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Early Stages of Flame Propagation in Tubes with Non-Slip Walls: Mechanism of Tulip Flame Formation

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Extended Abstract

Flame propagation in closed or semi-open tubes is a fundamental physicochemical model that provides a basic platform for theoretical and numerical studies of more complex scientific and engineering combustion processes. The early stages of flame propagation are of particular interest because they determine subsequent flame propagation modes: deflagration or detonation. The formation of the "tulip flame" was discovered experimentally almost a century ago [1]. It was found that the shape of the flame front ignited near the closed end of a tube and propagating toward the opposite closed or open end suddenly changes rapidly from a convex shape with the tip pointing forward to a concave shape with the tip pointing backward. Subsequent experiments showed that tulip flame formation is remarkably robust to all combustible mixtures and possible downstream conditions: open or closed tube end, tube shapes, etc. Despite numerous experimental, theoretical and numerical studies, the mechanism of the tulip flame formation remains one of the major unsolved fundamental problems in combustion theory [2, 3].

We show that the solution to the problem is an intriguingly simple one [4, 5]. In the theoretical thin flame model, where the flame front is a discontinuous surface between unburned and burned gas, the velocity of different points on the flame front is the sum of the laminar flame velocity relative to the unburned fuel and the velocity of the unburned flow with which the flow entrained that part of the flame front. The superposition of the unburned gas flow created by the flame during the acceleration phase after ignition and the flow created by the rarefaction wave(s) during the deceleration phase, when the flame skirt touches the tube walls, the flame front surface and hence the flame velocity decreases, creates a tulip shape of the unburned gas axial velocity profile near the flame front. Therefore, the flame front also takes on a tulip shape. The results of the theoretical thin flame model appeared to be in surprisingly good agreement with 2D and 3D simulations that used a detailed chemical-kinetic model and thus accounted for the true thickness of the flame front. We show that tulip flame formation by rarefaction waves, which are purely hydrodynamic processes, is much faster than the rates of development inherent flame instabilities considered in previous attempts to explain tulip flame formation. The ratio of the rarefaction wave formation time τ_{RW} to the time τ_{DL} of the Darrieus-Landau instability development is $\tau_{RW} / \tau_{DL} \sim U_f / a_s << 1$, where U_f is the laminar flame velocity, a_s is the speed of sound.

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