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Self-accelerating flames in long narrow open channels

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Abstract

In this work we extend our earlier asymptotic one-dimensional analysis of flame propagation in long narrow channels open at both ends to two-dimensional flames. The analysis follows two tracks; a multi-scale asymptotic study and a full numerical study of the unsteady propagation. We show that during the early stages of propagation the flame accelerates at a nearly constant rate, independent of the channel height. In sufficiently narrow channels, the flame retains a constant acceleration until it reaches the end of the channel, consistent with our earlier work. 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. The flame self-acceleration arises from the combined effects of gas expansion and lateral confinement. The gas expansion that results from the heat released by the chemical reactions produces a continuous flow of burned gas directed towards the ignition end of the channel. Due to the frictional forces at the walls and, since the pressure at both ends is maintained constant, the gas motion that develops in the burned gas sets a pressure gradient that drives the fresh unburned gas towards the other end of the channel. Stretching out to reach additional fuel, the flame extends towards the fresh mixture propagating faster. And because of lateral confinement, the gas expansion induces large straining on the elongated flame surface that further increases its propagation speed. The asymptotic approximation properly predicts the initial propagation stage, the location within the channel where the sudden acceleration begins and the early stages of the self-accelerating process. The full numerical study confirms and extends the asymptotic results, showing that in long but finite channels premixed flames could self-accelerate reaching velocities that are ten-to-twenty times larger than the laminar flame speed.

Keywords: Premixed flames; Accelerating flames; Thermal expansion; Long channels; DDT

1. Introduction

Understanding the propagation of premixed flames in narrow channels and tubes is of practical interest in the design of micro-propulsion devices, has various safety applications and is of great importance in understanding the deflagration-to-detonation transition in gases and condensed energetic materials. The early studies [1–3] have recognized that the boundary conditions imposed at the end of the channel have a significant effect on the flame propagation. The objective of this work is to study the propagation of premixed

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flames in sufficiently long but narrow channels open at both ends, that allows for the gas to leave the channel freely.

In a recent study, an asymptotic analysis based on the assumption that the channel height is smaller than the flame thickness [4] was presented. This simplification led to a one-dimensional formulation that enabled extracting simple results about the flame position and its propagation speed, as well as the overall travel time within the channel. In this work the aforementioned assumption has been removed and the two-dimensional problem is considered along two tracks: a multi-scale asymptotic study that assumes that the channel height is much smaller than its length, in which case the two-dimensional flame structure propagates quasi-steadily throughout the channel, and a full numerical study of the time-dependent problem that validates the asymptotic solution and extends its validity. We show that in the early stages following ignition the flame accelerates at a nearly constant rate, but after reaching a certain distance down the channel the flame suddenly begins to accelerate rapidly, at a nearly-exponential rate, that continues until it reaches the end of the channel. The self-acceleration process results from the combined effects of thermal expansion and lateral confinement.

Numerous theoretical [5,6], numerical [7–10] and experimental studies [11–13] discussing dynamical aspects of flame propagation in channels and tubes have been reported. The work most closely related to the present investigation is the numerical simulations reported in [14–16]. In [14,15] rapid acceleration was observed in tubes/channels closed at the ignition end. In this configuration, however, the burned gas is trapped between the flame and the closed boundary and the expanded gas acts as a piston on the fresh mixture that must leave the channel at the other end. Thus, despite the similarity with our results, it is not clear how the different boundary conditions and the inclusion of compressibility effects, included in their code but filtered out in our study, affect the dynamics. The simulations in [16] carried out in open channels also show rapid acceleration, but details about the flow and pressure fields and about the imposed conditions at the two ends of the tube, were not provided. Neither of these studies, however, provide details about the transition from a nearly-constant to a rapid exponential-like acceleration, nor do they identify the early-stage quasi-steady nature of the flame propagation.

2. General formulation

A combustible mixture is contained in a channel of length L and height h, and ignited at time $\tilde{t}=0$ at its left end; i.e., at $\tilde{x}=0$ (see Fig. 1). Upon ignition, the diaphragms containing the mixture in the channel are simultaneously removed and both ends remain open and exposed to a constant (atmospheric) pressure, allowing the gas to leave the channel freely. Of particular interest is to examine the flame propagation in sufficiently long but narrow channels, i.e., $L \gg h$ with the height h on the order of the flame thickness $\delta_T \equiv \mathcal{D}_T/S_L$, where $\mathcal{D}_T$ is the thermal diffusivity of the mixture and S_L the laminar flame speed. Hence $a \equiv h/\delta_T$ is an $O(1)$ parameter, but $\ell \equiv L/\delta_T \gg 1$. For simplicity, we consider here the case of adiabatic walls.

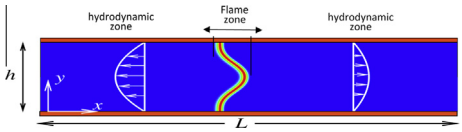

Fig. 1. Channel and flow configurations illustrating the various length scales associated with the flame propagation. The extent of the flame zone on the order of the diffusion length is much smaller than the length of the channel L.

The chemical reaction is modeled by a global step of the form $F+O\rightarrow P$, where F denotes the fuel, O the oxidizer and P the products, and proceeds at a rate $\tilde{\omega}=\mathcal{B}(\tilde{\rho}Y_F)(\tilde{\rho}Y_O)\exp(-E/\mathcal{R}\tilde{T})$ where $\tilde{\rho}$ is the density of the mixture, Y_F, Y_O the mass fractions of fuel and oxidizer, E the activation energy, $\mathcal{R}$ the gas constant, and $\mathcal{B}$ a pre-exponential factor. For a lean mixture, the oxidizer mass fraction is nearly constant and can be absorbed into $\mathcal{B}$, such that the reaction rate depends only on the mass fraction of the fuel, denoted below by Y.

We introduce dimensionless variables (when the same symbols are used the one with the accent "tilde" denotes the dimensional quantity) as follows:

$$x=\tilde{x}/\delta_T,\quad y=\tilde{y}/h,\quad t=\tilde{t}/(\delta_T/S_L),\quad u=\tilde{u}/S_L,$$
$$v=\tilde{v}/aS_L,\quad \rho=\tilde{\rho}/\rho_u,\quad p=a^2(\tilde{p}-p_{\rm atm})/\rho_u S_L^2,$$
$$Y=\tilde{Y}/Y_u\quad \theta=(\tilde{T}-T_u)/(T_a-T_u),$$

where $T_a=T_u+QY_u/c_p$ is the adiabatic temperature with Q the total heat release and c_p the specific heat (at constant pressure) of the mixture. Assuming constant properties and a low-Mach number approximation, the (dimensionless) governing equations are:

$$\rho_t+(\rho u)_x+(\rho v)_y=0, \tag{1}$$
$$\rho(u_t+uu_x+vu_y)=-\frac{1}{a^2}p_x+Pr\left[\frac{1}{a^2}u_{yy}+\frac{4}{3}u_{xx}+\frac{1}{3}v_{xy}\right], \tag{2}$$
$$\rho(v_t+uv_x+vv_y)=-\frac{1}{a^4}p_y+Pr\left[\frac{1}{a^2}\left(\frac{4}{3}v_{yy}+\frac{1}{3}u_{xy}\right)+v_{xx}\right], \tag{3}$$
$$\rho(\theta_t+u\theta_x+v\theta_x)-\left(\theta_{xx}+\frac{1}{a^2}\theta_{yy}\right)=\omega, \tag{4}$$
$$\rho(Y_t+uY_x+vY_y)-Le^{-1}\left(Y_{xx}+\frac{1}{a^2}Y_{yy}\right)=-\omega, \tag{5}$$
$$\rho=1/(1+\gamma\theta), \tag{6}$$

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