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Title(English)	Direct Numerical Simulations of Lifted Flames of Hydrogen and Steam Diluted Oxygen
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THESIS OUTLINE

Chapter 1: Introduction

In this chapter, the importance of using alternative fuels is discussed briefly. The structure and stabilization of lifted flames are introduced. The numerical methods used to simulate turbulent combustion are presented. DNS research on turbulent combustion of lifted flames is reviewed. Finally, the objectives of this study are explained. To reduce CO_2 emission from gas turbine power generation system, hydrogen will be used as an alternative fuel. Although the usage of hydrogen will reduce the CO_2 emission, NO_x will increase due to higher burnt gas temperature for hydrogen fuel. To reduce CO_2 and NO_x emissions simultaneously, a semi-closed gas turbine system based on hydrogen-oxygen combustion has been proposed. To realize this zero-emission system, characteristics of hydrogen and steam-diluted oxygen combustion should be investigated because the steam is used as a working fluid. In this study, the flame structure of lifted jet flames of non-premixed hydrogen and steam-diluted oxygen is investigated using direct numerical simulations (DNS) considering a detailed kinetic mechanism, which is available for high pressure and temperature dependence of thermal/transport properties.

Chapter 2: Laminar non-premixed lifted flames of H_2 and O_2 diluted with steam

This chapter investigates the fundamental aspects of a laminar lifted flame of hydrogen with steam diluted oxygen by conducting two-dimensional DNS. The simulations use a simple geometry in which a hydrogen stream and a steam-diluted oxygen stream make a non-premixed flame in an open space. The heat release rate and normalized flame index are investigated to comment on the flame structure, and the flame stabilization mechanism is determined by the transport budget analyses over the stoichiometric mixture fraction line. The results suggest that even though steam dilution does not affect the overall flame structure, it may alter the stabilization mechanism. The nitrogen diluted case stabilizes with autoignition, whereas the steam diluted case stabilizes with flame propagation. Zero-dimensional homogeneous reactor analyses show that the high-efficiency factor of steam for third body reactions causes different stabilization mechanisms. To investigate the pressure effects on the flame structure and the flame stabilization mechanism, DNS of hydrogen and steam diluted oxygen combustion are conducted up to 20 atm. The flame thickness decreases significantly with increasing pressure, while the flames show a similar structure for all pressures. The transport budget analyses show that the diffusion and reaction term show the same order of magnitude for higher pressures, which means that the flame propagation mechanism stabilizes the flame. These results suggest that the flame features of lifted jet flames under nominal gas turbine thermochemical conditions are not affected by the pressure.

Chapter 3: Laminar multi-jet flames of H_2 and O_2 diluted with steam

This chapter studies lifted multi-jet flames under the nominal gas turbine conditions using two-dimensional DNS for the regular arrangement of fuel jets. In practical combustors, the fuel and oxidizer are issued from multiple jet exits to enhance mixing, potentially producing multiple lifted-flame bases. In this chapter, two laminar multi-jet cases with different jet center separations are investigated to reveal the fundamental flame features of multi-jet flames without the influence of turbulence. Visual inspection and statistical analyses show that for both cases, the flames have a tribrachial structure with multiple flame-base regions, each of which is associated with the corresponding fuel jet. Furthermore, the transport budget analyses of both cases showed a similar trend with the laminar single-jet flame under the same conditions, suggesting that flame interactions do not affect the fundamental features of lifted flames significantly.

Chapter 4: Turbulent multi-jet flames of H_2 and O_2 diluted with steam

In this chapter, three-dimensional DNS of turbulent multi-jet flames is performed for the staggered arrangement of fuel jets. The distribution of the heat-release rate and the flame-base locations suggest that the turbulent flames, unlike the laminar ones, have a single connected flame-base region with large fluctuations in the streamwise direction. The highest heat release rate regions are observed well outside the flame core region. The typical triple flame structure is observed only around the flame base regions, and the overall structure becomes premixed afterwards. The stabilization of turbulent multi-jet flames is discussed by investigating the propagation characteristics of the flame base, critical scalar dissipation rate, and the transport budget analysis results. The results suggest that the unique structure of turbulent multi-jet flames prevents the critical scalar dissipation from assisting flame stabilization. However, the flame base propagation velocity is balanced by the local flame velocity, and the transport budget is similar to that of laminar flames, which shows that the flame propagation mechanism determines the stabilization.

Chapter 5: Conclusions

The conclusions of each chapter are summarized, and the importance of the investigation of steam diluted hydrogen flames for a sustainable future is emphasized.