgy method,[11] which were blown out of the reservoir through an opening with a gas flow at flame propagation from the left to the right, were ignited in a methane flame. Thus, burning iron nanoparticles visualized the gas flow during combustion. In some experiments, a complex obstacle with two symmetrical openings (Figure 2) and a flat obstacle with a single opening 15 mm in diameter located within 90 mm from the first obstacle was used.

We approximately illustrated the flame penetration through the obstacles by numerical modeling using compressible dimensionless reactive Navier–Stokes equations in a low Mach number approximation,[13] which describe flame propagation in a two-dimensional channel. The equations showed a qualitative consent with experiments.[6–8] The problem was solved by finite element analysis with the FlexPDE 6.08 package.[14] The simple chain mechanism[6] was used. Initiation condition was taken as $T = 10$ on the left boundary of the channel; there was an obstacle in the channel. Boundary conditions (including the orifice) were $C_\xi = 0$, $u = 0$, $v = 0$, $\rho_\xi = 0$ and $n = 0$ (type I of boundary conditions) only on the obstacle surface, as well as a convective heat exchange $T_t = T - T_0$, where ξ is a dimensionless coordinate. The initial density ρ_0 and the initial pressure P_0 were chosen[6] to provide the lack of flame penetration through the single central opening of the same width.

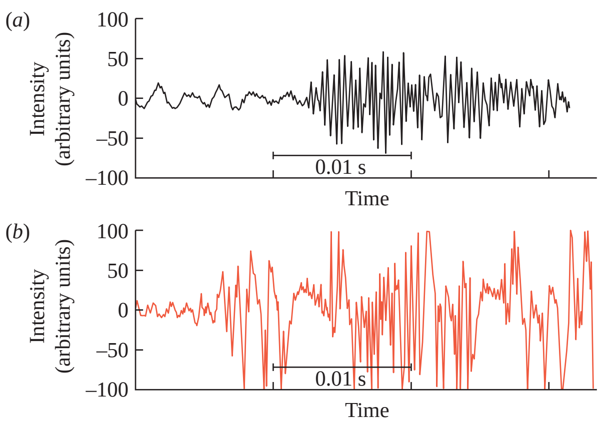


Figure 2 Dependence of acoustic intensity on the number of openings: (*a*) a flat obstacle with a central circular opening 20 mm in diameter (initial pressure, 170 Torr); (*b*) a flat obstacle with two asymmetric openings (see Figure 1), 155 Torr.

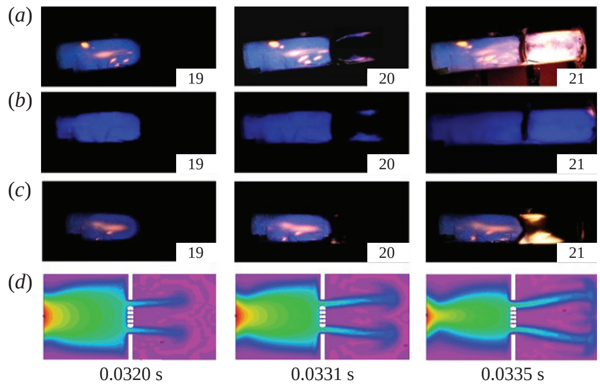


Figure 3 High-speed filming of FF propagation through (*a*) a flat obstacle 14 cm in diameter with two symmetrically arranged openings 15 mm in diameter (55 mm from the center); (*b*) interference filter 435 nm is placed in the front of the camera (initial pressure, 155 Torr); (*c*) the same obstacle, each opening is equipped with a reservoir with iron nanopowder; and (*d*) calculation of the process of flame propagation through the obstacle: change in dimensionless concentration of initial substance for $n = 0$ on the orifice (type I of boundary conditions).

We earlier determined the minimum diameter of flame penetration through an obstacle with a single central opening, which was 20 mm,[6] and the minimum pressure of flame penetration through this opening was 170 Torr. Note that a safety shutter did not swing outward under these conditions, *i.e.*, the maximum reactor pressure was lower than 1 atm.

Figure 1(*a*) shows the results on the high-speed filming of FF propagation in the above combustible mixture at an initial pressure of 155 Torr through a flat obstacle 14 cm in diameter with two asymmetrically arranged openings 15 mm in diameter. In Figure 1(*b*), the interference filter (435 nm) is placed in front of the lens of the camera to visualize the distribution of CH radicals during flame propagation. The flame jump is longer for the opening located closer to the surface of the reactor. The result of calculations in Figure 1(*c*) is in agreement with this experimental fact. Flame propagation is accompanied by a characteristic sound, and a safety shutter opened indicating that the maximum pressure exceeded 1 atm. The acoustic intensity for a flat obstacle with a central circular opening at an initial pressure of 170 Torr and the dependence for a flat obstacle with two asymmetric openings at 155 Torr are shown in Figures 2(*a*) and (*b*), respectively. Figure 3 demonstrates the typical frames of the high-speed filming of FF propagation in the combustible mixture at 155 Torr through a flat obstacle 14 cm in diameter with two symmetrical openings 15 mm in diameter placed in 55 mm from the center of the obstacle. The interference filter (435 nm) was placed in front of the camera lens to record the distribution of CH radicals during flame propagation, which was accompanied by a sharp

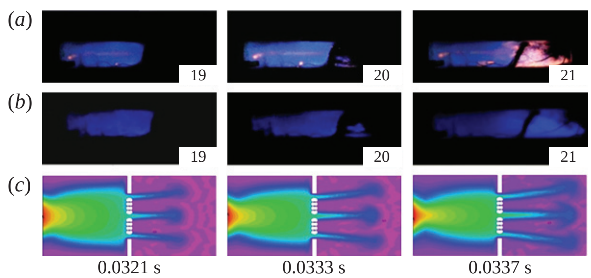


Figure 4 High-speed filming of FF propagation through (*a*) a flat obstacle 14 cm in diameter with three openings 12 mm in diameter placed in 55 mm from each other, one opening is in the center; (*b*) the same obstacle, interference filter 435 nm is placed in the front of the camera (initial pressure, 150 Torr); (*c*) calculation of the process of flame propagation through the obstacle: change in dimensionless concentration of initial substance for $n = 0$ on the mesh (type I of boundary conditions).

sound, and a shutter opened indicating that the maximum pressure exceeded 1 atm. Figure 4 illustrates the high-speed filming of flame propagation in the test mixture at 150 Torr through a flat obstacle 14 cm in diameter with three openings 12 mm in diameter (in 55 mm from each other, one opening is in the center) with the interference filter. As can be seen in Figure 4(*a*), flame penetrated only through two openings; therefore, the conditions can be considered limiting for this obstacle.

The diameters of obstacle openings in Figures 1, 3 and 4 are smaller than the minimum diameter of flame penetration through an obstacle with a single central opening (20 mm, see above). The total pressure of flame penetration is also lower than the minimum total pressure for flame penetration through a single opening (170 Torr). However, the maximum pressure and maximum acoustic intensity (Figure 2) are much greater for an obstacle with two openings. The observed pattern is due to the fact that two or three openings are more effective turbulators than a single one. The bear witness to that fact are the results of calculations of the process of flame penetration through the obstacle [Figures 1(*c*), 3(*c*), 4(*c*)], which qualitatively agree with the experimental data [Figures 1(*a*),(*b*), 3(*a*),(*b*), 4(*a*),(*b*)]. We recall that the conditions of calculations were chosen in such a way that flame penetration through the single central opening of the same width as that in Figure 1(*c*) was not achieved.

Figure 5(*a*) shows typical frame sequences of flame penetration through a complex obstacle containing a flat obstacle 14 cm in diameter with two symmetrically arranged openings 15 mm in diameter and the second flat obstacle with a single opening 15 mm in diameter located within 90 mm from the first obstacle at an initial pressure of 155 Torr. The flame penetrates through

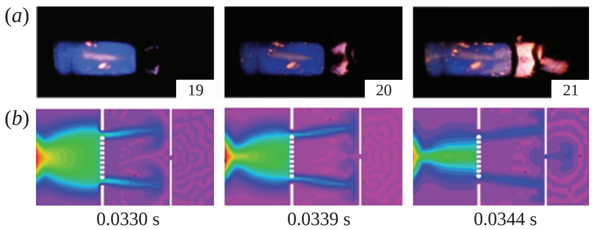


Figure 5 High-speed filming of FF propagation through a complex obstacle containing (*a*) a flat obstacle 14 cm in diameter with two symmetrically arranged openings 15 mm in diameter (see Figure 2) and the second flat obstacle with a single opening 15 mm in diameter located within 90 mm from the first obstacle (initial pressure, 155 Torr); (*b*) calculation of the process of flame propagation through the complex obstacle: change in dimensionless concentration of initial substance for $n = 0$ on the mesh (type I of boundary conditions).

both obstacles, though if we use a flat obstacle with a single central opening 15 mm in diameter instead of the obstacle with two openings, the flame would not penetrate through that complex obstacle at all. It means that preliminary flame turbulization with the first obstacle under conditions of Figure 5 provides flame penetration through the second obstacle.

Thus, we concluded that, in the assessment of the fire safety of a room or confinement with several openings, one should not use the minimum size of a single opening because the size sufficient for flame penetration decreases with raising the number of openings.

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