Flame Behaviour during Propagation in Small Tubes Characterized by Different Degrees of the End Opening

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1 Introduction

Premixed flame propagation in channels (tubes) has been investigated since the early flame studies [1]. Numerous theoretical [2], numerical [3, 4] and experimental investigations [5, 6] discussing various aspects of flame propagation in channels (tubes) have been reported. All previous studies are related to flame propagation in one-end closed channels or flames stabilized in the opposite flow. Flame behaviours differ depending on the conditions at the ends of the channel, i.e., one or both ends of the tube remain closed, or both ends are open. In the literature, there are a few works concerning freely moving flames in a tube or channel open at both ends [7, 8]. It seems that this problem has not been sufficiently examined yet. In [7] the authors obtained the equations for the total travel time depending on the length of the channel, which is proportional to $\gamma^{-1}\ln(1 + \gamma)$, where γ denotes the heat release parameter. A comparison of their results to the experimental results of Mason and Wheeler [9] shows that the flame position as a function of time has a similar trend. Kurdyumov and Matalon [8] show that during the early stages of flame propagation, the flame accelerates at an almost constant rate, independently of the channel height. If channels are sufficiently narrow, the flame retains constant acceleration until it reaches the end of the channel. In wider channels, however, the flame beyond a certain distance begins to accelerate at a nearly exponential rate, reaching exceedingly large speeds at the end of the channel. It is necessary to emphasize that the numerical simulations in [7, 8] were conducted on the assumption of no-slip and adiabatic conditions at the channel walls.

In the present work, we study numerically freely propagating flame in the stoichiometric propane-air mixture. The isothermal small tubes with one end fully open and the second one characterized by different degrees of opening are examined. The degree of opening of the tubes was equal to: 0% (completely closed), 25%, 50%, 75% and 100% (fully opened) of the tube cross-sectional area.

2 Computational methods

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Two-dimensional computations concerning a single-step irreversible global reaction of the stoichiometric propane-air mixture were conducted with the FLUENT software. The pressure-based conservation equations of mass, momentum and energy were solved. Because of the tube symmetry, the computational domain represented half of the tube. The length L along the axial direction equals twenty times the diameter ($L = 20d$). The diameter d was chosen to be 1.38, 2 and 3 mm, respectively. The first value corresponds to the numerical quenching diameter (d_q) for this mixture concentration. It is necessary to add that d_q is lower than the experimentally obtained value. The difference results from a simplified reaction model and boundary conditions that are applied. The quenching diameter is defined as the smallest tube diameter below which flame cannot propagate. Figure 1 shows a schematic view of the geometry used during the numerical calculations. The boundary condition of the wall surface was modelled as a non-slip wall, whereas the specified wall temperature was equal to 298.15 K.

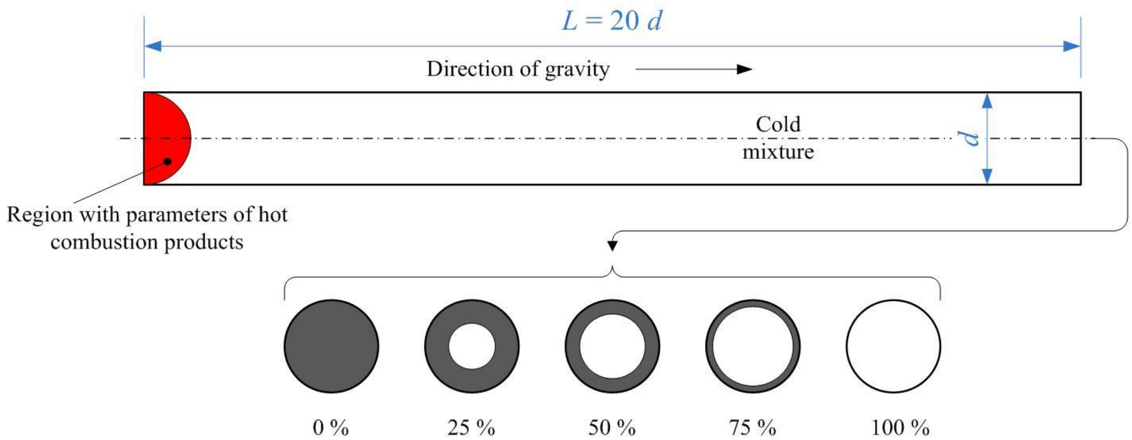


Figure 1. Schematic view of the geometry under analysis.

The value of the pre-exponential factor A (= 1.686×10^{10} $(\mathrm{kmol/m^3})^{-0.75}/\mathrm{s}$) from the fuel consumption rate equation was obtained from the numerical experiment in which we tried to find the calculated one-dimensional adiabatic flame speed consistent with the experimental data (41 cm/s [10]). The mixture is ignited at the left, always fully open, end of the tube. It takes place by extracting a part of the zone from the domain and assigning the values of hot combustion products, i.e., temperature and chemical composition, to it.

3 Results and Discussion

The calculations started with flames propagating with fully closed right end of the tubes (0% opening). Shortly after ignition, the flame front formed a hemispherical shape and propagated further without any changes. Figure 2 shows a structure of the obtained flames. The normalized temperature was defined as $\bar{T} = (T - T_u)/(T_{ad} - T_u)$, where T_u and T_{ad} (= 2393 K) are the unburned mixture temperature and the adiabatic flame temperature of the one-step reaction, respectively. The reaction rate was normalized with the maximum reaction rate of an adiabatic flat flame as $\bar{\omega} = \omega/\omega_{ad,max}$ ($\omega_{ad,max}$ = 3.50314 kmol/m^3/s). Within the given tube, the flames propagated with constant velocities, which, however, varied with changes in the tube diameter. The next step of our investigations concerned flames propagating in tubes with varying closing degrees of their right ends. In order to analyse the behaviour of those flames, the normalized flame position $\bar{x}$ was introduced. It was defined as a ratio of the flame tip axial position to the tube length L.

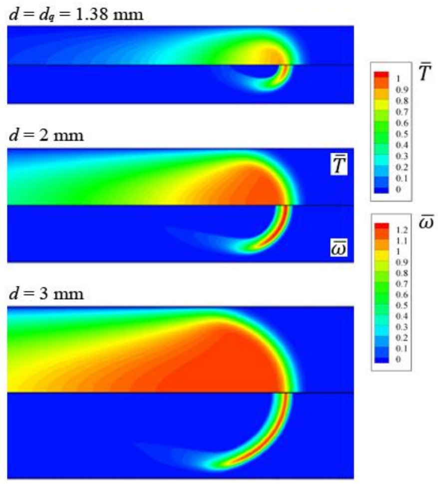


Figure 2. Distributions of the normalized temperature (top) and the normalized reaction rate (bottom) during flame propagation in tubes with the fully closed right end.

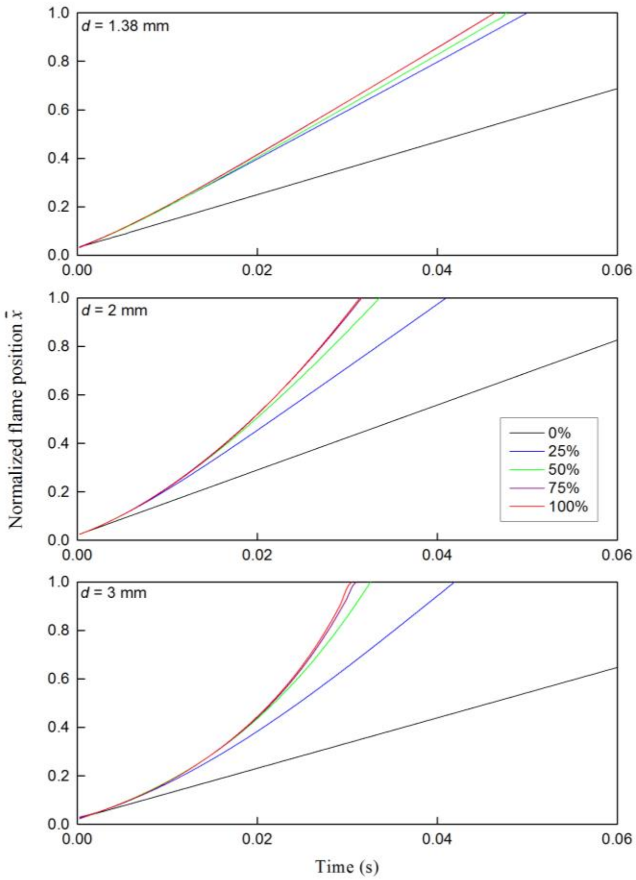


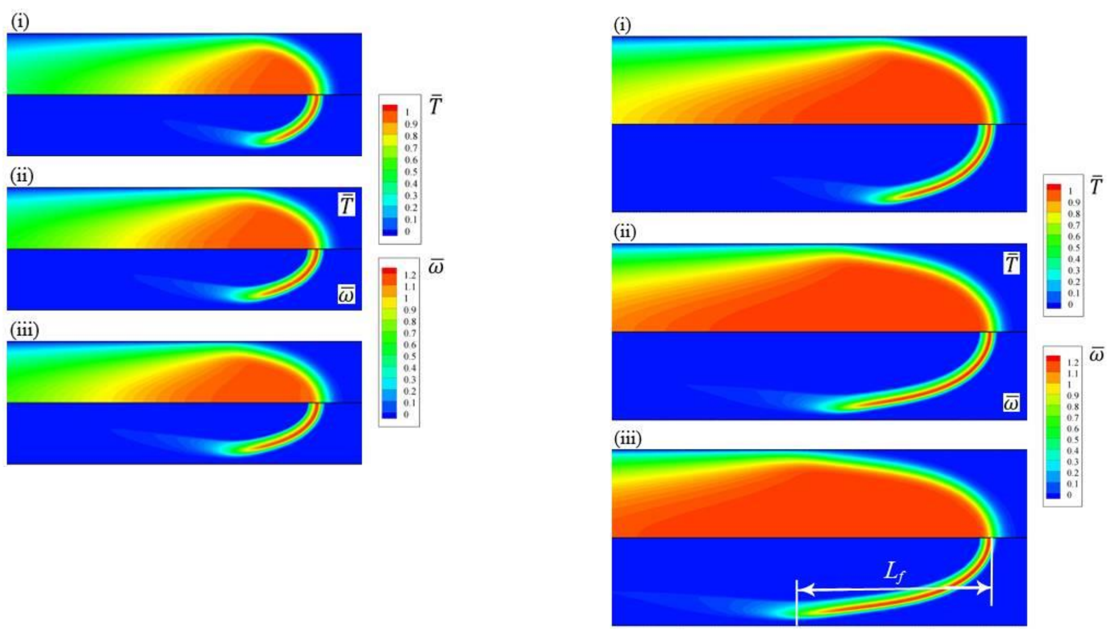
Figure 3. Flame position for different tubes and a varying degree of the right end opening versus time.

Figure 3 shows a time history of the normalized flame position in three tubes with a varying degree of the right end opening, namely: 0% (completely closed), 25%, 50%, 75% and 100% (fully opened). Opening of the right end of the tube is followed every time by an increase in the flame propagation velocity - an increase in the slope of the line $\bar{x} = f(t)$. The inclination is different, depending on the tube opening and its diameter. For the smallest diameter d = d_q, an influence of the tube end opening on the slope increase is visible. However, it is slight for the opening from 25 to 100%. The lines for cases of 70% and 100% overlap. The character of these relations is still linear, which shows that the flames propagate with higher velocity than in the case of 0%, but it is almost constant along the tube.

For the tube with a 2 mm diameter, there is a noticeable difference in the inclination for the cases 25% and 50%÷100%. Additionally, for a larger opening of the tube end, the relations lose their linear character. If the diameter of the tube is increased to 3 mm, the flame position as a function of time is no longer linear but becomes parabolic. This indicates that the flames propagate with certain acceleration.

The flame shape changes during its propagation in the tubes with both ends opened. This change depends on the tube diameter, the degree of opening of its right end but also the position of the flame in the tube. The most significant change is observed for tubes that are completely open (100%), therefore the results will be presented for this case only. We selected three positions of the flame: 1/3, 1/2 and 2/3 of the length of the tube. Figure 4 shows flame shapes for the tube diameter of 2 mm (4a) and 3 mm (4b). The 1.38 mm diameter tube was neglected because flame shape changes were unappreciable.

Comparing flame shapes for the cases of the totally closed (Figure 2) and completely opened (Figure 4) right end of the tube, one can notice that flames become elongated during their propagation. This is accompanied by a transition from the hemispherical flame shape to a more convex one ("finger-like" shape).



(a) (b)

Figure 4. Distributions of the normalized temperature (top) and the normalized reaction rate (bottom) during flame propagation in tubes with the fully open right end at the position of 1/3, 1/2 and 2/3 of the tube length for d = 2 mm (a) and d = 3 mm (b).

Examples of axial velocities as a function of normalized (by the tube length) axial coordinate for d = 3 mm and degree of the right end opening equal to 25% and 100% are presented in Figure 5.

To estimate the flame elongation, we introduce the flame length L_f which is defined as a distance from the flame tip to the point at which the gap between the flame skirt and the wall of the tube is the smallest (Figure 4b-iii). Then, this parameter is normalized with the flame length propagating in the closed tube (0%) $L_{f0\%}$. The normalized flame length is shown in Figure 6.

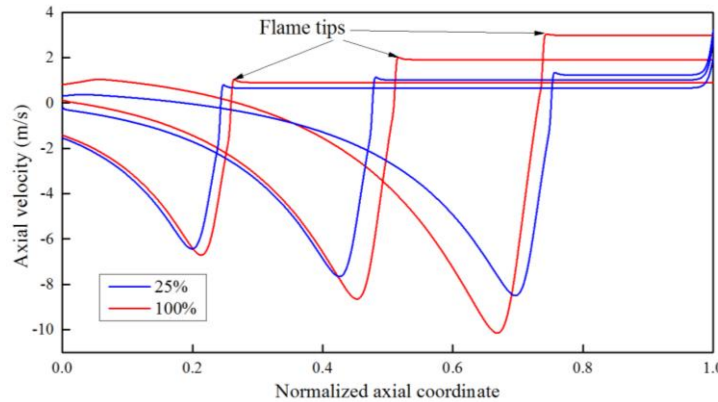


Figure 5. Axial velocity as a function of normalized axial coordinate at the position of 1/3, 1/2 and 2/3 of the tube length for d = 3 mm.

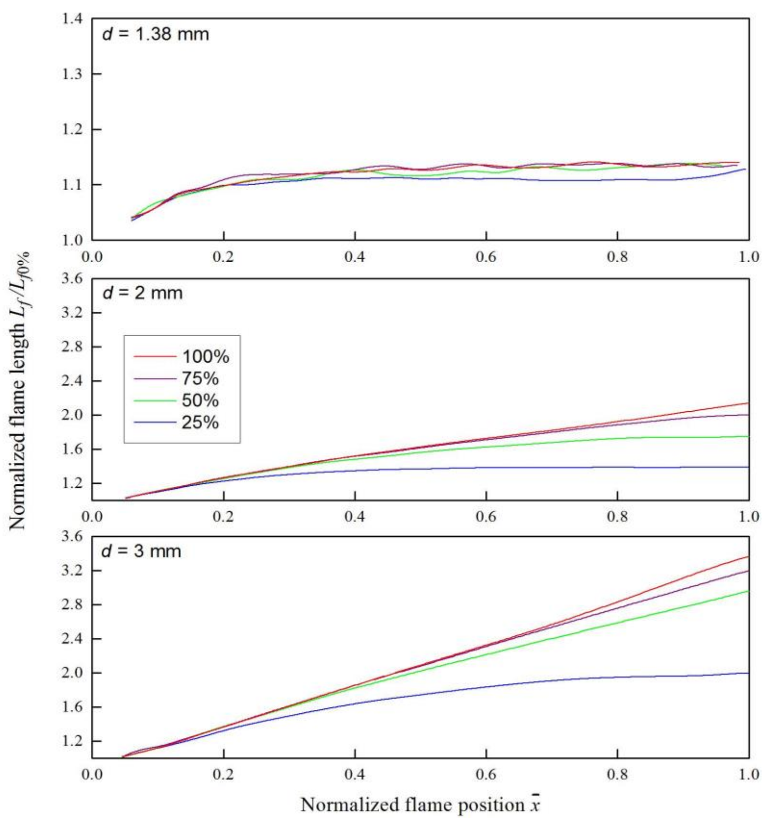


Figure 6. Normalized flame length as a function of the normalized flame position for different tubes and a varying degree of the right end opening.

For the 1.38 mm tube, the flame length increase is slight and amounts to about 10% of the $L_{f0\%}$. The flame length depends only inconsiderably on its axial position in the tube. For larger and fully open tubes, the flame length reaches approximately 200% (2 mm) and 320% (3 mm) of the $L_{f0\%}$ at the end of the tube. The flame lengths are slighter for a smaller opening of the right end of the tube.

4 Conclusions

Several mechanisms, such as thermal expansion of the burned gas which can leave the tube freely (fully opened left end of the tube), frictional forces and heat losses at the tube walls, movement of the unburned mixture generated by the propagating flame, occur simultaneously during flame propagation in the tubes under investigations. The fresh mixture can leave or not the domain at the right end of the tube, depending on the degree of its opening. As one could see, all of them exert some influence on the flame behaviour during its propagation in small tubes.

For the smallest tube, which corresponds to a quenching diameter, opening of the right end of the tube causes an increase in the flame propagation velocity (but this velocity is almost constant) and a slight change in the flame length with respect to the propagation in the closed right end tube.

For wider tubes, opening of the tube right end causes that flames propagate with higher velocities, which change with the flame position. These velocities depend on the degree of opening of the tube end as well. The larger opening, the higher velocity and flame acceleration.

To understand thoroughly the mechanism of flame propagation in small tubes characterized by different degrees of opening of their ends, a detailed analysis of velocity, pressure fields and heat transfer is required. This analysis will be conducted in the future.

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