Morphology, Structure and Burning Velocities of Spherically Propagating Premixed Turbulent Hydrogen Flames

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論 文 名　：Morphology, Structure and Burning Velocities of Spherically Propagating Premixed Turbulent Hydrogen Flames
（球状伝播予混合乱流水素火炎の形態，構造および燃焼速度に関する研究）

区　　分　：甲

論　文　内　容　の　要　旨

Hydrogen is a carbon-free fuel that has the potential to fit the global energy decarbonization plan because: (i) It is produced from renewable energy sources. (ii) It can be utilized for energy generation through combustion. Hydrogen has a significantly larger burning velocity with a low flammability limit compared to conventional fossil fuels. Thus, it would make it desirable to build hydrogen-based internal combustion engines and combustors. To develop such apparatuses a fundamental understanding of the mechanism and properties of hydrogen combustion is required.

Turbulent burning velocity is one of the most significant properties relating to the performance of engines and combustors. Turbulent burning velocity is well known to increase with the increase in the flame front area due to the wrinkling of the flame front by turbulent eddies. Turbulent burning velocity increases with turbulence intensity. However, the effects of turbulence scale on the turbulent burning velocity of such developing – flame front have not been clarified. Also, detailed information related to the influences of turbulence on flame structure and morphology, individual reactions in hydrogen oxidation mechanism, and their associated heat release rate was not available. Therefore, in this study, three – dimensional DNS were carried out for spherically propagating premixed hydrogen-air flames with detailed chemical kinetics to present the latest findings regarding (i) The influence of turbulence scale on the overall development of premixed flames and burning velocities. (ii) Small – scale turbulence – flame interaction concerning flame structure and morphology. Here, “Morphology” describes the global flame shape, while “Structure” describes the relevance to the local flame thickness and reaction layers. (iii) Turbulence – chemistry interactions with respect to heat release of elementary reactions as well as representative non – dimensional numbers, such as Lewis, Prandtl, and Schmidt numbers.

This dissertation consists of 6 chapters and can be summarized as follows.

In Chapter 1, the background of the study is introduced. The importance of hydrogen and its combustion are discussed in conjunction with the assessment and projections of the energy situation. Then, a review of literature on laminar and turbulent premixed combustion is presented including peculiar aspects of hydrogen. Especially it is focused on the development of research on morphology, structure, and burning velocity due to the turbulence – flame interaction. Finally, the objectives and originality of this study are described, which is to clarify the effects of turbulence on the turbulent burning velocity, flame structure, and morphology, turbulence – chemistry interactions for spherically propagating premixed turbulent hydrogen flames.

In Chapter 2, the research methodology is elaborately explained. A description of the numerical simulation methodologies of direct numerical simulation is described. This involves governing equations of reactive gas flow fields, physical properties of gases, detailed chemical reaction kinetics, and generation of turbulence field and initial flame kernel.

In Chapter 3, the numerical simulation results of the spherically propagating laminar flames are presented and discussed. Obtained laminar hydrogen-air flame solutions match experimental data. Comparison is done by evaluating general flame features, profiles of temperature, and mass fraction of involved chemical species. Moreover, unstretched laminar burning velocity is confirmed to be the same as the experimental one. Finally, the accuracy of the applied numerical simulation is described.

In Chapter 4, premixed turbulent flames are investigated to clarify the influence of turbulence scale on the wrinkling formation of the flame front, flame front area, and turbulent burning velocity. Results show that for spherical flame with a small radius, turbulent eddies with small integral length scales have hugely contributed to wrinkling the flame front. Therefore, increasing its area and the turbulent burning velocity. As flame propagated, it reaches an adequate size to be able to experience the contribution of turbulent eddies with large integral length scales. Hence, increasing the flame front area and turbulent burning velocity. At the same time, turbulent eddies with a small integral length scale would have no further influence on flame front development and its burning velocity. Such change in influence depends on the correlation between flame radius and size of turbulent eddies, which can only be clarified by utilizing a developing – flame front. An understanding of such correlation is useful in designing combustion engines, where a turbulence field with a specific turbulence scale is supplied to the combustion chamber, depending on the volume of the flame, to provide the maximum burning velocity. To add to that, turbulent burning velocity is found to be smaller than that estimated from the flame front area due to the thermo-diffusive effects. The quantitative dependency of the turbulent burning velocity with the flame front area is shown for the flames with positive Markstein number.

In Chapter 5, interactions of small scales of turbulence, Taylor microscale, and Kolmogorov length scale, and flame are investigated concerning the structure and morphology of spherically propagating flame front. Intense reaction zones diversity of shapes at the flame front are quantified using Minkowski functionals. The conditional averages of the local Taylor microscale scale are found to correlate with planarity and filamentarity of intense reaction zones. Hence, turbulent motions at Taylor microscale size are clarified to have a significant role in characterizing turbulence – flame interactions relevant to flame morphology, local flame thickness, and reaction layers of spherically propagating – flames. Such a correlation with the development of the local structure of the flame is not present for well – developed flames, highlighting the importance of current results for modeling of propagating turbulent flames. Furthermore, turbulence – chemistry interactions are investigated. Heat release of elementary reactions and representative non – dimensional numbers, such as Lewis number, Prandtl number, and Schmidt number are compared with those of laminar flame. A decorrelation between total heat release and fuel consumption for stoichiometric hydrogen-air flames is found to occur. The decorrelation is attributed to small – scale turbulent motions as they enhance the mixing of the mixture. The decorrelation increases as turbulence level increases resulting in a significant increase in the released heat. Its main contributor is clarified to be chemical species relevant to the three-body recombination reaction. For flames propagating in high turbulence levels, local convective motions led to the transport of heat and radicals away from the burned gas region and reaction zone of the flame front towards the unburned mixture region. Hence, some parts of the unburned mixture experienced heating and an increase in the concentration of radicals. Thus, lower values of Lewis number in those parts of the unburned mixture region were observed when compared to the ones for the laminar flame solution.

In Chapter 6, the summary and conclusions are presented.

〔作成要領〕

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