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Multi-layer cellular automaton for fingering instabilities

Nieves Fernandez-Anez (1), Vidar Frette (1), Guillermo Rein (2), Kim Christensen (3,4)

(1) Department of Fire Safety and HSE Engineering, Western Norway University of Applied Sciences, , Bjøornsonsgate 45, 5528, Haugesund, Norway, (2) Department of Mechanical Engineering, Imperial College London, SW7 2AZ, United Kingdom, (3) Centre for Complexity Science, Imperial College London, SW7 2AZ, London, United Kingdom, (4) Blackett Laboratory, Imperial College London, SW7 2AZ, London, United Kingdom

Fingered flow refers to an instability of the interface between two immiscible fluids when one invades the other. The so-called fingering instabilities can therefore be observed in several situations. In the case of fluids, they are normally reversible situations that can be changed by reversing the flow direction, going back to the initial condition. However, in other cases irreversible changes occur and the initial condition cannot be reached.
One of this irreversible cases occurs in a specific process of combustion, smouldering, a slow, low-temperature flameless form of combustion [1], which is sustained by the heat generated when oxygen reacts at the surface of a condensed-phase fuel. Fingering instabilities in smouldering combustion fronts appear in a thin fuel layer, with an opposed laminar oxygen flow, when conduction is the dominant heat transfer mode.
In the late 90s, Zik et al. [2] observed this behaviour and concluded that there is a dependence between the Peclet number (Pe) (proportional to the speed of the oxygen flow) and the appearance of fingers. Above a critical Pe value, the front is smooth, but as Pe decreases, small bumps along the interface begin to compete over the oxygen, and the front develops a more complicated structure, marking the onset of fingers. If the oxygen supply further decreases, lateral diffusion becomes more important and the bumps become periodic, depleting the oxygen in their vicinity, and fingers are formed.
The two parameters used to characterise the fingers are the distance between them and their width. The first one is related with Pe [2], while the second one is related with the Lewis number (ratio of thermal diffusivity to mass diffusivity) [3]. By combining both, it can be seen that the higher the oxygen speed, the wider the fingers and the smallest the distance between them are, until a point where the front becomes smooth and fingers are not present.
To study these influences and to reproduce this behaviour, we have developed a multi-layer cellular automaton [4]. This is a stochastic and non-dimensional model based on a three-step reaction scheme, which was conceived as the simplest mathematical model able to reproduce smouldering fires. This cellular automaton reproduces the patterns observed in the experiments and the numerical results show the importance of the oxygen flow and the heat transfer on the appearance and development of the fingering behaviour.

References

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