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Suppression of laminar flames of natural gas–oxygen mixtures with complex obstacles

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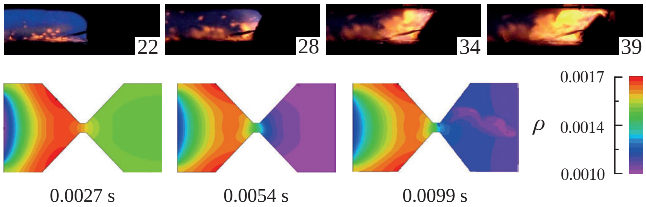
It has been experimentally shown that a complex obstacle consisting of two confusers oriented in opposite directions of a cylindrical vessel completely prevents the propagation of diluted methane – oxygen flames, *i.e.*, the obstacle is the most effective flame arrester; the theoretical predictions are consistent with the experiments.



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In the event of an emergency at an industrial plant or during the transport of combustible gases, a significant amount of flammable gas can be released. Mixed with ambient air, the resulting mixture can damage production equipment and cause significant harm to personnel. Due to the complex chemical and physical combustion processes, as well as the geometry of the production area or transport unit (pipe), flame propagation and the resulting pressure load cannot yet be simulated with reasonable accuracy.[1] Modeling turbulent premixed explosions involved in deflagrating flames inside a confined chamber remains a challenge, especially with respect to adequate representation of the combustion velocity and flame front structure. The compressible Navier–Stokes equations for reacting media can be simplified and used to solve a nonisothermal reacting flow only in the low Mach number approximation. In applications with subsonic turbulent combustion, the low Mach number, variable density approximation of the Navier–Stokes equations is a reasonable basis for simulation.[2,3] When a laminar flame propagates into an unburned region of pre-mixed combustible gases, it moves due to the transfer of heat and active centers ahead of the flame front, which causes a self-sustaining reaction in the source gas.[4,5] The release of heat during combustion brings about flow instability in the form of buoyancy and gas expansion, which, in turn, causes a transition from laminar to turbulent flow. Turbulence also enhances combustion by increasing the mixing process. Thus, the premixed flame first propagates as a laminar front, wrinkled by, *e.g.*, obstacles, and turns into a turbulent flame propagating at a higher velocity. While large-scale experimental studies of this process are difficult due to a number of objective factors, such as high cost, high temperatures, high gas content and strong smoke, which create an immediate danger to experimenters, our studies based on a model experiment are free from these shortcomings.

We have previously shown[6–8] that a flame in a diluted methane–oxygen mixture penetrates through a diffuser; however, the penetration of the flame through a confuser is not observed, the flame is extinguished. This qualitative difference from the process of flame penetration through a plane obstacle with a central hole indicates the significant role of the interaction of acoustic vibrations of a reactor containing a conical cavity with a propagating combustion front[6] even in the case of a subsonic flame. The simulation on a small scale assumes that in the event of an emergency, the flame will not penetrate through the open valve located in the center of the confuser located in the pipe. However, if a flame occurs in a pipe on the other side of this obstacle, it will easily penetrate through the valve, since the obstacle will already be a diffuser.

In addition, we point out that a fairly complete and modern review of the problem under consideration is given in the Introduction and Chapter I of the recent monograph.[7]

In this work, a double-sided flame arrester for a pipe is experimentally investigated, which is a system of two confusers, the funnels of which are located on the axis of the pipe along the gas flow and against it, along with other obstacles. The experimental results are compared with combustion simulations.

A schematic view of the obstacles used in the work is shown in Figure 1. Complex obstacles **A** and **B** are two funnels located on the axis of the pipe and serving as confusers and diffusers, respectively, relative to the direction of the gas flow. In other obstacles, between two diffusers (obstacle **C**) or in front of two confusers (obstacle **E**), a plane mesh from wire 0.1 mm in diameter with a mesh size of 0.15 mm^2 is additionally installed. Obstacle **D** consists of two diffusers, between which there is a plane obstacle 14 cm in diameter with a mesh sphere 4 cm in diameter inserted into it with the same mesh parameters as in obstacles **C** and **E**.

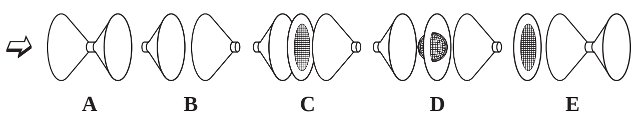

Figure 1 Schematic view of the obstacles used in the work The arrow indicates the direction of flame front propagation.

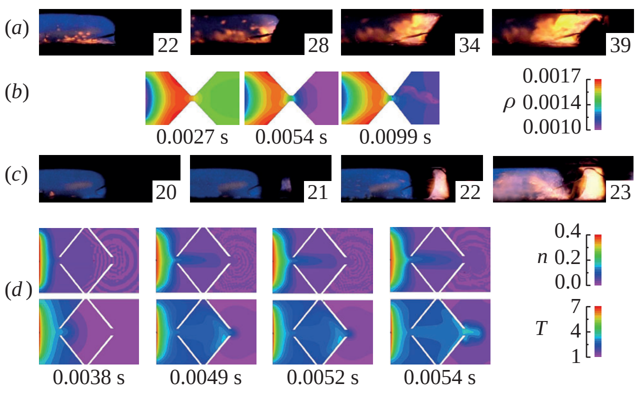

Figure 2 High-speed filming of flame front propagation through (*a*) obstacle **A** and (*c*) obstacle **B**. Initial pressure 170 Torr. The number on each frame corresponds to the frame number after the discharge. Calculation results of changes in the dimensionless (*b*) density ρ, (*d*) concentration n of an active intermediate and (*d*) temperature T during flame propagation through (*b*) obstacle **A** and (*d*) obstacle *B* for (*b*) a simple chain mechanism. Scales for ρ, n and T are shown on the right.

Figure 2 shows high-speed video filming of the flame front propagation through obstacles **A** and **B** in a combustible mixture at an initial pressure of 170 Torr. As can be seen in Figure 2(*a*), under these conditions, the flame does not penetrate through obstacle **A** from the two confusers. After the moment corresponding to frame 39, the flame displaces the loosely fixed obstacle and spreads to the end of the reactor. In this case, the combustion is accompanied by a loud and sharp sound, and the shutter swings outward.

This obstacle is symmetrical about the normal to the pipe axis. Then, if the flame arises behind the obstacle (to the right of it), it will not penetrate through the obstacle either. This means that obstacle **A** consisting of two strictly fixed confusers is the most effective flame arrester. Note that in the case of obstacle **B** in which the diffuser is located in front of the confuser in the direction of flame propagation, the flame easily penetrates through this complex obstacle. Flame propagation under these conditions is not accompanied by a sharp sound effect, and the shutter does not swing.

Such a qualitative difference from the process of flame penetration through a plane obstacle with a central hole[7] indicates a significant role of the interaction of acoustic vibrations with the combustion front in the case of a conical obstacle for subsonic flames.

Figure 3 shows the time dependence of the acoustic amplitude during flame propagation, illustrating the above, in a reactor containing either a two-confuser obstacle **A** [Figure 2(*a*)], or a two-diffuser obstacle **B** [Figure 2(*c*)].

Thus, it is shown above that the location of the flame permeable obstacle (in the case of obstacle **B**, this is a diffuser) in front of the confuser causes the flame to penetrate through the complex obstacle. This emphasizes the importance of the process of interaction of the flame front with acoustic vibrations when the flame penetrates through a complex obstacle. In the next series of experiments, the effect of mesh obstacles on the flame penetration through complex obstacles was studied in order to establish whether this would lead to any qualitative changes in the flame propagation. Figure 4(*a*),(*c*),(*e*) shows frames of high-speed filming of flame propagation in the combustible mixture at an initial pressure of 165 Torr through complex obstacles **C**–**E** (see Figure 1), respectively. In all three cases of the process of interaction of the flame with obstacles, the result of the interaction of the flame with each complex obstacle remains the same. The flame penetrates through any complex obstacle even when a plane mesh is in front of the two-confuser obstacle **E**, for which the penetration of the flame through the complex obstacle does

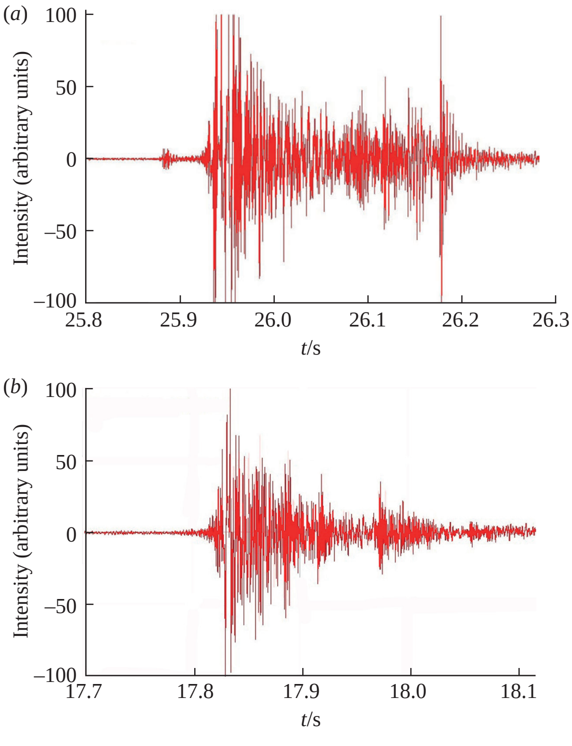

Figure 3 Time dependence of the amplitudes of acoustic perturbations during the flame propagation in a gas mixture at an initial pressure of 165 Torr through (*a*) two-confuser obstacle **A** or (*b*) two-diffuser obstacle **B**.

not occur, *i.e.*, the impermeable obstacle [see Figure 2(*a*)] becomes permeable.

The numerical modeling performed using the previously proposed[7–12] dimensionless reactive Navier–Stokes equations for a compressible medium in the low Mach number approximation[7–9] describing flame propagation in a two-dimensional channel showed a qualitative agreement with the published experimental data.[6–9]

The problem was solved by the finite element analysis using the FlexPDE 6.08 package (PDE Solutions Inc.).[12] The initiation condition was taken as $T = 10$ at the right boundary of the channel; there was a vertically located orifice in the channel. The boundary conditions (including the orifice) were $C_x = 0$, $C_y = 0$, $n = 0$, $u = 0$, $v = 0$, $\rho_x = 0$, $\rho_y = 0$ and convective heat exchange $T_t = T - T_0$. In the calculations, the chemical transformation was represented as a simple chain mechanism or a single first order Arrhenius reaction.[7,8]

The calculation results for flame penetration through the complex obstacle **A** containing two confusers are shown in Figure 2(*b*). As can be seen, the result of the analysis using a simple chain mechanism is in qualitative agreement with the experiment presented in Figure 2(*a*), namely, the flame does not penetrate through the complex obstacle. Figure 2(*d*) presents the results of calculations that demonstrate that if the diffuser is located in front of the confuser (in the direction of flame propagation), then the flame penetrates through this complex obstacle **B** in full agreement with the experiment [see Figure 2(*c*)].

The features of flame penetration through complex obstacles also qualitatively agree with the experiment. In qualitative agreement with Figure 4(*b*),(*d*),(*f*) in the presence of a plane mesh (obstacle **C**) or a meshed sphere (obstacle **D**) between two diffusers, the flame penetrates through the complex obstacle. A plane mesh placed in front of the complex obstacle containing two confusers (obstacle **E**) does not provide flame penetration through the obstacle. Therefore, regardless of the qualitative consideration, as well as the rather conventional modeling of the spherical mesh, we managed to take into account the main

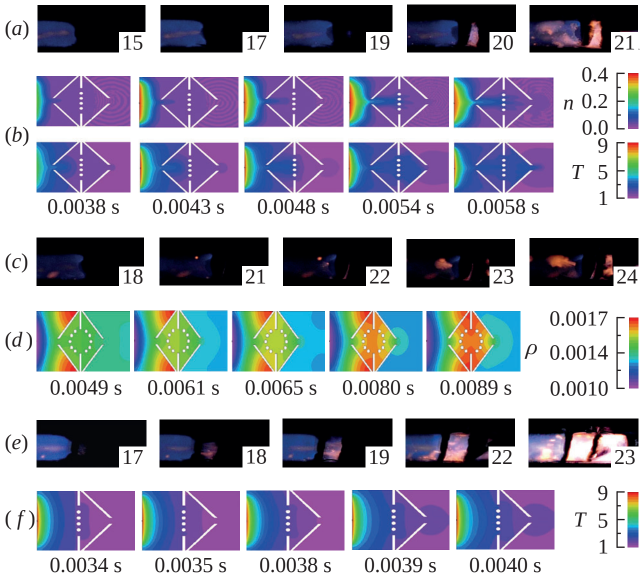

Figure 4 High-speed filming of flame front propagation through (*a*) obstacle **C**, (*c*) obstacle **D** and (*e*) obstacle **E**. Initial pressure 170 Torr. The number on each frame corresponds to the frame number after the discharge. Calculation results of changes in the values of (*d*) ρ, (*b*) n and (*b*),(*f*) T during flame propagation through (*b*) obstacle **C**, (*d*) obstacle **D** and (*f*) obstacle **E** (without the second funnel) for (*b*),(*d*) a simple chain mechanism. Scales for ρ, n and T are shown on the right.

features of flame propagation through the complex obstacles considered in this work.

From the results obtained above, it can be concluded that the most effective double-sided flame retardant in a pipe can be a system of two confusers, the funnels of which are located on the axis of the pipe along the gas flow and against it (Figure 1, obstacle **A)**, since an emergency situation can occur before and after the obstacle. A hole or valve may be located in the middle.

Note that the analysis of a three-dimensional model is necessary for the interpretation of the quantitative regularities of flame penetration through complex obstacles. However, the results of the two-dimensional modeling are in qualitative agreement with the experimentally observed features. In addition, the results obtained by visualizing the penetration of a flame through orifices of various shapes are important for solving the problems of explosion safety for volumes of complex geometry.

Online Supplementary Materials

Supplementary data associated with this article can be found in the online version at doi: 10.1016/j.mencom.2023.02.042.

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