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Review

Effect of material anisotropy on the fingering instability in reverse smoldering combustion

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ABSTRACT

It is well known from experiments that a sample of thin porous material burning against an oxidizing air under microgravity exhibits various finger-like char patterns. The patterns are classified into three distinct types depending on the oxidizer flow rate. (I) Sparse fingers; (II) tip-splitting fingers; (III) connected front. We presently extend our modeling strategy based on the homogenization approach, which has been applied for the case of isotropic porous media, to analyze the pattern behavior on anisotropic porous media. In order to understand the characteristic features of the patterns based on the influence of the local structure, we simply rely on fixed anisotropic two-dimensional geometries representative of the microstructure of interest. Thus, we illustrate numerically the consequence of the material anisotropy on the fingering patterns based on effective diffusion tensors calculated using the homogenization method and the mechanism of thermal-diffusion instability. Besides revealing new insights on the experimental observations, our numerical results show that material anisotropy can influence the uniformity on the patterns, but the distinct fingering regimes are independent of the local microstructure of materials. This effect is consistent with the qualitative experimental findings from Zik and Moses (1999).

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1. Introduction

Smoldering describes a slow, low temperature and non-flaming mode of combustion. Smolder waves basically proceed as a self-sustaining reaction front that propagates on the surface of a solid porous sample, which reacts with an oxidizer gas infiltrating its pores. The direction of flow of the oxidizer gas relative to the direction of propagation of the reaction front can be classified into distinct regimes and has been a subject of practical interest due to the characteristic features exhibited by each of the regimes. For a detailed discussion on the distinct smoldering regimes, we refer to [2–5, e.g.]. In this paper, we focus on the smoldering regime in which the oxidizer gas flows in a direction opposite to the direction of the reaction front. In the literature, this regime is referred to as the reverse smoldering regime. Our interest in reverse smolder fronts is motivated by the experimental work detailed in [1]. It is shown in [1] that the reverse regime promotes the destabilization of a combustion front. The instability of the combustion front arises due to a destabilizing effect of oxidizer transport [1,6,7], which manifest in the form of finger-like char patterns in the absence of natural convection. Similar phenomenological finger-like patterns have been observed aboard a spacecraft [8]. The fingering instability can be grouped into three distinct fingering regimes based on the velocity of the oxidizer flow; the sparse fingers, tip-splitting fingers, and connected front (see Fig. 1). According to [1], the experiment is setup in such a way as to maintain uniform flow, ignition and material. Thus, the fingering patterns are uniform, in the sense that the direction of propagation of the fingers are in the direction of the prescribed flow field and the fingers do not emerge in clusters or promote propagation along a lateral boundary of the material. This is depicted in Fig. 2(a). The development of the uniform fingering patterns has been previously interpreted in the literature in various contexts [9–13]. From the point of view of the experiment [1], nonuniformity of the patterns manifests if the gap between the plates of the Hele-Shaw cell is increased, i.e. increasing the vertical convection and hence nonuniformity of the flow. Also, if nonuniform ignition is used during the experiment, the patterns turn out to be nonuniform. The nonuniformity of the patterns implies that the direction of propagation of the fingers may not necessarily be in the direction of the oxidizer flow. The patterns may manifest distinct forms of nonuniformities as described in [1]. Here, we illustrate in Fig. 2(b) some forms of nonuniformity. Thus, the experimental observations lead to the basic question of whether the local microstructure of a porous material can influence the fingering behavior under conditions of uniform flow and ignition. This is the main objective of the present paper. Recently, the macroscopic description of the smoldering combustion problem has been derived from a basic pore scale description in an isotropic porous medium [9] by using the homogenization theory based on periodic structures [14–18] and two-scale convergence methods [19,20]. The main assumptions related to the method by homogenization, the physics of the phenomenon of interest at the pore scale and the main results deduced from the upscaling procedure are briefly recalled in Section 2. In Section 3, we analyze numerically the properties of the effective diffusion tensors derived through homogenization method for different angular orientations of a centered elliptical inclusion. The correct forms of the anisotropic diffusion tensors are also deduced. In Section 4, the tensorial properties of the elliptical geometry are then used to formulate distinct functional forms of macroscopic system of equations for smoldering combustion of anisotropic porous media. The behavior of the fingering patterns is analyzed numerically for simplified anisotropic media having distinct angular orientations of the elliptical inclusions in Section 5. For each realization based on an angular orientation, the medium is assumed to be uniformly periodic with fixed volume fraction of the elliptical inclusion. We point out that the choice of elliptical microstructures used in this

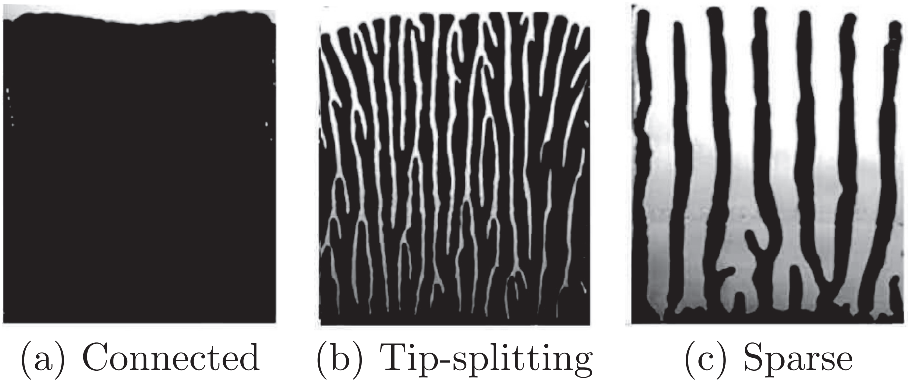
(a) Connected (b) Tip-splitting (c) Sparse

Fig. 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 oxidizer gas is passed from the top, in a typical counterflow configuration. The char is identified by the dark finger-like patterns, and the light shades are the quenched part of the flame, which separates regions of burned parts from unburned parts. (a) Connected front which manifests at high flux velocity; the fingers are connected. (b) Tip-splitting regime marked by splitting of sole fingers at the tips; it is observed at a moderate flux velocity. (c) Sparse fingers, which manifest at a relatively low flux velocity; 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).