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Computational Study of Nonadiabatic Wave Patterns in Smouldering Combustion under Microgravity

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Abstract. We numerically study a thermal-diffusive model for smouldering combustion under microgravity with convective heat losses. In accordance with previous experimental observations, it is well known that porous materials burning against a gaseous oxidiser under microgravity exhibit various finger-like char patterns due to the destabilising effect of oxidiser transport. There is a close resemblance between the pattern-forming dynamics observed in the experiments with the mechanism of thermal-diffusive instability, similar to that occurring in low Lewis number premixtures. At large values of the Lewis number, the finger-like pattern coalesces and propagates as a stable front reminiscent of the pattern behaviour at large Péclet numbers in diffusion-limited systems. The significance of the order of the chemical kinetics for the coexistence of both upstream and downstream smoulder waves is also considered.

AMS subject classifications: 80A25, 35K57, 80A30, 35B36

Key words: Filtration combustion, smouldering, fingering instability, nonadiabatic, chemical kinetics.

1. Introduction

Smouldering combustion occurs in many domestic and technological processes. However, it can also be a potential fire hazard, and understanding the mechanism of smoulder wave propagation is important. We are presently interested in the structure of smoulder waves arising in microgravity environments, specifically aboard a spacecraft where fire safety measures are paramount. It is known that the structure of smoulder waves exhibits different finger-like patterns in microgravity experiments aboard spacecraft [15] and in

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(a) Connected (b) Tip-splitting (c) Sparse

Figure 1: Spatial profiles of two-dimensional fingering (char) patterns of a filter paper sample, observed experimentally in a Hele-Shaw cell; The char propagation is from bottom to top. Ignition is initiated at the bottom and oxidiser gas is passed from the top, in a typical counterflow configuration. The char is identified by the dark finger-like patterns, and the lighter shades are the quenched part of the flame that separates the regions of burned parts from unburned parts. (a) Connected front that occurs at high flux velocity, where the front is stable. (b) Tip-splitting regime marked by splitting of sole fingers at the tip, observed at moderate flux velocity. (c) Sparse fingers that appear at relatively low flux velocity, where the fingers are more distinct from each other and the tips do not split. The snapshots are courtesy of E. Moses (Weizmann Institute of Science).

quasi-two-dimensional Hele Shaw cells [20–22]. The fingering patterns differ from those observed in a natural convection dominated environment, and include distinct states that depend upon the velocity of a gaseous oxidiser. Thus although the oxidiser exerts a destabilising effect on the emerging smoulder waves, there are three steady states — viz. sparse, tip-splitting and connected front (cf. Fig. 1). The smoulder wave basically proceeds as a self-sustaining reaction front. This front propagates on the surface of a solid porous sample, which reacts with an oxidiser gas infiltrating its pores. The direction of flow of the gaseous oxidiser, relative to the direction of propagation of the reaction front, can be classified into distinct configurations of practical interest due to the characteristic features they exhibit. For a detailed discussion of distinct smouldering configurations, see Refs. [13, 14, 17, 18]. In this article, we focus on the smouldering regime referred to as reverse smoulder, where the direction of the gaseous oxidiser flow is opposite to the direction of the reaction front.

In order to understand the pattern-forming dynamics, various macroscopic models have been studied in different contexts. In Refs. [4,8], a reaction-diffusion system was proposed to study the distinct fingering regimes based on the mechanism of diffusion-limited instability exhibited in the experimental observations reported [15, 20–22]. The diffusion-limited mechanism describes the destabilisation of the smoulder waves through the oxidiser velocity (or Péclet number in dimensionless systems), emphasising the effect of reactant transport on the propagating smoulder waves. Filtration combustion models have also been proposed [7, 10, 12]. However, in thermal-diffusive models the instability of propagating smoulder waves is easier to understand based on two competing transport processes — viz. the transport of reactants and the transport of heat. It is known that the transport of heat has a stabilising effect on the waves. There are various thermal-diffusive models in the literature, notably in the framework of premixed combustion, exhibiting similar qualitative behaviour to the observed situation in non-premixed flames. For instance, it