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Effects of cryogenic temperature on the propagation of turbulent hydrogen/air flames

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Hydrogen is a promising alternative fuel with the potential to significantly reduce carbon dioxide emissions. To increase its energy density for efficient use, hydrogen is often stored and transported at cryogenic temperatures. However, due to its high diffusivity and reactivity, cryogenic hydrogen released accidentally can rapidly mix with ambient air and form a cryogenic hydrogen/air mixture. Owing to its extremely low ignition energy, this mixture can be easily ignited, potentially leading to fires or explosions. Therefore, understanding the propagation of hydrogen/air flames under cryogenic conditions is essential to control and mitigate combustion hazards, particularly in turbulent flows relevant to practical scenarios. In this study, the propagation and acceleration of turbulent premixed hydrogen/air flames at ambient temperature ($T_0 = 300$ K) and cryogenic temperature ($T_0 = 100$ K) are investigated through three-dimensional direct numerical simulations considering detailed chemical kinetics and transport models. Both stoichiometric and fuel-lean hydrogen/air mixtures are considered to examine the effects of Darrieus–Landau instability (DLI) and diffusional–thermal instability (DTI) on flame front evolution and acceleration. For stoichiometric hydrogen/air flames with a near-unity Lewis number, DLI is the dominant mechanism influencing turbulent flame behavior. It is found that DLI is significantly enhanced under cryogenic conditions due to the increased gas expansion ratio (i.e., the density ratio of unburnt to burnt gases) associated with the lower initial temperature (T_0). For fuel-lean hydrogen/air flames, both DLI and DTI contribute to the wrinkling and distortion of the turbulent flame front. A comparison between stoichiometric and fuel-lean flames at cryogenic temperatures shows that DTI also plays a critical role in the propagation and acceleration of turbulent hydrogen/air flames. Moreover, a substantial increase in the local chemical reaction rate promotes the accelerative propagation of fuel-lean hydrogen/air flames. This study reveals the differences in turbulent premixed hydrogen/air flames at ambient and cryogenic temperatures, suggesting that the cryogenic hydrogen/air flames, especially in fuel-lean mixtures, are prone to strong acceleration. The findings of this study provide valuable insights into the safe use of hydrogen.