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学 位 論 文 内 容 の 要 旨

博士の専攻分野の名称　博士（工学）　氏名　Tongtong Cui

学 位 論 文 題 名

A Localized Thickened Flame Model for Stretched Premixed Flame of Hydrogen and Hydrocarbon Fuels
(水素および炭化水素燃焼における火炎伸張効果を考慮した局所火炎帯増大モデルに関する研究)

In the context of the rapid transition toward a carbon-neutrality society, there is a growing demand for high-accuracy and high-efficiency numerical combustion prediction to optimize the use the existing energy source and to develop technologies for alternative energy utilization. This requires precise modeling of complex transient combustion phenomenon such as ignition, extinction, pollutant species formation, and turbulence-combustion interactions in complex combustor geometries. As a result, detailed chemical reaction simulations that account for finite-rate chemistry have become increasingly important. However, due to the extremely small times scales of the combustion reactions and the steep spatial gradients across flame fronts, direct numerical simulation (DNS) of reactive flows demands enormous computational resources and time. At the same time, it is essential to respond quickly to emerging market needs, which are influenced by political decisions and other external factors. Faced with the gap between the limited predictive efficiency in computational modeling and the need for rapid transitions in the physical world, the development of advanced combustion models poses significant challenges and has become increasingly crucial.

The purpose of this study is to develop a combustion model that includes detailed reaction kinetics in order to accurately and reliably predict the dynamics of premixed flames. The model is intended to overcome the constraints that the extremely small temporal and spatial scales of premixed flame fronts place on the computational grid and on the time-integration step size, to accelerate the speed of numerical simulations of combustion.

Chapter 1 describes the research background, the current state of research, and the objectives of this study.

Chapter 2 provides a detailed description of the governing equations for reacting flows that account for detailed chemical kinetics, as well as the numerical methods for solving these equations.

Chapter 3 describes the concept of the LTF model, its validation results, and the main focus of this chapter: the development of the extended LTF-S model, and its validation results. In this study, the artificially thickened flame approach, specifically the localized thickened flame (LTF) model, is employed to relax the demands on spatial and temporal resolution. In the one-dimensional LTF formulation, a flame-thickening factor is introduced to increase diffusion at the flame front, while the reaction rate term is scaled by the inverse of this factor to maintain the correct laminar burning velocity (S_L). The thickening factor is adjusted dynamically so that flame broadening is confined to the flame zone and does not influence the surrounding flow. We have firstly validate this LTF model using two-dimensional cylindrical flame propagation of premixed hydrogen–air. The results show that, for stretched flames with thickening, the sensitivity of the flame propagation speed to stretch is affected leading to an incorrectly predicted propagation speed. The sensitivity is also known as the Markstein length. This study found that the Markstein length ratio exhibits a linear relationship with the thickening factor, where the Markstein length ratio is the ratio of the Markstein length of the thickened flame to that of the original non-thickened flame. To achieve accurate prediction of the burning velocity of thickened flames under stretch, this study proposed a new LTF-S model (LTF model for stretched flames) by introducing a new model parameter $1 + \psi$. This model parameter allows to restore the sensitivity of the thickened flame to stretch basing on the local stretch rate, and thereby corrects the burning velocity of the thickened flame. Compared with the LTF model, the new LTF-S model, while still using a thickened flame front to reduce computational cost, is able to accurately reproduce the reference DNS flame propagation results.

Chapter 4 further verifies the predictive accuracy of the LTF-S model when dealing with more complex combustion scenario, the flame-vortex interaction. This numerical configuration includes both the straining of the vortex acting on the flame and the curvature effects caused by flame deformation. The study considers three vortex conditions interacting with a stationary, stoichiometric, premixed hydrogen flame. In all cases, the vortex length scale is set to five times the flame thickness, while the velocity scales are chosen as 0.1, 1, and 10 times the laminar burning velocity. These interaction regimes correspond to wrinkled flamelets, corrugated flamelets, and the distributed reaction zone in the turbulent combustion diagram. It is shown that the latter two vortex conditions significantly modify the flame structure, and the case with $10S_L$ generates an unburnt gas pocket within the burnt gases. The LTF-S model successfully reproduces the detailed flame shape during vortex–flame interaction and quantitatively yields the identical fuel consumption rate obtained from the reference DNS results. Although the LTF-S model is derived from a simple cylindrical stretched flame configuration, the LTF-S model can reliably predict general premixed combustion behavior.

Chapter 5 further applies the new LTF-S model to hydrocarbon fuels, specifically methane and propane. The previously proposed linear correlation between the Markstein length ratio and the flame thickening factor is confirmed for these cases, and a proportionality coefficient is shown to exist for both fuels. While the values of this coefficient vary among different fuels, they typically fall within the range of 0.4–0.6. A sensitivity analysis of the prediction error with respect to this coefficient indicates that using a universal value of $A = 0.5$ is suitable for predicting premixed flames of hydrogen, methane, and propane. Because the key flame characteristics, the laminar burning velocity and the Markstein length, can be readily obtained (for instance, from 1D flame simulations), the identification of the universal proportionality coefficient of $A = 0.5$ renders the LTF-S model highly flexible and easy-to-use model for the combustion simulations. Finally, the LTF-S model is implemented on a practical combustor, namely a perforated plate burner. This configuration, in particular, enables the study of purely strain-induced stretch effects and the spatial variation of the local burning velocity. The new LTF-S model accurately captures both the local and overall combustion behavior in this system.

Chapter 6 concludes this study by introducing the development of a stretched premixed flame model for reactive flow simulations that includes detailed chemical kinetics, and by outlining potential future directions for this line of research.