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Boundary layer flashback mechanisms:
A kinematic analysis of hydrogen/air flames in turbulent flow

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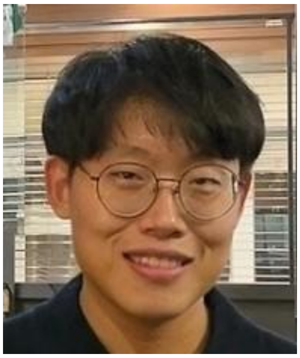
Abstract: Hydrogen is a promising fuel for low-carbon propulsion and power generation, but its high reactivity and strong diffusive transport make premixed systems prone to flashback, threatening performance and safety. This study uses high-fidelity direct numerical simulations (DNS), G-equation–based analysis, and topology-resolved kinematic diagnostics to clarify hydrogen flame propagation and flashback mechanisms in turbulent channel flow.

A flame-kinematic extraction framework is established using a controlled G-equation methodology and applied to lean premixed hydrogen–air flames interacting with fully developed wall-bounded turbulence. The highly wrinkled flame front is decomposed into (i) front-facing flame bulges (FFB) and (ii) flame cusps (FC) to quantify topology-dependent behavior. Both the laminar flame speed and the approaching flow velocity upstream of the flame are found to be strongly modulated by local geometry, and their correlation provides quantitative insight into local flashback propensity. A physically intuitive metric, the flashback velocity is introduced to diagnose upstream propagation. FC regions frequently exhibit locally negative flashback velocity, but such events remain transient and do not develop into global flashback due to the unstable nature of cusp structures. In contrast, FFB regions show a sustained negative bias in flashback velocity, indicating that bulged topologies promote coherent upstream propagation and can act as dominant precursors to global flashback in lean hydrogen flames.

Stoichiometric hydrogen–air flames are also examined, where flashback occurs readily due to high flame speed and strong thermal expansion. Using time-synchronized averaging over multiple realizations, two distinct pathways are identified: kernel-induced flashback (KIF), initiated away from the wall by a localized flashback kernel, and wall-boundary flashback (WBF), initiated near the wall where boundary-layer velocity deficits enable upstream propagation. In both pathways, global flashback onset is marked by a kinematic crossover between synchronized profiles of x-components of flame speed and approaching flow velocity. Restricting the statistics to FFB regions further isolates the key kinematic signatures linked to flashback initiation.



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Biography: Jungho Sohn received his B.S. (2018) and M.S. (2020) in Mechanical Engineering from Yonsei University, and his Ph.D. (2026) in Aerospace Engineering from KAIST under the supervision of Prof. Dong-Hyuk Shin. He continues his career at KAIST as a postdoctoral researcher, with the goal of deepening his research and understanding of hydrogen flame characteristics, while actively seeking new opportunities to expand his career and collaborations in computational combustion and sustainable energy technologies. His research interests include computational combustion, turbulent reacting flows, flame–turbulence interaction, flame–wall interaction, and high-performance computing, with an emphasis on hydrogen combustion and gas-turbine-relevant configurations. He has authored publications in venues including Proceedings of the Combustion Institute and Combustion Science and Technology and has presented his work at multiple international conferences. He recently won the Young Investigator Award at the 15th Asia-Pacific Conference on Combustion (ASPACC).

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