Title: Turbulent flame propagation behavior and mechanism of solid particle cloud/ammonia co-combustion

題名：固体粒子群とアンモニアの混焼における乱流火炎伝播挙動とメカニズム

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Summary of the present study

To curb the risks and impacts of climate change, the reduction of carbon dioxide (CO_2) emission is a critical issue for humankind because CO_2 is the green-house gas (GHG) causing the largest impact on our climate by creating a greenhouse effect. Ammonia is one of the most promising candidates for energy carrier in the future, various applications of ammonia as a fuel are currently considered. Application ammonia in thermal power plant for co-combustion is considered an efficient and feasible method to reduce CO_2 emissions from the viewpoint to step into a carbon free society. In combustor, the turbulent environment is used. Turbulent flame propagation velocity is a basic physical property for evaluating the flame stabilization performance of combustion of fuels. Therefore, the present research aims to clarify the fundamental solid particle cloud/ammonia/oxidizer co-combustion turbulent flame propagation characteristics and mechanism. To achieve this aim, four types of experiments were performed, including pure ammonia turbulent combustion, pure solid particle cloud turbulent combustion, solid particle cloud/ammonia turbulent co-combustion, and silica particle cloud/gas-fuel mixing-combustion experiments. The experiments were conducted by using a unique constant-volume turbulent combustion chamber.

In chapter 1, a brief review of turbulent combustion of solid particle cloud, ammonia, and solid particle cloud/ammonia was introduced. Then, the objective and structure of this thesis were presented.

In Chapter 2, the experimental setup was described. The experimental conditions and procedures for pure ammonia turbulent combustion, pure solid particle cloud turbulent combustion, solid particle cloud/gas-fuel co-combustion, and silica particle cloud/gas-fuel mixing-combustion were specified respectively.

In chapter 3, laminar and turbulent burning velocities of ammonia/oxygen/nitrogen flames were investigated under the condition of oxygen enrichment. The turbulent burning velocity of ammonia/oxygen/nitrogen mixtures was found to increase with increasing turbulence intensity. The ratio of the turbulent burning velocity to stretched laminar burning velocity, U_{tr}/U_N, increased with the turbulence Karlovitz number. However, because of the diffusional–thermal instability effect, given the same turbulent Karlovitz numbers, U_{tr}/U_N in ammonia-lean cases is larger than in ammonia-rich cases. Therefore, the effects of diffusional–thermal instability and the turbulence is important factors for affecting the turbulent flame propagation velocity of ammonia combustion.

In Chapter 4, the effects of the particle cloud concentration and particle size on the turbulent flame propagation of solid particle clouds were studied using the quasi-monodispersed PMMA particle clouds. A simplified polydispersed particle cloud was formed by mixing two different diameters of the quasi-monodispersed particles to study the turbulent combustion phenomenon associated with small–large particle interactions. For the quasi-monodispersed particle clouds, the flame propagation velocity increased with the increase in the turbulence intensity and the decrease in the quasi-monodispersed particle size. However, the particle concentration weakly affected the flame propagation velocity, which is unique in a turbulent flow field. The consistency of the results between the current study of PMMA particle clouds and the previous study for coal particle clouds showed that the heterogeneous combustion of char particles weakly affected the turbulent flame propagation velocity of the solid particle clouds. Further, two types of quasi-monodispersed particles were mixed to study how the interactions between small and large (polydispersed) particles affect turbulent flame propagation. The turbulent flame propagation velocity had a nonlinear relationship with the mass ratio of small particles (J-shaped curve). The turbulent flame propagation velocity slightly increased with low mass ratio of small particles, while it sharply increased with high mass ratio of small particles. Increasing the turbulence intensity and decreasing the primary particle (large particle) size can advance the starting point of the sharp increase.

In Chapter 5, based on the turbulent flame propagation mechanism in pure ammonia combustion and pure solid particle cloud combustion, the effect of the ammonia/oxygen/nitrogen equivalence ratio on the flame propagation characteristics of pulverized coal/ammonia co-combustion under various turbulence intensities were investigated. It was discovered the turbulent flame propagation velocity of co-combustion is higher than that of the pure pulverized coal combustion and whether the turbulent flame propagation velocity of the co-combustion is higher than that of the pure ammonia combustion is dependent on the equivalence ratio of the ammonia-oxidizer. In ammonia-lean cases, the turbulent flame propagation velocity of co-combustion is larger than that of the pure ammonia co-combustion. In ammonia-rich cases, the turbulent flame propagation velocity of the co-combustion is lower than the pure ammonia co-combustion. In stoichiometric condition, both are almost same. This unique feature was explained by a mechanism including three competing effects proposed by the authors. In an ammonia lean condition, the positive effects, which are the strong radiation from the luminous flame and the increment of the local equivalence ratio by the addition of volatile matter, are larger than the negative effect, which is the heat absorption by the unburned particles in the preheat zone. In an ammonia rich condition, the effect of the increment of the local equivalence ratio by the addition of the volatile matter turns into a negative effect. Consequently, the negative effects overcome the positive effect in an ammonia rich condition resulting a lower flame propagation velocity of the solid particle fuel/ammonia co-combustion.

In Chapter 6, to furtherly validate the proposed three effects, the silica particle cloud/ammonia mixing-combustion and silica particle cloud/acetylene/air mixing-combustion, and PMMA particle cloud/ammonia co-combustion experiments were conducted. It was found that the turbulent flame propagation velocity of the silica particle cloud/ammonia mixing-combustion was lower than that of the pure ammonia combustion irrespective to the ammonia equivalence ratio. Therefore, the heat sink effect from the unburned particles is validated. Moreover, the turbulent flame propagation velocity of the silica particle cloud/acetylene/air mixing combustion was lower than that of the pure acetylene/air combustion. Therefore, the radiation effect from the soot particle on the co-combustion weakly affects the flame propagation of co-combustion. Further, in PMMA particle cloud/ammonia co-combustion, the same turbulent flame propagation phenomena with pulverized coal particle cloud/ammonia co-combustion were observed. Therefore, in solid particle cloud/ammonia/oxidizer co-combustion, the turbulent flame propagation mechanism is mainly controlled by the heat sink negative effect from the unburned particles in the preheat zone of the flame front and the local equivalence ratio increment effect by the volatile matter released from the solid particles in the preheat zone of the flame front.

In Chapter 7, conclusions of the present work were summarized based on the experimental findings.