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Influence of transverse temperature gradient on the propagation of triple flames in porous channels

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ABSTRACT

We present in this paper a numerical simulation to the problem of triple flame propagation in a porous-walls channel in the presence of a temperature gradient across the channel. The problem has been formulated using the thermo-diffusive approximation and then solved numerically using finite elements method. The study showed that temperature gradient plays a crucial role on the existence and propagation of triple flames. More precisely, the effect of temperature gradient on the flame propagation was found to: (i) cause the flame to exist only for a limited range of values of the temperature gradient parameter, (ii) establish multiplicity of solutions each of them characterizes unique combustion regimes, (iii) modifies the flame shape from the usual triple flame shape when the temperature gradient is large, and finally (iv) enhance the reactivity of the underlying mixture, but on the other hand will have serious implications on the safety of the combustion chamber.

1. Introduction

Combustion in nonuniform mixtures is a fundamental problem from both theoretical and experimental points of view. The problem is characterized by the presence of a wide range of chemical and physical processes in addition to the spatial and temporal non-homogeneities within the combustion chamber. A well known example of flames arising as a result of combustion of non-uniform mixtures in mixing layers is triple flames. When two opposing streams combustion reactants inject toward each other, a structure – widely known as triple flames – that consists of two branches of premixed flames and a trailing diffusion flame joined together at a point is being developed [1,2]. These flames can be seen in many practical applications such as in the burning of light gaseous of fuel, flame propagation over vaporizing liquid fuels, and in engines of direct-injection of fuels [3]. These flames were initially observed experimentally by Phillips [4] in 1965 in a chemical reaction between methane and air. Theoretical studies of such flames have been directed toward understanding their existence and characteristics under a wide range of physical and chemical conditions such as heat-loss [5,6], diffusivity of reactants [7], reversibility [8,9], flow [10–13], Lewis numbers [14,15] among others.

We shall focus our attention in this paper to numerically study the propagation of triple flames formed within a porous-walls channel when the reactants are supplied to the mixing layer with different initial temperatures. We have recently carried out [16] an asymptotic analysis of the problem in the limit of a large activation energy and thin flames. It has been shown asymptotically that the structure and propagation of triple flames were significantly influenced by the presence of a temperature gradient across the mixing layer. It was found in particular that modifying the temperature gradient can enhance the propagation speed of the flame up to a critical value of the temperature gradient beyond which flame extinguishes. In addition, it was predicted that the flame exhibits a new structure and we called it the inverse triple flame structure when the temperature gradient is large. The study had also derived analytical expressions for the propagation

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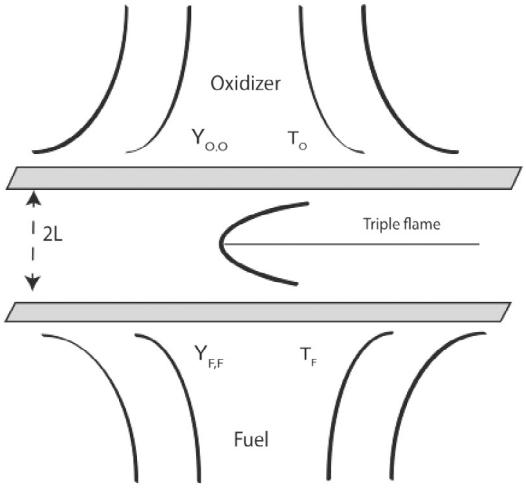

Fig. 1. A schematic illustration of flame propagating in a mixing layer in a channel.

speed, the flame shape and local burning speed in terms of the temperature gradient parameter Δ_T. The aim of the numerical simulation carried out in this paper is first to assess the asymptotic findings shown in [16], and then to describe qualitatively and quantitatively the response of the characteristics of triple flames such as its speed and shape to the variation of the transverse temperature gradient. We would like also to compare the effect of temperature gradient on triple flames formed within porous walls channels with flames formed within the counterflow configuration, which has been studied by Daou et al. [8].

This paper is organized as follows: we present in Section 2 the adopted mathematical model. A summary of the asymptotic findings derived in [16] is then provided in Section 3. The numerical method along with the main results is then shown in Section 4. A summary of the main results is finally provided in Section 5.

2. Mathematical model

The problem under consideration is the triple flame propagation inside a porous walls channel in the presence of a transverse temperature gradient across the channel as illustrated in Fig. 1. Such configuration was widely used by many studies to generate triple flames [5,11,17–19]. In this configuration, two opposing streams of chemical reactants: oxidizer (**O**) and fuel (**F**) are initially separated at the boundaries of a porous-walls channel of width $2L$, and then injected toward each other with different initial temperatures namely, T_O and T_F. As the reactants diffuse into each other, a single-step chemical reaction of the form

$$\mathbf{F} + s\mathbf{O} \rightarrow (1+s)\mathbf{P} + \mathbf{q},$$

takes place to produce a combustion product **P**. Here, s denotes the mass of oxidizer consumed and **q** the heat released, both per unit mass of fuel. Upon a successful ignition, a triple flame propagating across the channel is expected. The reaction rate, defined as the mass of fuel consumed per unit volume and unit time, is assumed to follow an Arrhenius law

$$\tilde{\omega} = B\rho^2 Y_F Y_O \exp(-\frac{E}{RT}),$$

where B and E are the pre-exponential factor and the activation energy, ρ is density, T, Y_F and Y_O represent respectively the temperature and the mass fractions of fuel and oxidizer, and R the universal gas constant.

For the sake of brevity, we present here the mathematical model in non-dimensional form and refer to our paper [16] for a detailed discussion of the model. We shall consider a frame of reference attached to the flame in which the flame can be seen to propagate relative to the laboratory at a speed U, with $U > 0$ indicating a propagation to the left. We shall use also the flame radius of curvature L/β as a unit length, which represents the ratio between the mixing layer thickness L and the Zeldovich number $\beta \equiv E(T_{\rm ad} - T_O)/RT_{\rm ad}^2$ with $T_{\rm ad}$ referring to the adiabatic flame temperature. In addition, we use as a unit speed the laminar speed of the stoichiometric planar flame S_L^0, which is given by

$$S_L^0 = \frac{4{\rm Le}_F{\rm Le}_O}{\beta^3} Y_{O,{\rm st}}(\rho D_T)B\exp(-E/RT_{ad}),$$

where Le_F and Le_O are the fuel and oxidizer Lewis numbers [7], D_T is the diffusion coefficient of heat, and $Y_{O,\rm st}$ is the oxidizer mass fraction at the stoichiometric surface. Since the flame-front region is expected to be centered around the stoichiometric

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