

## Interaction of the laminar flames of natural gas–oxygen mixtures with planar obstacles, diffusers and confusers

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DOI: 10.1016/j.mencom.2016.01.024

It is experimentally shown that the limit on diameter of an opening of penetration of diluted methane–oxygen flames through a confuser is markedly less than in the case of a plain orifice, and is still less than in the case of a diffuser under the same conditions, *i.e.* the diffuser is the most effective flame arrester.

In a hypothetical severe accident, a significant amount of flammable gas can be released. Mixed with ambient air, the resulting explosive mixture can significantly endanger the containment integrity. Due to the complex physical processes of combustion and the geometry of reactor containment, the propagation of a flame and the resulting pressure load cannot be simulated with sufficient accuracy. The full compressible Navier–Stokes equations can be simplified and used to solve non-isothermal flow only if we assume the flow with a low Mach number. In low-speed turbulent combustion applications, the low Mach number, variable-density approximation of the Navier–Stokes equations is a good basis for simulation.<sup>1–3</sup> Unfortunately, any comparison of experimentally recorded movement of the flame front (FF) with the result of numerical modeling is credible only in a qualitative aspect, *e.g.*, on a velocity change of movement of the boundary of initial and reacting gas, as well as on the shape of this border and the degree of its ‘smoothness’. The consideration of detailed kinetics in calculations provides additional uncertainty since most of kinetic parameters are not accurate enough to draw adequate conclusions. The completeness of the kinetic mechanism is always under question because an important reaction can be overlooked. In addition, there are no unicity theorems on reactive Navier–Stokes equations; therefore, any agreement between calculated and experimental quantities does not argue for consent between calculation and experiment, as there can be other sets of governing parameters describing the same experimental profiles.<sup>2,3</sup>

When a laminar flame moves into an unburned region of premixed combustible gases, it propagates due to heat and active centers transfer ahead of the FF, which causes a self-sustained reaction in unreacted gases.<sup>4</sup> The structure of the flame determines how much energy is passed forward of the flame. The flame ceases to propagate, or it accelerates depending on how gradients of temperature and active centers change. Fluid mechanics also has a major influence on the flame structure, especially when the characteristic time scales of the flow are of the same order as the chemical kinetics.

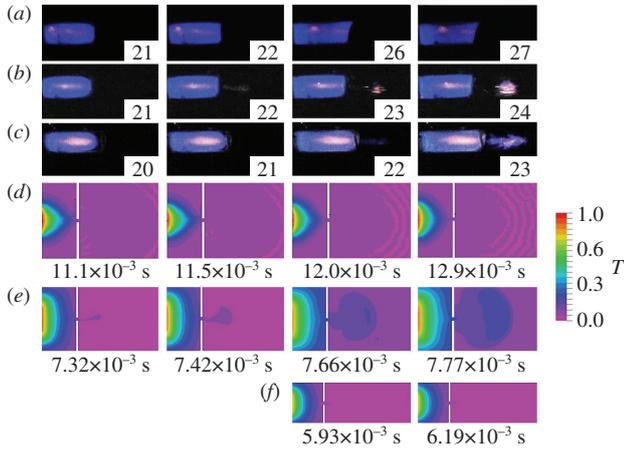
Here we studied the flame propagation through a single orifice, a diffuser and a confuser with round openings. It is of practical interest for fire safety problems to estimate both the obstacle shape and the diameter of opening through which FF does not propagate.<sup>5</sup>

In the literature, the flame quenching at different blocking ratios (BRs) [BR = 1 – (d/D)<sup>2</sup>, where *d* and *D* denote the orifice and tube inner diameters, respectively] of a single orifice with

a round opening was discussed.<sup>6–8</sup> It was suggested<sup>9</sup> that the Karlovitz number for isotropic turbulent flame propagation can be used for estimating the probability of propagation through the single orifice:  $K \approx (v u_{\text{jet}}^2 / d_{\text{jet}})^{1/2} u_l^{-2}$ , where *v* is the kinematic viscosity of the gas mixture, *u<sub>l</sub>* is the laminar burning velocity, *u<sub>jet</sub>* is the local flow velocity at the entrance to the receiver volume, and *d<sub>jet</sub>* is the diameter of the opening. It was postulated that quenching occurs at a critical value of *K*. Flame quenching takes place<sup>8</sup> when the product of the Karlovitz flame stretch factor *K* times the Lewis number *Le* exceeds a value of 1.5. Unfortunately, the value of *K* is difficult to determine, but several efforts were described.<sup>10</sup> This semiempirical approach points to the influence of the chain nature of combustion on flame penetration through the orifice, which is considered in *u<sub>l</sub>* value.

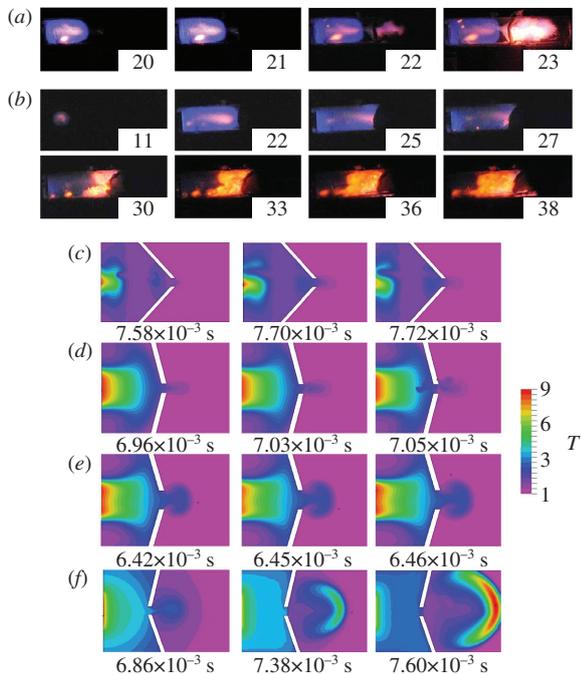
In this work, experimental investigation into both limits on diameter of flame penetration of dilute methane–oxygen mixtures through a single orifice, a diffuser and a confuser has been performed.<sup>†</sup>

<sup>†</sup> The experiments were carried out with stoichiometric methane–oxygen mixtures diluted with CO<sub>2</sub> and Kr at initial pressures of 100–200 Torr and 298 K in a horizontal cylindrical quartz reactor of 70 cm in length and 14 cm in diameter. A pair of spark ignition electrodes was located near the butt-end of the reactor. 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.<sup>11</sup> Planar plastic orifices (*d* = 14 cm) with round openings of BR = 0.993, 0.968 and 0.918 were placed in the reactor. Plastic funnels (*d* = 14 cm) (the opening angle of the funnel was 90°, BR = 0.998, 0.994 and 0.993) were used both as a diffuser and a confuser. Complex obstacles consisted of the confuser (BR = 0.99) and a plain mesh (*d* = 4 cm, obstacle A) or a meshed sphere (*d* = 4 cm, obstacle B) (wire, *d* = 0.1 mm, cell size of 0.15 mm<sup>2</sup>) inserted into a planar obstacle *d* = 14 cm placed right behind the confuser. The obstacles were rigidly fixed in such a way that the combustion wave could slightly deform them, but it could penetrate only through the central opening. The combustible mixture (15.4% CH<sub>4</sub> + 30.8% O<sub>2</sub> + 46% CO<sub>2</sub> + 7.8% Kr) was prepared; CO<sub>2</sub> was added to decrease a FF velocity and to enhance the quality of filming; Kr was added to diminish the discharge threshold. The reactor was filled with the mixture up to a necessary pressure. Then, spark initiation was performed (the discharge energy was 1.5 J). Speed filming of ignition dynamics and FF propagation was carried out from the side of the reactor with a Casio Exilim F1 Pro color high-speed digital camera (frames frequency of 600 s<sup>-1</sup>).<sup>12,13</sup> The pressure change in the course of combustion was recorded by a piezoelectric gage synchronized with the discharge.



**Figure 1** High-speed filming of FF propagation through the round opening of (a) 1.2 cm in diameter, BR = 0.993, (b) 2.5 cm in diameter, BR = 0.968, (c) 4 cm in diameter, BR = 0.918, in a planar obstacle of 14 cm in diameter. Initial pressure 170 Torr. The figure on each frame corresponds to frame number after discharge. Results of calculation of flame propagation through a single plain orifice: change in the degree of advancement of the reaction for (d) the simple chain mechanism, (e) a single Arrhenius reaction, (f) a single Arrhenius reaction for more narrow channel. The scale of the degree of advancement of the reaction is presented on the right.

In Figure 1, a representative experiment of the high-speed filming of FF propagation in the combustible mixture at an initial pressure 170 Torr through the round openings with BR = 0.993, 0.968 and 0.918 in a planar obstacle of 14 cm in diameter is shown. After ignition, laminar combustion occurs. When the flame passes the orifice, one can observe both a quenching effect at the smaller opening (BR = 0.993), resulting in the extinction of a flame behind the orifice, and FF penetration through the orifice at BR = 0.968 and 0.918. It means that the critical



**Figure 2** High-speed filming of FF propagation through the conic funnel of 14 cm in diameter (a) a confuser and (b) a diffuser. Initial pressure 170 Torr. The figure on each frame corresponds to the frame number after discharge. Results of calculation of the process of flame propagation through the conic funnel: change in dimensionless temperature for flame propagation through a diffuser for the single Arrhenius reaction, the opening angle of the diffuser is (c) 90°, (d) 150°, (e) 150°, a larger opening and (f) 150°, a smaller opening. The scale of dimensionless temperature is presented on the right.

diameter of the opening is consistent with experimental data.<sup>7,8,10</sup> Since the Karlovitz number  $K$  is difficult to measure<sup>10</sup> and the use of the semiempirical criterion given above is complicated, we made an effort to reveal important parameters that determine the critical conditions of FF quenching at the orifice.

The high-speed filming of FF propagation in the combustible mixture at 170 Torr through the conic funnel of 14 cm in diameter as a confuser and a diffuser is shown in Figure 2(a). Under used conditions, FF penetrates through the confuser, but the flame extinguishes at the diffuser [Figure 2(b)]. Note that, in the case of a funnel (both a diffuser and a confuser) as an obstacle, the use of BR to characterize an obstacle becomes ambiguous because, at a value much lower than the penetration flame limit on diameter of an opening (Figure 1), the flame does not pass through the diffuser but readily penetrates through the confuser. In other words, under the same conditions, the limit of penetration of a dilute methane–oxygen flame through a confuser is markedly less than that in the case of a plain orifice; on the other hand, the limit of penetration of this flame through a diffuser is markedly greater than in the case of a plain orifice. Therefore, a diffuser seems the most effective flame arrester.

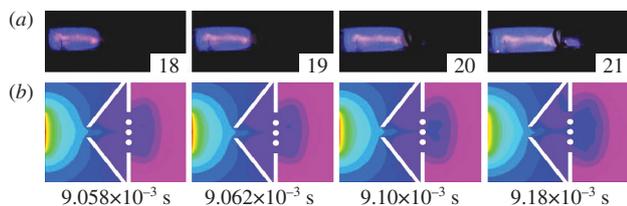
The high-speed filming of FF propagation in the combustible mixture at 180 Torr through complex obstacles A and B is displayed in Figures 3(a) and 4(a), respectively. The ignition after complex obstacles does not occur in the immediate vicinity of the obstacles under our conditions; the first spot of ignition is observed considerably far from the obstacle surface, especially in the case of obstacle B. The flame jump (the distance of flame origination behind an obstacle) is much longer in the presence of a meshed sphere, as compared with the obstacle containing a plain mesh. Note that, in line with Figure 2(b) (a diffuser), the flame under our conditions does not pass through the complex obstacle containing a diffuser instead of a confuser.

The numerical modeling performed using compressible dimensionless reactive Navier–Stokes equations in a low Mach number approximation,<sup>11</sup> which describe flame propagation in a two-dimensional channel,<sup>11–17</sup> showed a qualitative agreement with experiments.<sup>11,16</sup>

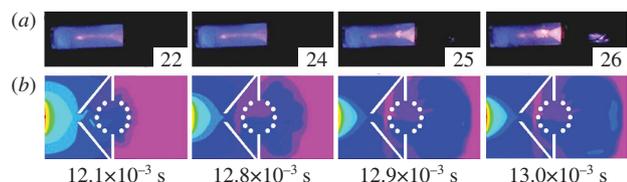
The solution of the problem was carried out by finite element analysis with the package (FlexPDE 6.08, 1996–2008 PDE Solutions Inc.<sup>18</sup>). Initiation condition was taken as  $T = 10$  on the right boundary of the channel; there was a vertically located orifice in the channel. Boundary conditions (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  $T_i = T - T_0$ .

The results of the calculations are shown in Figure 1(d)–(f). For the conditions of FF penetration through the orifice [Figure 1(e)], taking into account either the chain mechanism instead of a single first order Arrhenius reaction or heat losses [the width of the channel in Figure 1(f) is 0.6 of that in Figure 1(e)] leads to FF quenching at the orifice. Actually, in the case of simple chain mechanism accounting for active centers termination ( $n|_{\text{wall}} = 0$ ) provides additional chemical losses<sup>19</sup> along with thermal losses.

The results of calculations of FF penetration through both the diffuser and confuser [Figure 2(c)–(f)] are qualitatively consistent with the experiments [Figure 2(a),(b)]. Such a qualitative difference from flame penetration through a plain obstacle with the central opening indicates a noticeable role of the interaction of acoustic fluctuations in the reactor containing an obstacle with the propagating front of combustion even for a subsonic flame. In addition, the numerical experiments show that, (i) at wider orifice opening FF penetrates through the diffuser; (ii) the opening angle of the funnel in the certain interval has a little effect on the limit of flame penetration.



**Figure 3** (a) High-speed filming of FF propagation through the complex obstacle consisting of a confuser of 14 cm in diameter and a plain meshed orifice of 4 cm in diameter 15.4% NG + 30.8% O<sub>2</sub> + 46% CO<sub>2</sub> + 7.8% Kr at initial pressure 180 Torr. The figure on each frame corresponds to frame number after discharge. (b) Results of calculation of the process of flame propagation through the complex obstacle.



**Figure 4** (a) High-speed filming of FF propagation through the complex obstacle consisting of a confuser of 14 cm in diameter and a spherical meshed orifice of 4 cm in diameter 15.4% NG + 30.8% O<sub>2</sub> + 46% CO<sub>2</sub> + 7.8% Kr at initial pressure 180 Torr. The figure on each frame corresponds to frame number after discharge. (b) Results of calculation of the process of flame propagation through the complex obstacle.

The FF penetration through complex obstacles also qualitatively agrees with the experimental data. In a qualitative accordance with Figures 3(a), 4(a), in the presence of the meshed sphere as an obstacle, a flame jump is much longer, as compared with a plain mesh. Therefore, regardless of qualitative considerations, we managed to take into account the main features of FF propagation through the complex obstacles.

Note that the analysis of a three-dimensional model is necessary for the quantitative description of FF penetration through a single orifice. At the same time, the results of the two-dimensional modeling are in qualitative agreement with experimentally observed features. In addition, the data obtained by the visualization of FF penetration through orifices of different shapes are important for the solution of explosion safety problems for volumes of complex geometry.

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Received: 4th March 2015; Com. 15/4579