



HOKKAIDO UNIVERSITY

Title	Turbulent flame propagation behavior and mechanism of solid particle cloud/ammonia co-combustion
Author(s)	XIA, Yu
Degree Grantor	北海道大学
Degree Name	博士(工学)
Dissertation Number	甲第14675号
Issue Date	2021-09-24
DOI	https://doi.org/10.14943/doctoral.k14675
Doc URL	https://hdl.handle.net/2115/93091
Type	doctoral thesis
File Information	Xia_Yu.pdf



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ズム)

By

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Submitted to the Division of Mechanical and Space Engineering,
Graduate School of Engineering, Hokkaido University, Japan,
in Partial Fulfillment of the Requirement for the Degree of
Doctor of Philosophy in Mechanical and Space Engineering

August 2021

Acknowledgments

The highest expression of gratitude must be extended to my supervisor, Prof. Nozomu Hashimoto at Hokkaido University, for giving a chance to study under his supervision and work at one of best laboratory. Without his support and encouragement, it would be impossible for me to have the honor and privilege of pursuing my doctoral works. During the three years study and research, Prof. Nozomu Hashimoto has given me constructive guidance. He professionally guides me very details in various skills in research works. He also teaches me the ways to research. His patient, sensitivity, genuine kindness, and spontaneous encouragement will play a significant role in my life, never to be forgotten.

On top of that, I like to furtherly express my appreciation to Prof. Osamu Fujita. He guides me in the research activities and gave me a lot of supports. Both professors are very nice and the great scientists. I also want to thank the secretary, Ms. Miho Taga for her kind help and support dealing a lot of paper works related to my research and business trip.

Besides, I would like to thank Prof. Hideaki Kobayashi and Prof. Akihiro Hayakawa from Tohoku University for the collaborative research on ammonia combustion. They were kindly sharing their knowledge and supporting us on research, and the related activities as well. I like to thank Prof. Masaya Muto from Meijo University for the professional support and discussion on the numerical simulation of ammonia combustion. I have learnt a lot from him in the numerical simulation in our collaboration project. Furthermore, I like to thank Prof. Kaoru Maruta and Prof. Hisashi Nakamura from Tohoku University for his kind discussion in the research works.

Further, I would like to thank Prof. Harunori Nagata, Prof. Nobuyuki Oshima, Prof. Osamu Fujita, and Prof Nozomu Hashimoto for their services on my doctoral committee and also for

their helps on my study and research in the past years. I appreciated Prof. Masao Watanabe, Prof. Takashi Nakamura, Prof. Takemi Chikahisa, Prof. Hideyuki Ogawa, Prof. Tsuyoshi Totani, Prof. Yuichi Murai, Prof. Yutaka Tabe, Prof. Hiroshi Terashima and Prof. Gen Shibata on judgment committee.

I appreciate Prof. Hui Yan, Prof. Ajit Kumar Dubey, Dr. Yongho Chung, Dr. Masashi Nagachi, Dr. Guo Feng, Dr. Yusuke Konno, Dr. Nguyen Truong Gia Tri and Mr. Yushin Naito for their helpful discussion with my research and helps in my Hokudai life. I would like to appreciate my research group members, Dr. Khalid Hadi, Mr. Ryo Ichimura, Mr. Genya Hashimoto, Mr. Shunya Kitagawa, Ms. Aainaa Hamid and Mr. Song SeungMin for their helps and academic discussions along my research.

I like to appreciate Chinese Scholar Council (CSC) for providing me the scholarship to pursue my study in Japan for Ph.D. course. I like to thank all the people who are supporting me until these days. I am sorry that it is difficult to state all the names here.

I like to appreciate my love, Ms. Yanyue Jiu. I am very lucky to meet her in my life in Hokudai. Finally, with great humble and gratitude, I thank my parents, for their endless love and concern.

Thank you very much!

Abstract

To curb the risks and impacts of climate change, the reduction of carbon dioxide (CO_2) emissions 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 of ammonia in thermal power plant for co-combustion is considered as 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, the turbulent flame propagation velocity of pure ammonia/oxygen/nitrogen was first introduced under the condition of oxygen enrichment. Then, laminar and turbulent burning velocities of ammonia/oxygen/nitrogen flames were investigated. 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 are 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 had little effect on 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 has little effect on the turbulent flame propagation velocity of the solid particle clouds. Further, three

types of quasi-monodispersed particles were mixed to study how the interactions between small and large (polydispersed) particles affects 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 the combustion of turbulent polydispersed particle cloud, the particle-particle agglomeration and the agglomeration break-up in the turbulent flow field affect turbulent flame propagation.

In Chapter 5, based on the turbulent flame propagation mechanisms 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 further 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. Notably, in present research, co-combustion is the combustion of solid particle fuel/gas fuel hybrid mixtures. Mixing-combustion is combustion of gas fuel with non-reactive particles. 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 has little effect on the flame propagation of co-combustion for small scale flame. Further, in PMMA particle cloud/ammonia co-combustion, the same turbulent flame propagation phenomenon with pulverized coal particle cloud/ammonia co-combustion was 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. Besides, to clarify the effect of particles size on turbulent flame propagation of solid particle

cloud/ammonia/oxidizer co-combustion, the co-combustion experiments were conducted by using the different size of quasi-monodispersed polymethylmethacrylate (PMMA) particles through changing the ammonia equivalence ratio from 0 to 1.6. It was found that decreasing the particles size advances the co-combustion maximum turbulent flame propagation velocity to ammonia leaner side. Moreover, it was found that decreasing the particles size can largely increase the turbulent flame propagation velocity in ammonia lean cases, where it can slightly decrease the turbulent flame propagation velocity in ammonia-rich cases. Through the CHEMKIN simulation, it was confirmed that, in co-combustion, decreasing the particles size increases the amount of volatile matter devolatilized from the particles. The chemical reaction of the MMA/ammonia/oxygen/nitrogen mixture affects the co-combustion turbulent flame propagation.

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

Keywords: Solid particle cloud/ammonia co-combustion; Turbulent flame propagation; Ammonia combustion; solid particle cloud combustion; Particle size effect; Particle concentration effect

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Nomenclature

c_p	Specific heat at constant pressure, [J/kg/K]
D	Mass diffusivity, m ² /s
D_{M-P}	Turbulent flame propagation velocity difference between mixing different size and pure large particles in pure PMMA particle cloud combustion, m/s
E_a	Activation energy, kJ/mol
F	Mole of fuel, mole
f_s	Fan rotation speed, rpm
g	Acceleration of gravity, m/s ²
Ka	Turbulence Karlovitz number, -
L_f	Longitudinal integral length scale, mm
L_b	Burned gas Markstein length, mm
Le	Lewis number ($=\alpha/D$), -
Le_{eff}	Effective Lewis number, -
Ma	Markstein number, -
O	Mole of oxidizer, mole
r_{sch}	Flame radius calculated by the flame area method, m
R_0	Universal gas constant, J/(K·mol)
R_C	Difference of luminous flame propagation velocity between pulverized coal/ammonia co-combustion and pure coal combustion relative to the luminous flame propagation velocity of pure coal combustion, -
R_{A-C}	Difference of propagation velocity between ammonia/oxygen/nitrogen flame and pure coal flame relative to the propagation velocity of pure

	coal combustion, -
R_R	Difference of propagation velocity between pulverized coal/ammonia co-combustion and pure ammonia combustion relative to the propagation velocity of pure ammonia combustion, -
R	Difference of propagation velocity of silica particle cloud/gas fuel mixing-combustion and pure gas fuel combustion relative to the propagation velocity of pure gas fuel combustion, -
R_p	Difference of propagation velocity of PMMA particle cloud/gas fuel co-combustion and pure gas fuel combustion relative to the propagation velocity of pure gas fuel combustion, -
S_n	Flame propagation velocity, m/s
S_s	Unstretched laminar flame propagation velocity, m/s
S_{ws}	Turbulent flame propagation velocity under mixing different size of PMMA particles in pure PMMA particle cloud combustion, m/s
S_{wos}	Turbulent flame propagation velocity of pure large PMMA particles, m/s
S_{LCO}	Luminous flame propagation velocity in pulverized coal particle cloud/ammonia co-combustion, m/s
S_{LC}	Luminous flame propagation velocity of pure coal combustion, m/s
S_A	Turbulent flame propagation velocity of ammonia/oxygen/nitrogen flame, m/s
S_R	Reaction front turbulent flame propagation velocity in pulverized coal/ammonia co-combustion, m/s
S_{Mix}	Turbulent flame propagation velocity in the silica particle cloud/gas fuel mixing-combustion, m/s
S_{CO}	Turbulent flame propagation velocity in PMMA particle cloud/ammonia/oxygen/nitrogen co-combustion, m/s
t	Time, s
T_b	Temperature in burned mixture, K

T_u	Temperature in unburned mixture, K
T_{ad}	Adiabatic flame temperature, K
u'	Turbulence intensity, m/s
U_L	Unstretched laminar burning velocity, m/s
U_N	Stretched laminar burning velocity, m/s
U_{tr}	Turbulent burning velocity, m/s
Ze	Zel'dovich number, -

Greek Symbols

ε	Flame stretch rate, 1/s
λ	Thermal conductivity, W/m/K
α	Thermal diffusivity, m ² /s
δ_F	Flame thickness, mm
ν	Kinematic viscosity, m ² /s
ρ	Density, kg/m ³
ρ_b	Density in burned mixture, kg/m ³
ρ_u	Density in unburned mixture, kg/m ³
ϕ	Equivalence ratio
Ω	Oxygen concentration in oxidizer
ϕ_{Ammonia}	Ammonia/oxygen/nitrogen equivalence ratio in co-combustion

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Chapter 1. Introduction

1.1. Research background

To strength the global response to the urgent threat of climate changes, the Paris Agreement on climate change was adopted at Conference of Parties 21. The goal of Paris Agreement is to hold the increase in the global average temperature to well below 2 °C above pre-industrial levels, preferably to below 1.5 °C. To curb the risks and impacts of climate change, the reduction of carbon dioxide (CO₂) emission is a critical issue for humankind because CO₂ is the greenhouse gas (GHG) causing the largest impact on our climate by creating a greenhouse effect. Therefore, most countries have set their own emissions reduction goals. In Japan, the government set its targeted GHG emission reduction goals to be carbon-neutral by fiscal year 2050 as its long-term goal.

To achieve the low emission goal, most countries has promoted the development of renewable and sustainable energy sources. However, most of the renewable energy sources, such as solar, wind, and tidal, typically have the intermittent properties. Therefore, the energy storage, such as battery and chemical storage, is necessary to cushion the effects of fluctuation in the energy production. Further, compared with the batteries, the chemical storage is more economical [1]. Hydrogen, which can be produced renewably from the green energy sources via the electrolysis of water, is one of the most promising energy carriers. However, its economic storage and shipment challenge the sustainable utilization. Therefore, the research and development of energy carriers and alternatives for hydrogen storage have attracted much attentions[1]. Fig. 1.1 shows various ways for producing, transporting and using hydrogen.

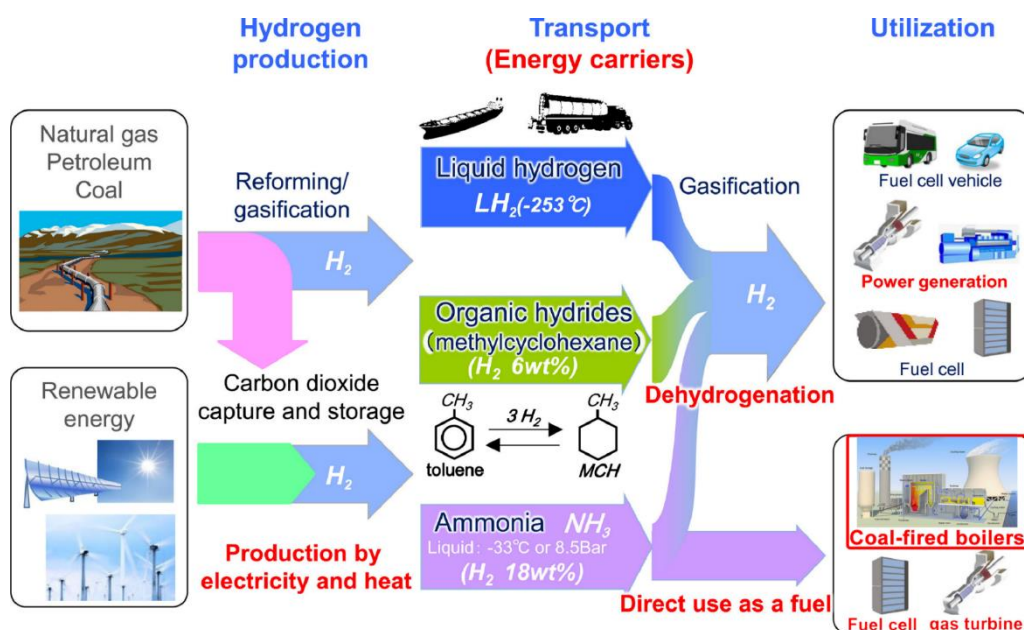


Fig. 1.1. various ways for producing, transporting and using hydrogen (Modify from [1]).

Ammonia is considered to be one of the most-promising hydrogen-energy-carrier candidates and is an independent alternative to hydrocarbon-based fuels [2]. The combustion of ammonia does not release CO_2 , SO_x and soot [3–5]. Moreover, ammonia can be synthesized from renewable hydrogen and nitrogen separated from air [6]. Since the thermal properties of ammonia are similar to those of propane in terms of boiling temperature and liquefaction pressure, it is economical to be stored in large quantities and transported in liquid-form [1]. Therefore, at present, the ammonia combustion research has been raised much attentions in combustion community [1,7–10]. However, there remains some major challenges to be overcome for directly using ammonia as a fuel, such as high auto-ignition temperature (903 K), narrow flammability range, high NO_x emission, and slow laminar burning velocity, which make it difficult to use in various energy devices. Fig. 1.2 shows the ammonia/air flame with the buoyancy effect.

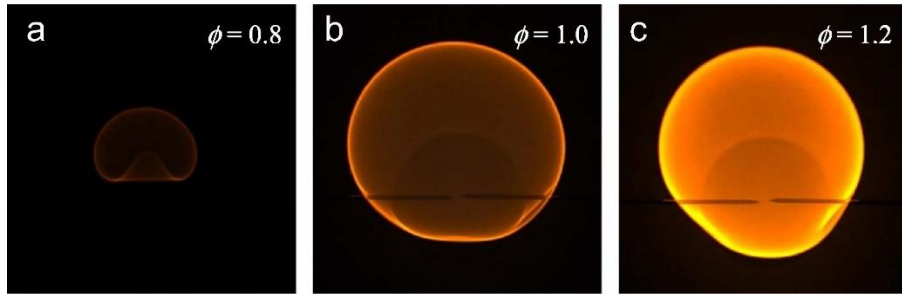


Fig. 1.2. Ammonia/air premixed flames [7].

Further, in fact, around 30% of the world's primary energy is supplied by the coal-fired power generation because coal involves the lowest geopolitical risk and has the lowest price per unit of heat energy among fossil fuels [11]. In China, coal made up 57.7 % of the energy use. Even though coal is internationally recognized as an essential energy source, the combustion of coal in coal-fired power plants causes large amount of GHG emissions, which challenges the GHG emission reduction goals. However, in a short term, it is impossible to completely replace the coal with other fuels. Therefore, from the viewpoint to step into a carbon-free society, the use of ammonia in coal-fired boilers for co-combustion is considered an efficient and feasible method to reduce CO₂ emissions [11–16]. It was suggested by researchers that decreasing CO₂ and NO emissions in coal-fired boilers could be realized by pulverized coal/ammonia/oxidizer co-combustion [11,14]. Besides, for high-fuel-ratio coals, the pulverized coal particle cloud/ammonia/oxidizer co-combustion can enhance the flame stability [16]. Therefore, the pulverized coal particle cloud/ammonia co-combustion has immense potential and is one of the most promising way to step into a carbon-free society.

Further, for power generation from other solid particle fuels such as solid wastes and biomass, co-combustion can facilitate a carbon neutral society. Therefore, it is essential to investigate the solid particle cloud/ammonia/oxygen/nitrogen co-combustion characteristics and mechanism. Fig. 1.3 shows the basic concept of utilization of ammonia in thermal power plant.

Besides, flame propagation velocity is a basic physical quantity for evaluating the flame stabilization performance [17]. In a coal-fired boiler, flame propagation velocity is an essential physical value to characterize the flame instability in the burner [18]. Further, burning velocity is used to characterize many combustion behaviors as it contains much physicochemical information [19].

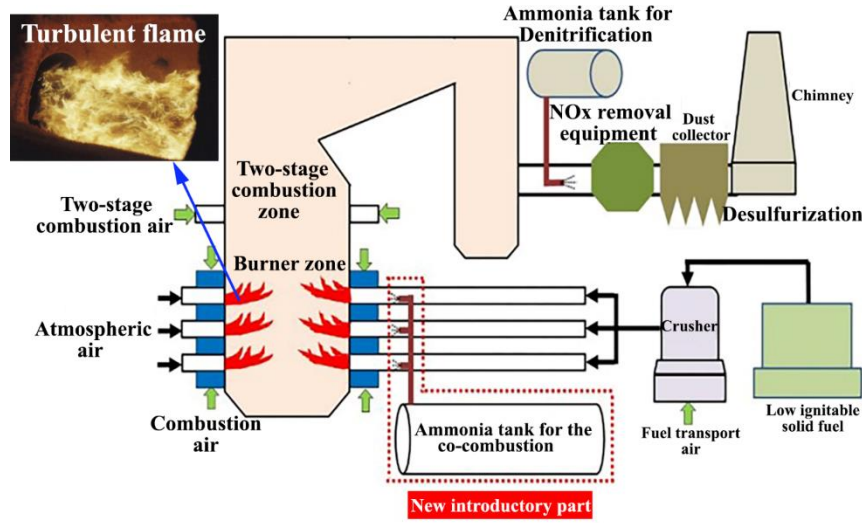


Fig. 1.3. Concept of application ammonia in thermal power plant [20].

In addition, in a real burner, the turbulent environment is used. The turbulent flame is important for the practical use of fuels in combustors. Under turbulent vortices, the flame front is wrinkled, and the flame surface area increases. Turbulence also induces strong, unsteady velocity gradients, which modify the local transport of reactants and lead to local flame structures that

depart significantly from the generic one-dimensional flame structures [21]. Thus, a turbulent flame characteristically burns faster than a laminar one.

Therefore, for the application of ammonia in the thermal-power plant, it is essential to investigate the solid particle cloud/ammonia co-combustion turbulent flame propagation behaviors and mechanism. Before giving a deep understanding of the co-combustion turbulent flame propagation behavior and mechanism, the fundamental turbulent flame propagation behavior and mechanism of pure ammonia combustion and pure solid particle cloud combustion were reviewed.

1.2. Turbulent flame propagation of solid particle cloud

The combustion of solid particle clouds, such as pulverized coal, biomass, and metal, has been extensively used in many engineering areas, such as energy generation and propulsion systems. The combustion characteristics of solid particle cloud have been studied under a laminar condition, such as flame structure [22], flame propagation speed [18,23–27], flammability limit [28–30], quenching distance [31,32]. From a practical perspective, almost all the combustion of solid particle cloud is utilized under a turbulent environment. However, studies concerning the combustion of the turbulent solid particle cloud have remained limited. Three major problems exist regarding the turbulent combustion of solid particle clouds [33]. The first one is the complexity of the combustion process. Under particle cloud combustion, the particles undergo the process of heat-up, pyrolysis or devolatilization, mixing with an oxidizer, ignition and combustion. Second, interactions between particles differ due to particle size, shape, size distribution, and fuel type. Third, if the solid particle combustion occurs in a turbulent

environment, turbulence affects heat and mass transfer and flame shape [15,34]. Besides, turbulence can accelerate particle motion to enhance particle–particle interactions. Consequently, the combustion process of solid particle clouds in the turbulent environment is complicated.

Therefore, a few studies have been conducted to investigate on the combustion of solid particle clouds in the turbulent environment, such as minimum ignition energy (MIE) [35,36], pressure [37], and particle burning time [38]. Because the combustion of solid particle clouds is affected by the physical and chemical properties of the particles and combustion circumstances such as the oxidizer concentration, gravitation and atmospheric temperature, the flame propagation velocity becomes important to characterize the combustion of solid particle clouds.

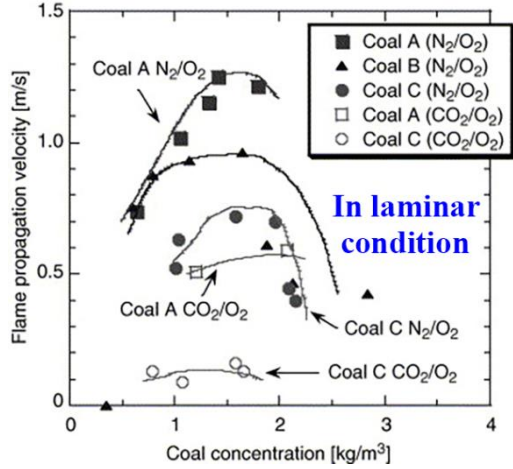
Further, as discussed above, there are three main factors that affect the turbulent flame propagation characteristics and mechanism of solid particle cloud, including the particle combustion characteristics, particle–particle interaction, and the turbulence effect.

First, the flame propagation of the particle cloud is affected by the combustion characteristics of particles (The discussed particles are the general used particles in the energy generation system, such as the coal particle, biomass particle, and solid waste particles). The flame propagation through particle cloud involving devolatilization followed by the combustion of gas phase [39]. Therefore, the devolatilization rate of particles, amount of volatile matter released by particles, and composition of the volatile mater affect flame propagation characteristics of the solid particle cloud.

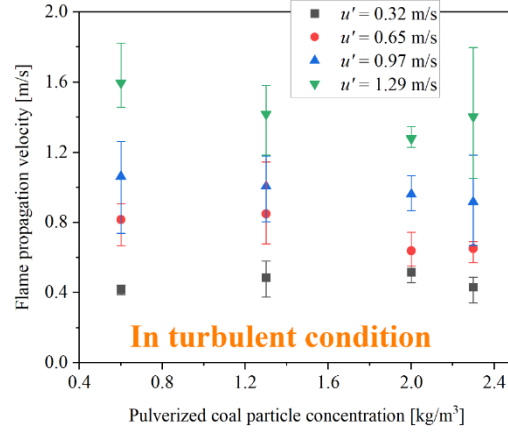
As clarified in the laminar condition, the particle size strongly affects the flame propagation of particle cloud due to the vast change in the specific surface area [26]. For small size particles, the particles can be devolatilized in a short period. Therefore, the flame propagates faster for the small size particles. Various studies have been conducted to study the particle size effect on

particle cloud flame propagation in a laminar condition [40–42]. However, most of previous research used the polydispersed particle cloud as the research particles. In polydispersed particles, the small–large particle interaction affects the flame propagation phenomenon [43]. Furthermore, the quasi-monodispersed particle size effect on flame propagation in a near-homogeneous turbulent flow field has not been studied.

The particle concentration affects the flame propagation of solid particle cloud. As shown Fig. 1.4, in a laminar condition in which there is no natural convection and buoyancy effect, the flame propagation velocity of particle cloud first increases, and then decreases with the increase of the particle concentration. As suggested by Suda et al. [18], in a quiescent condition, the flame propagation velocity of particle cloud is mainly controlled by the heat conduction between gas and particles and radiation between particles. Therefore, the distance between particles plays a key role in the flame propagation. Accordingly, the particle concentration dominates the flame propagation phenomenon in a quiescent condition. However, in a turbulent condition, as suggested by Hadi et al. [34], the turbulent flame propagation of particle cloud is dominated by the turbulent heat and mass transfer. The radiation between particles has little effect on the turbulent flame propagation for small-scale flame. Therefore, the concentration has little effect on the flame propagation in a turbulent environment. However, this conclusion was obtained by using polydispersed coal particle cloud. In the combustion of polydispersed particle clouds, some interactions between small and large particles affect the turbulent flame propagation [43]. Therefore, the quasi-monodispersed particle cloud is expected to validate above conclusion.



(a) Flame propagation velocity as coal particle clouds concentration in the laminar condition (Microgravity environment) [18]



(b) Flame propagation velocity as coal particle clouds concentration in the turbulent condition [34]

Fig. 1.4. Flame propagation in quiescent and turbulent conditions.

Different material particles have different combustion characteristics. After the particles being heated to elevated temperature, the particles release the volatile matter. The composition of the volatile matter is different under different heating rate and particle material [44]. For coal particles, the combustion of coal is occurring in several steps. First, the coal is heated at high rates, and rapid devolatilization occurs. The volatile matter then reacts in the gas phase. The char remaining after devolatilization consists of carbon, together with a major part of ash component and some volatile matter. The heterogeneous reactions of the char with oxidizing gases account for the most of time required for particle burnout [44]. Generally, as discussed above, the flame propagation of solid particles is mainly controlled by the volatile matter. However, for the effect of heterogeneous reaction of char on the turbulent flame propagation velocity of solid particle cloud remains unknown.

Second, particle–particle interaction affects the flame propagation and combustion characteristics of solid particle cloud. From an actual properspective, most of particles used in the

engineering area have the polydispersed characteristics and are in micron-size or nano-size level. Therefore, most of cloud consist of particles in a wide range of sizes. As suggested by Green and Lane [43,45], the more the dust particles in a dust cloud deviate from mono-dispersity, the faster the cloud coagulates. After the particle being dispersed into a turbulent flow, the turbulent eddies cause the particle motion. The particle motion can cause two kinds of the particle-particle interactions: collision and contact [46]. Collision is a kind of contact within short time period. Under the turbulent particle-particle interaction, the particles tend to stick together to cause the agglomeration when the particles collide with each other. During the process of the collision and deformation of the two particles, the energy is dissipated. If the impact kinetic energy is smaller than the dissipated energy, the particles will agglomerate together to form the large agglomerate. If the energy dissipated is smaller than the impact energy, the available energy will cause the particle rebound [46]. The adhesion of particles to another particles is caused by inter-particle forces due to the wetness of particles surface, electrostatic charges, and the van der Waals' forces [43][46]. However, limit works have been done to clarify the particle–particle interaction effect on combustion characteristics. The effect of agglomeration has been studied for metal combustion and soot formation [47–54]. In solid particle cloud combustion such as coal particles, biomass particles, and plastic particles, many researchers has emphasized the importance of consideration of the agglomeration effect on combustion [43,55–57]. However, the fundamental turbulent flame propagation mechanism of solid particle clouds associated with the particle–particle interactions remains unknown in combustion field.

Third, in a turbulent environment, the turbulence intensity strongly affects the turbulent flame propagation of solid particle cloud. Kauffman et al. and Pu et al. [58–60] reported the quantitative effect of turbulence on the premixed dust/air flame under various turbulence

intensities and particle sizes and concentrations through the dispersion-induced nonstationary turbulence method. Schneider et al. [61] the relationship between the turbulent burning velocity and the turbulence intensity by the open-tube method with the dispersion-induced turbulence. Most recently, Zhang et al. [62] studied the turbulent intensity effect on the nano-PMMA flame propagation behavior by the dispersion induced turbulence method. However, most of solid particle cloud combustion research groups in the world employ the dispersion-induced turbulence method to study the turbulent flame propagation phenomenon of solid particle cloud and the homogeneous turbulence cannot be sustained by using this method. To sustain the uniform turbulence intensity during the solid particle combustion, our research group [9,15,16,34,63,64] developed a unique turbulence combustion apparatus for solid particle clouds. The near-homogeneous turbulence and uniform dispersion can be obtained using their combustion apparatus.

1.3. Turbulent burning characteristics of ammonia flame

Ammonia is considered a promising hydrogen-energy-carrier and a carbon-free fuel. However, the low combustion intensity of the ammonia/air flame restricts its application in various combustion facilities. Therefore, the ammonia/air flame enhancement is important for its application as a fuel. Various methods have been proposed to enhance ammonia combustion. Hydrogen addition is a reasonable way of achieving environmentally friendly flame enhancement. The relationship between laminar burning velocity and hydrogen fraction in an ammonia/hydrogen binary fuel was revealed by Ichikawa et al. [8], Lee et al. [5], Li et al. [65] and Kumar et al.[66]. In addition, blending hydrocarbon fuels with ammonia is also important

from the perspective of reducing greenhouse-gas emissions. Henshaw et al. [67] and Okafor et al. [10] measured the CH_4/NH_3 mixture laminar burning velocity. Besides, ammonia combustion under conditions of O_2 enrichment is also a promising way to enhance ammonia combustion due to the thermal enhancement without changing the dominant chemistry. Such O_2 -enriched combustion enhances ammonia laminar burning velocity, a positive effect previously verified by Takeishi et al.[68], Li et al. [2] and Mei et al.[69] .

As reviewed above, laminar burning velocity is one of the most important parameters for characterizing ammonia combustion behavior as it contains much physicochemical information. It also is a reference parameter for many premixture flame phenomena, such as extinction, flashback, blow off, and turbulent flame propagation [19].

However, because of the weak intensity of premixed ammonia/air flames and corresponding ease of being extinguished, which are due to their low laminar burning velocity [70], most prior ammonia turbulent combustion research focused on the stabilization of ammonia flames [9,71–73], while no research was conducted to reveal the fundamental turbulent burning behavior of ammonia flame. Therefore, the fundamental turbulent burning characteristics of ammonia flame remains unknown. To give a better understanding of the turbulent flame propagation mechanism of pure ammonia combustion, the oxygen enriched environment is used to prevent the flame extinction in a turbulent environment.

1.4. Turbulent flame propagation characteristics of solid particle cloud/ammonia co-combustion

In pure solid particle cloud turbulent combustion, the individual particle combustion follows the sequential process of heat-up, devolatilization, volatile matter release and mixing with oxidizer, ignition, and combustion. However, in pure premixed-gas combustion, after the premixed gases being ignited, there is no phase transfer for sustaining of the combustion reaction. Therefore, generally, the burning velocity of gaseous fuel is faster than that of solid particles. If co-combustion gas-fuel with solid particles, there are some interactions between gas-fuel and solid particles combustion. On the one hand, the premixed gas combustion affects the combustion of solid particles. If the flame propagation velocity of premixed-gas combustion is much larger than that of solid particle cloud, the solid particles can be directly preheated by the premixed gas flame to enhance the ignition probability and the flame stabilization. Hadi et al. suggested that ammonia flame can enhance the ignition performance and flame stability of the high fuel ratio coals which is generally not used in the thermal power plant. On the other hand, particles affect the combustion behavior of the premixed gas. First, particles will absorb the heat from the flame [74–79]. Second, as suggested by Taniguchi et al. [28], the pyrolysis rate and amount of volatile matter affected the flame instability in solid particle cloud combustion. Therefore, in co-combustion, the volatile matter combustion will affect the flame propagation of the gas fuel.

Besides, two-phase hybrid mixtures of combustible solid particles and flammable gas can be found in many industries such as mining (coal and methane), nuclear (graphite and hydrogen), pharmaceutical (pharmaceutical dust and solvent vapor), textile manufacturing (fiber and fiber vapor), and general manufacturing (organic dust and volatiles). Most of prior research on solid particle cloud/gas hybrid mixture co-combustion was conducted to clarify the explosion characteristics for the safety purpose. Two key pressure-related values have been studied to

describe the explosion severity of hybrid-mixture co-combustion, namely, the maximum pressure and maximum pressure rise rate. Denkevits et al. [80] studied the effect of the addition of graphite dust to a flammable mixture of hydrogen. It was found that the maximum pressure of the hybrid mixture is higher than that derived from pure hydrogen combustion and pure graphite combustion. Dufaud et al. and Amyotte et al. [81–83] suggested that the deflagration index for hybrid mixture is higher than those of the pure gas or pure solid particle cloud. Jiang et al. [84] suggested that the hybrid mixtures can be flammable when concentration of each fuel is below its lean flammability limit. To visualize the coal dust/methane flame, Liu et al. [85] develop a schlieren optical system. They found that co-presence of coal dust and methane improves the flame propagation speed and maximum flame temperature notably, which become much higher than that of the single-coal dust flame. A.S. Rangwala et al. developed a Hybrid Flame Analyzer (HFA) to measure burning velocity of gas, dust, and hybrid (gas and dust) premixed flames [86,87]. However, even though the hybrid mixture co-combustion characteristics have been studied for many years, the fundamental turbulent flame propagation mechanism remains unknown in combustion field.

1.5. Objectives of the present study and structure of the dissertation

To investigate the turbulent flame propagation characteristics and mechanism of the solid particle cloud/ammonia/oxidizer co-combustion, the experiments on pure solid particle cloud turbulent flame propagation and pure ammonia/oxidizer turbulent flame propagation were first conducted. The turbulent flame propagation mechanisms of pure solid particle cloud and pure

ammonia/oxidizer were proposed respectively. Based on above two mechanisms, the solid particle cloud/ammonia co-combustion experiments were conducted. The results were compared with the results obtained in pure ammonia combustion and pure particle cloud combustion. Based on the difference, the turbulent flame propagation mechanism of solid particle cloud/ammonia co-combustion was proposed. Further, to validate the proposed mechanism, the silica particle cloud/ammonia/oxidizer mixing-combustion, silica particle cloud/acetylene/air mixing-combustion, and PMMA particle cloud/ammonia/oxidizer co-combustion experiments were conducted. In summary, the objectives of the present research can be divided into the following four aspects.

1. Clarification of turbulent flame propagation and turbulent burning characteristics of pure ammonia/oxidizer premixed flame.
2. Clarification of turbulent flame propagation characteristics and mechanism of solid particle cloud.
3. Clarification of turbulent flame characteristics and mechanism of the solid particle cloud/ammonia co-combustion.
4. Validation of the turbulent flame propagation mechanism of co-combustion.

The dissertation includes seven chapters. Part of the work in the dissertation was published in peer-reviewed journals.

Chapter 1 summarized the existing research on pure solid particle cloud combustion, pure ammonia combustion, and solid particle cloud/gas hybrid mixture co-combustion. From perspective of the energy generation and safety issue, the turbulent flame propagation property

and mechanism of the solid particle cloud/gas hybrid-mixture co-combustion is essential to be clarified.

Chapter 2 introduced the designed turbulent combustion chamber. The unique turbulent combustion chamber consisted of a constant-volume combustion chamber, a capacitor discharge ignition circuit ignition system, a pressure recording system, and the high-speed photography system. Besides, the experimental conditions and procedures for pure ammonia turbulent combustion, pure solid particle cloud turbulent combustion, solid particle cloud/ammonia co-combustion, and silica particle cloud/gas-fuel mixing combustion were represented separately.

Chapter 3 discussed the turbulent flame propagation velocity and turbulent burning velocity of ammonia flame in an oxygen enriched environment. Because of the weak intensity of the ammonia flame, the turbulent characteristics of the ammonia flame was studied under an oxygen enriched environment. The turbulent flame structure of ammonia flame was studied. The laminar and turbulent burning characteristics were compared to understand the factors affecting the turbulent flame propagation of pure ammonia combustion.

Chapter 4 discussed the experimental result of turbulent flame propagation of pure solid particle cloud combustion. Turbulent flame propagation characteristics and mechanisms of two types of particle cloud were clarified: quasi-monodispersed particle cloud and mixing different size quasi-monodispersed particle cloud. For quasi-monodispersed particle cloud, the particle size and concentration effect on turbulent flame propagation were discussed. For mixing different size quasi-monodispersed particle cloud, the effects of turbulence, particle size difference, and small particle mass ratio were discussed.

Chapter 5 discussed the ammonia/oxygen/nitrogen equivalence ratio effect on pulverized coal/ammonia/oxygen/nitrogen co-combustion turbulent flame propagation. The flame

propagation velocity of pulverized coal/ammonia co-combustion was compared with those of pure coal combustion and pure ammonia combustion. The turbulent flame propagation mechanism of pulverized coal/ammonia co-combustion was derived from the comparison. Three types of factors were proposed to explain the difference between co-combustion and pure coal or pure ammonia combustion.

Chapter 6 summarize the experimental results obtained by the silica particle cloud/ammonia mixing-combustion, silica particle cloud/acetylene/air mixing-combustion, and PMMA particle cloud/ammonia co-combustion. Three types of factors for affecting the co-combustion turbulent flame propagation mechanism were furtherly discussed and validated.

Chapter 7 summarized the conclusions obtained by pure ammonia turbulent combustion, pure solid particle cloud turbulent combustion, pulverized coal particle cloud/ammonia co-combustion, silica particle cloud/ammonia mixing-combustion, silica particle cloud/acetylene mixing co-combustion, and PMMA particle cloud/ammonia co-combustion.

Based on the experimental works of present research, the fundamental turbulent flame propagation mechanism of solid particle cloud/ammonia/oxidizer co-combustion was clearly clarified.

Chapter 2. Experimental Approach

2.1. Experimental Apparatus

To investigate the turbulent flame propagation characteristics of pure ammonia combustion, pure solid particle cloud combustion, solid particle cloud/ammonia co-combustion, and silica particle cloud/gas-fuel mixing-combustion, a high-speed observation system that enabled detailed observation of turbulent flame propagation and pressure history was developed. The developed experimental apparatus for turbulent combustion consisted of a constant-volume combustion chamber, a capacitor discharge ignition (CDI) circuit ignition system, a pressure recording system, and the high-speed photography system. The schematic of the experimental setup can be seen in Fig. 2.1.

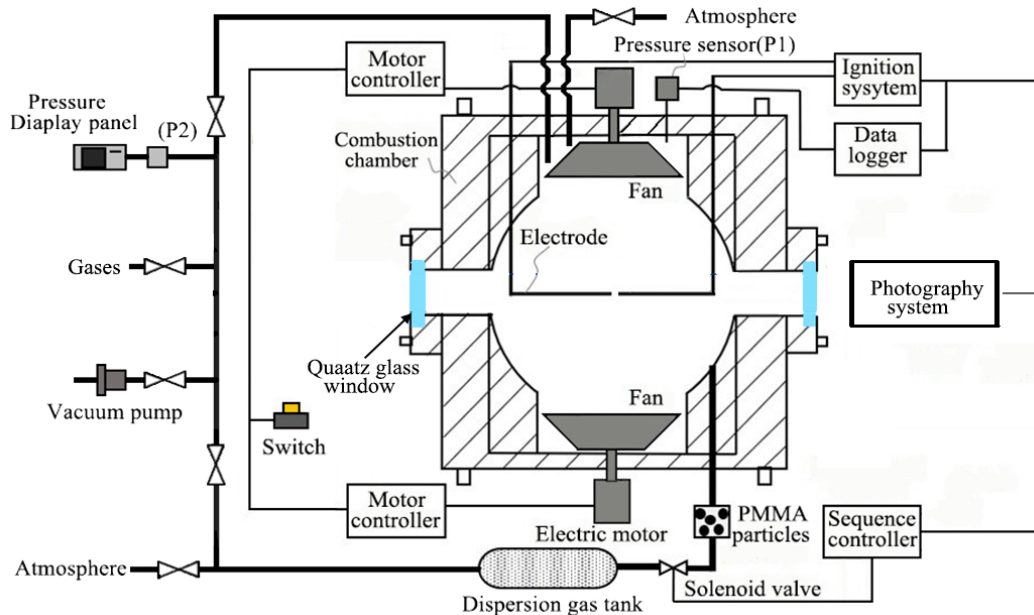


Fig. 2.1. Schematic of the experimental setup.

As shown in Fig. 2.1, the inner chamber was designed based on a 200-mm diameter sphere. Taking consideration of the space of the two fans, the cylindrical-shaped chamber was designed. The distance between floor and ceiling of chamber is 280 mm. The total volume of the chamber is $6.19 \times 10^{-3} \text{ m}^3$. For the observation of the turbulent flame propagation, four optical-quartz glass windows were installed opposite each other in the chamber. The top cover was designed as a lid for the purpose of easily cleaning the inner of the chamber. The pressure sensor and thermocouple were mounted inner of the top cover for the detection of the pressure and temperature inside of the chamber. The gas inlet and exhaust line were crossing the top cover for the purpose of supply the fresh gases and exhaust the burned gases.

A spark ignitor composed of two 1.8-mm-diam stainless-steel electrodes was employed to ignite the mixture in present research. The gap between the two electrodes' sharp tips was set to 2.0 mm [9,34]. As shown in Fig. 2.2, a capacitor discharge ignition (CDI) circuit system was connected to the spark electrode assembly to ignite the mixture. A series of capacitors with a total capacitance of 50 μF was charged by 469 V direct current in the CDI circuit. The charged-voltage error was within $\pm 1.5\%$. The ignition energy was set as 5.5 J [15,16,34]. It should be noted that, for a better visual observation of the combustion phenomenon, the electrodes were mounted with a 45° angle corresponding to the interrogation path.

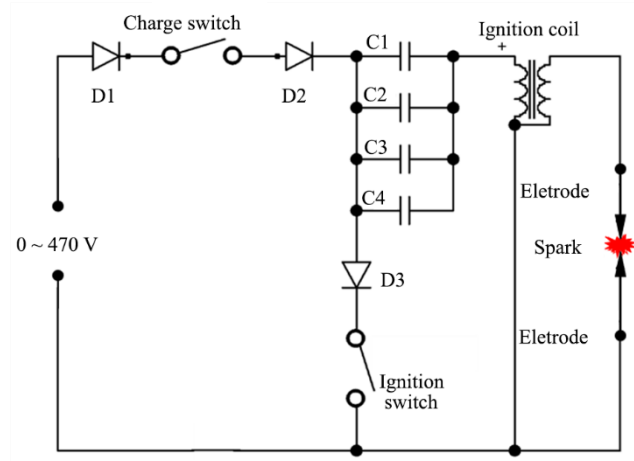


Fig. 2.2. Schematic of CDI circuit embedded in the spark ignition system.

Turbulence was generated by two identical counter-rotation seven-bladed fans mounted vertically and symmetrically in top and bottom of the chamber. Each fan, which was rotated by directly coupled electric motors (Maxon Motor, RE50) with separate speed controllers (Maxon Motor, ESCON 50/5), can be precisely adjustable between 0 and 15,000 rpm. The fan rotation speed error was within ± 1 rpm. Turbulence characteristics were measured by particle image velocimetry (PIV) (which was detailed explained in previous research [9,34]). In PIV measurement, an oil mist with 1- μm -sized particles was used as the particle tracing seed. Various scales of turbulent eddies exist in a turbulent field. A small measurement field through an 8 mm window with a 7 μm pixel size in the flow for high resolution; and a larger field through a 60 mm window with a 54 μm pixel size in the flow. The analysis window was set to 32×32 pixels with a 50% overlap for both measurement fields. Four kinds of fan speed were used to carry out PIV experiments, including 500 rpm, 1000 rpm, 1500 rpm, and 2000 rpm. As a result of PIV measurement, the turbulence was found to be isotropic and homogeneous, and there was almost no regular bulk motion. As shown in Fig. 2.3, turbulence intensity, u' , which was proportional to

the fan speed [9,34,63], found to be represented by Eq. (2.1):

$$u' = 0.00129 f_s, \quad (2.1)$$

where f_s was the fan speed in rpm. The longitudinal integral length scale, L_f , determined by two-point correlation, was 20.9 mm regardless of the turbulence intensity [34].

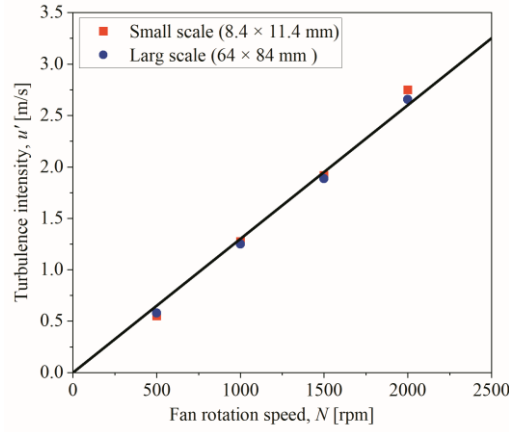


Fig. 2.3. Turbulence intensity as fan speed.

Fig. 2.4 shows the schematic of the particle dispersion system. Notably, the dispersion system was used for the solid particle cloud turbulent combustion, co-combustion, and mixing combustion experiments. For pure ammonia turbulent combustion experiments, the dispersion system was disabled. The dispersion system was used to disperse the particles into the center of the chamber. Four cup-shaped filters with 0.5 μm nominal pore sizes were adopted to load the particles before the dispersion. The inlet of filter was connected to the dispersion gas tank, and the outlet of filter was connected to the chamber. The start/stop of the gas dispersion flow were controlled by a solenoid valve (AB41-02 CKD). This configuration allowed the particles to be dispersed into the chamber via a 300 kPa dispersion gas within 0.7 s.

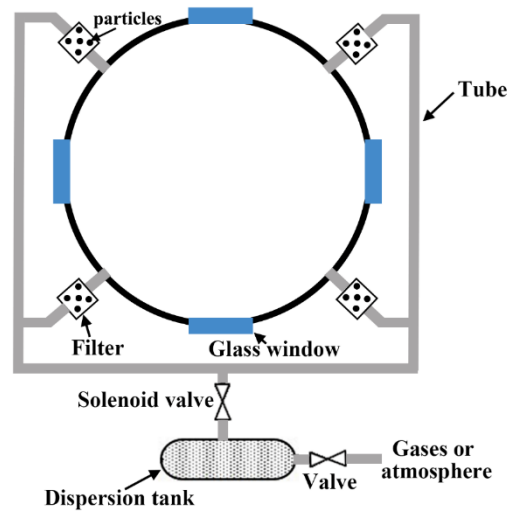


Fig. 2.4. Schematic of the particle dispersion system.

Three types of photography were used to capture the flame propagation: direct imaging, OH radical photography, and schlieren photography. The detailed setting of the three photography can be seen in Fig. 2.5. Schlieren photography, which can capture the position of high-density gradient caused by the rapid change in gas temperature, detects the preheat zone front of flame. The OH radical photography was used to capture the reaction front of flame. The OH radical photography detects the reaction front, which follows the preheat zone [15,16]. The direct imaging was used to capture the luminous flame. The luminous flame indicates the existence of high density of soot particles with high temperature.

Ammonia/air and ammonia/oxygen/nitrogen (diluted oxidizer: 40% oxygen with 60% nitrogen) mixtures were used to investigate the effect of dispersion flow on the turbulent flame propagation behavior [20]. Isolated experiments were performed on the quiescent mixtures, and mixtures with dispersion flow in the same procedure as PMMA particle combustion. The dispersion flow effect on the turbulent flame radius and propagation velocity can be seen in Fig.

A and Table. A in Appendix. Both ammonia/air and ammonia/oxygen/nitrogen mixtures showed that the dispersion flow does not influence the flame propagation behavior.

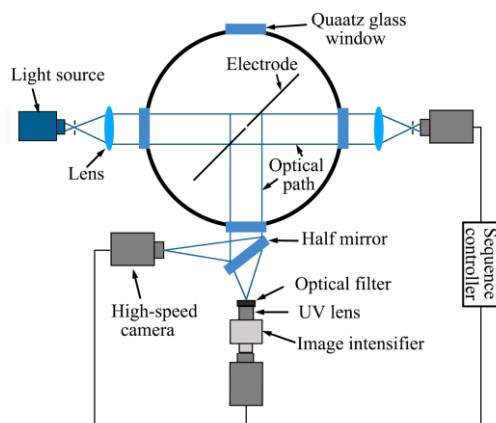


Fig. 2.5. Detailed setting of the three types of the photography.

Schlieren photography was taken by a high-speed camera (Phantom, Miro C210) with an LED light source (Hayashi-repic co., ltd., LA-HDF5010C). A pinhole was fixed in front of the light source to form the spotlight effect. The pixel resolution of the camera was set to 576×576 . Besides, a half mirror was adopted for simultaneously recording the direct image and OH radical image from the same window. The direct image was observed by a high-speed camera (MotionPro X4) with a lens (Nikon, AI Nikkor 50 mm f/1.2S), and the OH radical image was taken by a high-speed camera (Phantom, Miro C210) in combination with the image intensifier (Hamamatsu, c9548-03) with a UV lens (Hamamatsu, 50 mm f/3.5) and a 300 nm bandwidth filter (Edmund optics, 67884 (Y158-23)). To obtain high quality and enough images for analysis, the frame rates of the two high speed cameras was set as 2000 fps, and the pixels' settings for the direct camera and the OH radical photography were 512×512 and 896×896 , respectively.

For different experiments, different photography was used. For pure ammonia turbulent combustion, PMMA particle cloud/ammonia co-combustion, and silica particle cloud/gas mixing-combustion experiments, both three types of photography were enabled to obtain different image for processing. However, unfortunately, for the pulverized coal particle cloud/ammonia co-combustion, because of the strong light scattering by the polydispersed coal particles, the schlieren photography cannot capture any flame propagation images. Therefore, OH radical photography and direct imaging were used for capturing the flame propagation in pulverized coal particle cloud/ammonia co-combustion.

2.2. Experimental methodology for pure ammonia combustion

For pure ammonia/oxygen/nitrogen turbulent combustion experiments, the experimental conditions are summarized in Table 2.1. In all experiments, the initial pressure and temperature were 0.1 MPa and 298 K. The temperature variations of the mixtures were within ± 3 K. The turbulence intensity varied as 0–1.29 m/s. The composition of ammonia/oxygen/nitrogen mixture was defined by the equivalence ratio, ϕ , varied as 0.6–1.6, and was calculated on the basis of the ratio of ammonia to oxygen in the gas mixture [88] by Eq. (2.2):

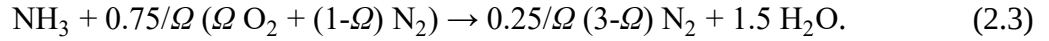
$$\phi = \frac{(O/F)_{stoic}}{O/F} = \frac{F/O}{(F/O)_{stoic}}, \quad (2.2)$$

where F represents mole of ammonia, and O represents mole of oxygen in the premixed gas mixture.

Table 2.1. Experimental conditions of ammonia/oxygen/nitrogen premixture combustion

Experiment type	Ω	Equivalence ratio, ϕ	Turbulence intensity, u' (m/s)
Laminar	0.35	0.6, 0.8, 0.9, 1.0, 1.1, 1.2, 1.4	-
	0.4	0.6, 0.8, 0.9, 1.0, 1.1, 1.2, 1.4, 1.6	
Turbulent	0.4		0.32, 0.65, 0.97, 1.29

The chemical equation for ammonia/oxygen/nitrogen combustion under stoichiometric condition is given by Eq. (2.3):



Ω is expressed by Eq. (2.4):

$$\Omega = \frac{X_{\text{O}_2}}{X_{\text{O}_2} + X_{\text{N}_2}}, \quad (2.4)$$

where X represents mole fraction. Taking consideration of the power density of ammonia flame and minimizing buoyancy effects [7,9,69], oxidizers with Ω of 0.35 and 0.4 were used for the research. Laminar experiments under $\Omega = 0.35$ were performed to verify the setup suitable for O₂-enriched ammonia combustion experiments through comparing with the results of Mei et al. [69]. Experiments on turbulent condition were carried out under $\Omega = 0.4$. The premixed gases had composition ratios based on their partial pressures, as measured with a pressure sensor (Valcom, VPRTF-A4-(-0.1–1MPa)-5, P2). The maximum errors of NH₃ concentration, O₂ concentration, and pressure inside the chamber were 1.5%, 1.5%, 5%, respectively. After filling the ammonia/oxygen/nitrogen mixtures in the chamber, an isotropic mixture was formed by running the top and bottom fans. In laminar experiments, the mixtures were ignited after 5

minutes of finishing stirring. For turbulence experiments, two fans were kept running during experiments. At least six experiments were performed for each condition to ensure repeatability of the results.

Fig. 2.6 shows the pressure history inside the combustion chamber for $\phi = 0.6$ and $\phi = 1.0$ at $u' = 1.23$ m/s. The observation time range differed depending on the equivalence ratio and turbulence intensity. For $\phi = 0.6$, the pressure was constant at ± 5 % of ambient pressure during the observation range (0–15 ms), whereas for $\phi = 1.0$, the observation range was lower because of the greater flame propagation velocity. Overall, there was no pressure rise in the chamber during the observation range for all conditions.

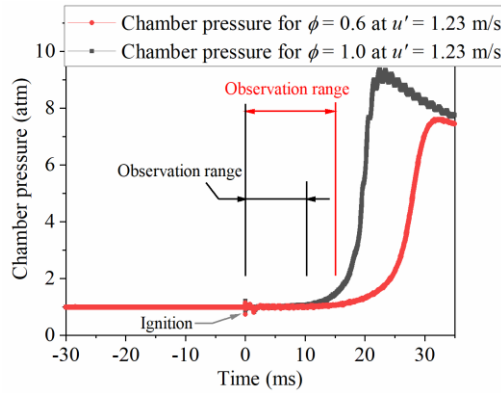


Fig. 2.6. Pressure history in chamber during combustion for $\phi = 0.6$ and 1.0 at $u' = 1.23$ m/s.

2.3. Experiment methodology for turbulent combustion of pure solid particle clouds

2.3.1. Particle properties

Four types of the quasi-monodispersed PMMA particles with diameters of 3, 10, 20 and 30 μm [89] were used. Fig. 2.7 (a–d) shows micrographs of different size PMMA particles obtained by the scanning electron microscopy (JSM-7001FA). Additionally, the size distribution of the particles was almost uniform. The particle size characteristic parameters can be seen in Table B in Appendix. As shown in Fig. 2.7, the spherical PMMA particles used in the present study have a narrow particle size distribution which can be treated as the quasi-monodispersed particles.

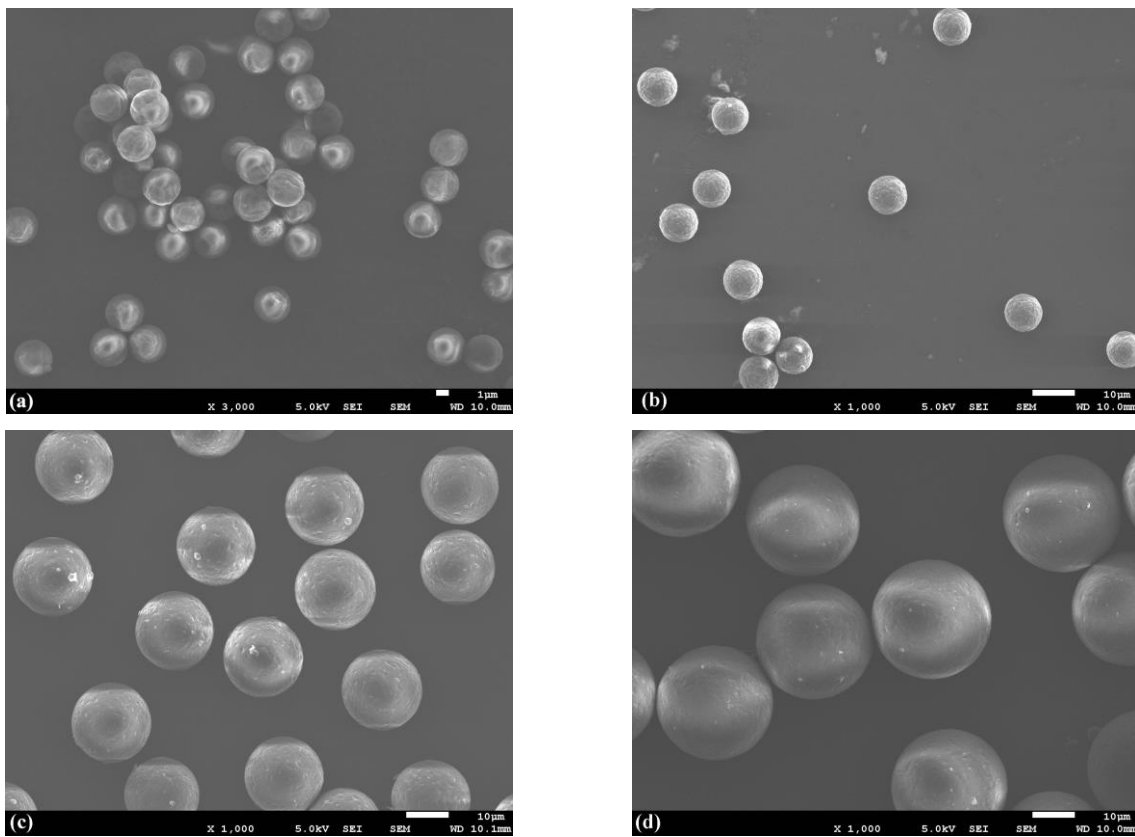


Fig. 2.7. Scanning electron microscopy (SEM) micrographs of the quasi-mono-dispersed particles; (a) the 3 μm particles (b) the 10 μm particles; (c) the 20 μm particles; (d) the 30 μm particles.

2.3.2. Experimental conditions and procedures

The particle concentration effect was studied by changing the PMMA particles concentration from 0.6 kg/m^3 to 2.3 kg/m^3 for the quasi-monodispersed particles with a diameter of $30 \text{ }\mu\text{m}$. To reveal the particle size effect, three types of quasi-monodispersed particles with diameters of 10 , 20 , and $30 \text{ }\mu\text{m}$ were used. However, for the $10\text{-}\mu\text{m}$ quasi-monodispersed particles, schlieren and OH photography cannot capture flame propagation images due to strong light scattering. Therefore, to clarify the quasi-monodispersed particle size effect on the flame propagation, the pressure histories for all conditions were recorded. The detailed experimental conditions can be seen in Table 2.2.

Table 2.2. Experimental conditions

Effect to be clarified	Experimental conditions		
	Particle diameter, μm	Particle concentration, kg/m^3	Mixing ratio
Particle concentration effect	30	0.6, 1.0, 1.3, 1.6, 2.0, 2.3	-
Particle size effect	30 or 20 or 10	0.6	-
Small-large particle interaction effect (mixing quasi-monodispersed particles with different sizes)	30 + 10	0.6, 1.0, 1.3	0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9 (Mass ratio of $10 \text{ }\mu\text{m}$)
	30 + 3	0.6	0.1, 0.2 (Mass ratio of $3 \text{ }\mu\text{m}$)
	20 + 10	0.6	0.1, 0.2, 0.3, 0.4 (Mass ratio of $10 \text{ }\mu\text{m}$)

A simplified polydispersed particle cloud was made by mixing two types of quasi-monodispersed particles to clarify the interparticle interaction effect on the combustion of solid particle clouds in the turbulent environment. Three particle mixtures were prepared, including the mixture of $10\text{-}\mu\text{m}$ quasi-monodispersed particles and $30\text{-}\mu\text{m}$ quasi-monodispersed particles, the mixture of $3\text{-}\mu\text{m}$ quasi-monodispersed particles and $30\text{-}\mu\text{m}$ quasi-monodispersed particles, and the mixture of $10\text{-}\mu\text{m}$ quasi-mono-dispersed particles and $20\text{-}\mu\text{m}$ quasi-monodispersed particles. To ensure the repeatability of the experiments for each condition, the total mass of the particle

clouds after mixing was constant at 100 g. For the mixing procedure, first, the mass of the small quasi-monodispersed particles and large quasi-monodispersed particles were measured by the electric scale (Mettler AJ150) based on the mass ratio. Subsequently, the quasi-monodispersed particles were loaded into a 1-L pillar-shaped bottle (Monotaro M1000L). Then, the bottle was shaken for about an hour.

To guarantee the reliability of the mixing method, SEM observations were conducted. As shown in Fig. 2.8, near-homogeneous mixing can be achieved through the mixing method. The detailed experimental conditions can be seen in Table 2.2.

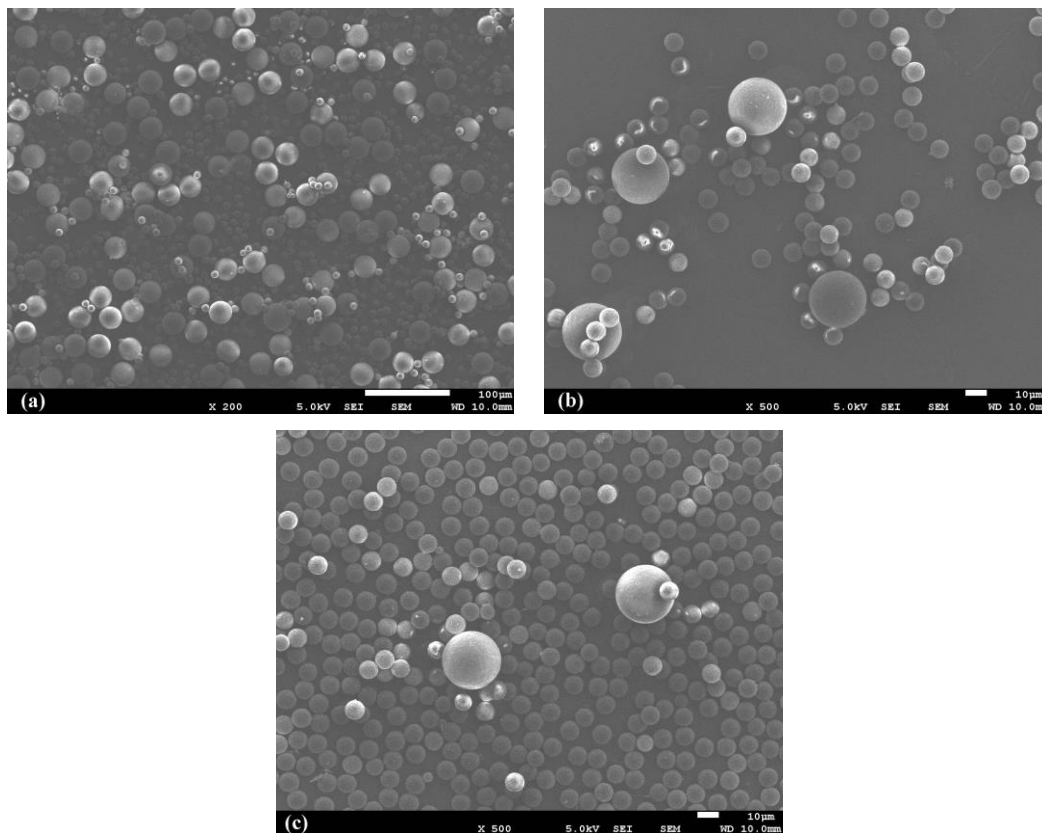


Fig. 2.8. SEM micrographs after mixing quasi-monodispersed particles with different diameters: (a) 80% 30-μm particles and 20% 10-μm particles; (b) 50% 30-μm particles and 50% 10-μm particles; (c) 20% 30-μm particles with 80% 10-μm particles.

As the first procedure of the experiments, the PMMA particles were equally filled into four filter cups connected to the inlets. Then, the combustion chamber and the dispersion tank were emptied to 0 kPa through a vacuum pump. Subsequently, the dispersion tank was filled with 40% O₂ and 60% N₂ at 300 kPa. Similarly, the gas mixture with the same composition was supplied into the chamber. However, the gas mixture in the chamber was set to 75 kPa to ignite the solid particle cloud/oxygen/nitrogen mixture at 101 kPa (atmosphere pressure) after dispersion. The dispersion gas swept the PMMA particles into the center of the spherical chamber within 0.7 s. 0.3 s after the dispersion ended, the mixture was ignited at atmosphere pressure [15,16,34]. The fans started to rotate for 5 min before dispersion to give the desired turbulence intensity. The initial temperature of the mixture for all experiments was constant at 293 ± 3 K. The maximum errors for the O₂ concentration, pressure, and particle concentration were 1%, 5%, and 3%, respectively. At least three experiments were conducted for each condition to ensure the reliability of the experimental data.

2.4. Experimental methodologies for solid particle cloud/gas co-combustion and silica particles/gas mixing-combustion

2.4.1 Solid particle fuel/ammonia co-combustion

Common bituminous pulverized coal with a mean particle size of 48 μ m was used for the pulverized coal particle cloud/ammonia co-combustion experiments, and its properties have been listed in Table 2.3 [34]. To conduct a comparison with previous coal combustion research, the same diluted oxygen gases, which comprised 40 vol% O₂ and 60 vol% N₂, were used.

Table 2.3. Analyzed properties of common bituminous coal

Analysis	Common bituminous coal
Proximate [wt %]	
Moisture ^b	0.7
Volatile matter ^a	33.5
Fixed carbon ^a	52.3
ash ^a	14.2
Ultimate [wt%,dry]	
Carbon	70.5
Hydrogen	4.64
Oxygen	8.59
Nitrogen	1.66
sulfur	0.46
LHV [MJ/kg]	27.8

^a Dry basis.^b As received

In case of co-combustion, ammonia and coal combustion simultaneously occurred in the chamber. The thermal heat input from co-combustion was kept the same as that with pure coal combustion, which was under a coal concentration of 0.6 kg/m^3 , by theoretically subtracting a portion of the coal particles' thermal heat input by ammonia combustion. Additionally, the total thermal heat input from co-combustion was 0.10325 MJ, which was calculated from the pure coal combustion by the lower heating value (LHV) of the bituminous coal of 27.8 MJ/kg. Table 2.4 shows the coal needed (by weight) in the mixing field on the condition of changing the ammonia equivalence ratio from 0.4 to 1.4. The same experimental procedure with the pure PMMA particle cloud turbulent combustion was used for the pulverized coal particle cloud/ammonia co-combustion experiments.

Table 2.4. Coal needed in the calculation in pulverized coal/ammonia co-combustion

Equivalence ratio of ammonia/oxygen/nitrogen in co-combustion filed	Thermal heat input from ammonia/oxygen/nitrogen combustion [MJ]	Coal needed [kg]
0.4	0.01539	0.00316
0.6	0.02122	0.00295
0.8	0.02618	0.00277
1.0	0.03045	0.00262
1.2	0.03416	0.00248
1.4	0.03742	0.00238

In the PMMA particle cloud/ammonia/oxygen/nitrogen co-combustion, the thermal heat input from the co-combustion was kept the same with that of the pure PMMA particle clouds combustion by subtracting a portion of the PMMA particles thermal heat input from the ammonia combustion theoretically.

Table 2.5 shows the PMMA particle clouds needed (by weight) in the co-combustion field under the condition of changing the ammonia equivalence ratio from 0 to 1.6. The total thermal heat input was calculated from the pure PMMA particle clouds combustion under a certain particles concentration by the lower heating value (LHV) of the PMMA particle which was 24.4 MJ/kg [90].

Table 2.5. Table PMMA particles mass needed in PMMA particles/ammonia co-combustion

Equivalence ratio of ammonia in the co-combustion filed	PMMA particles needed in the co-combustion filed under the PMMA particles' concentration of 0.6 kg/m ³ [g]
0	3.7140 (0.60)
0.2	3.3688 (0.54)
0.4	3.0843 (0.50)
0.6	2.8458 (0.46)
0.8	2.6429 (0.43)
1.0	2.4683 (0.40)
1.2	2.3163 (0.37)
1.4	2.1830 (0.35)
1.6	2.0650 (0.33)

() – Indicate the actual PMMA particles' concentration in the co-combustion filed under a certain PMMA particles' concentration, kg/m^3

To investigate the particle size effect on turbulent flame propagation behavior of PMMA particle cloud/ammonia co-combustion, the co-combustion experiments were conducted by changing the PMMA particle size from 30- μm to 10- μm .

2.4.2. Silica particle cloud/gas-fuel mixing-combustion

In silica particle cloud/ammonia/oxygen/nitrogen mixing-combustion experiments, to compare with the PMMA particle cloud/ammonia/oxygen/nitrogen co-combustion, the same mass of the silica particles as the PMMA particles was used under a same ammonia equivalence ratio. Notably, the silica particles with an average particles size of 46.08 μm used in present study had a polydispersed characteristic. The size distribution of silica particles was measured by Microtrac MT3000 particle size analyzer. The size distribution of silica particles can be seen in Table C, Fig. B, and Table D in Appendix.

Further, to investigate the radiation-positive effect from soot particles on co-combustion turbulent flame propagation and simultaneously eliminate the equivalence ratio increment effect induced by reactive particles, silica particle cloud/acetylene/air mixing-combustion and the pure acetylene/air combustion experiments were conducted. However, the mass of silica particles used in mixing-combustion was constant at 3.714 g (which was equivalent to 0.6 kg/m^3).

The same experimental procedure with the PMMA particle cloud combustion was used for co-combustion and mixing-combustion experiments.

Chapter 3. Turbulent Burning characteristics of ammonia/oxygen/nitrogen premixed flames

3.1. Turbulent flame propagation behavior of pure ammonia/oxygen/nitrogen combustion

Before giving the deep discussions with turbulent burning velocity of pure ammonia combustion, it would be better to obtain the simpler turbulent flame propagation characteristics of ammonia/oxygen/nitrogen flame. Burning velocity is the burned gas velocity relative to the unburned gas flow velocity. However, in present research, for the pure solid particle cloud combustion, pulverized coal particle cloud/ammonia co-combustion, and PMMA particle cloud/ammonia co-combustion, the density of the burned and unburned mixture is hard to be defined because the complicate combustion process of the solid particles. Therefore, just the flame propagation characteristics were discussed for the pure solid particle cloud combustion, pulverized coal particle cloud/ammonia co-combustion, and PMMA particle cloud/ammonia co-combustion. The flame propagation velocity is the velocity of flame front. To compare the turbulent flame propagation velocity between co-combustion (or mixing combustion) and that of the pure ammonia combustion, the turbulent flame propagation velocity of the pure ammonia combustion was first introduced.

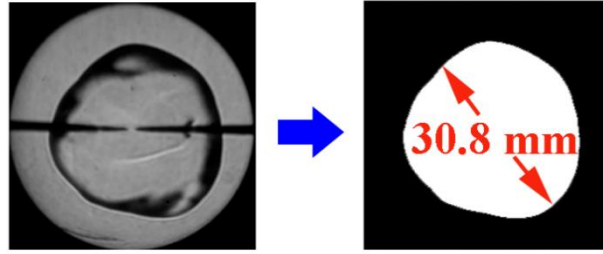
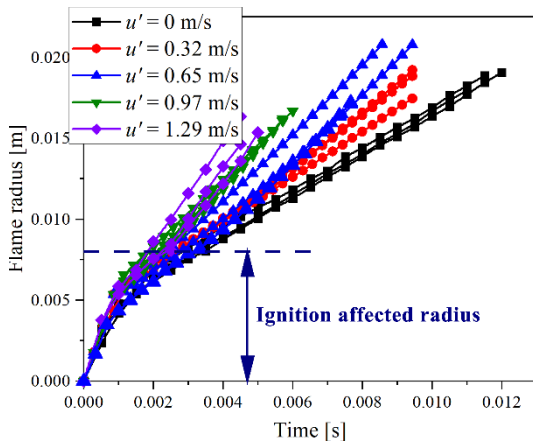


Fig. 3.1. Image processing for the schlieren image

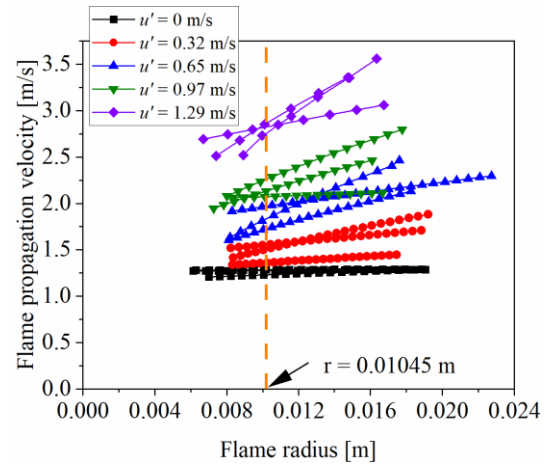
The 16-bit images were processed by gray levels from 0 = black (flame) to 255 = white (background). The threshold value was selected based on visual inspection. The range of the threshold value used for processing the images was from 50 to 100 depending on the obtained images. The threshold-value effect on the radius and velocity deviations was within $\pm 2\%$. Then the processed image was transferred to the binary image in which the flame was black, and background was white. Subsequently, the flame radii were calculated by measuring the flame tips. The ignition-affected radius for the flame propagation was checked by changing the ignition energy from 0.3 J to 5.5 J. The result shows that the radius affected by the ignition energy is within 0.008 m (The detailed discussion can be seen Chapter 3.5). Therefore, only the flame radii data from 0.008 m to the flame front touching the window edge was used for calculating the flame propagation speed.

A polynomial relationship for the measured flame propagation radius as a function of time was applied to obtain the propagation velocity. Fig. 3.2(b) shows the turbulent flame propagation velocity as a function of the flame radius. For all turbulent combustion experiments, the propagation velocity increases with the increase in flame radius. In the initial period of flame propagation, only eddies whose size is smaller than the flame size could wrinkle the flame front,

but with the development of the flame radius, the flame can be affected by a wider range of turbulence wavelength. Therefore, the flame propagation velocity increases with the increase of the flame radius. The flame propagation velocities at a flame diameter of 0.02090 m (which is equivalent to the integral length scale (L_f) of the turbulent field) were chosen to compare the flame propagation velocities obtained under different conditions. This methodology has been used in many solid and gas combustion studies [15,16,34,63,91–93]. The flame radius of 10.45 mm was chosen because it is equivalent to the flame diameter of 20.9 mm, which is the same length as the longitudinal integral length scale, L_f .



(a) Flame radius histories measured by schlieren photography



(b) Turbulent flame propagation velocity as a function of the flame radius

Fig. 3.2. Turbulent flame propagation behavior of pure ammonia/oxygen/nitrogen mixture

Fig. 3.3 shows the turbulent flame propagation velocity as a function of the ammonia equivalence ratio under different turbulence intensities. Turbulent flame propagation velocity increases with the increase of the turbulence intensity. This is caused by the enhanced turbulence heat and mass transfer and the increased flame surface area by increasing turbulence intensity.

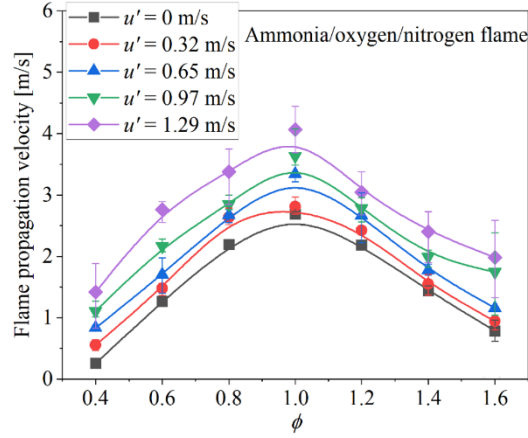


Fig. 3.3. Turbulent flame propagation velocity as a function of the ammonia equivalence ratio under various turbulence intensities

3.2. Evaluation of burning velocity of ammonia/oxygen/nitrogen premixed flame

3.2.1. Evaluation of unstretched laminar burning velocity

Unstretched laminar burning velocity was derived from measuring the spherical propagation flame images obtained by the high-speed camera. The flame propagation velocity, S_n , was calculated from the mean flame radius, r_{sch} , of a circle whose area was equal to area of the schlieren image of spherical flame against time by Eq. (3.1):

$$S_n = \frac{dr_{sch}}{dt}. \quad (3.1)$$

During the laminar flame propagation process, the effects of the flame stretch must be considered, given that the spherically propagating flame had curvature. The flame stretch rate, ε , acting on the flame is defined [7,94,95] as Eq. (3.2):

$$\varepsilon = \frac{1}{Area} \cdot \frac{d(Area)}{dt} = \frac{2}{r_{sch}} \cdot \frac{dr_{sch}}{dt}, \quad (3.2)$$

where *Area* was the area of the spherical propagation flame front. Owing to the effect of diffusional–thermal instability, for non-unity Lewis number cases, the flame temperature and the laminar flame propagation velocity were different from those in the unstretched case. The difference between stretched laminar flame propagation velocity, S_n , and unstretched laminar flame propagation velocity, S_s , can be expressed as a proportional relationship between burned gas Markstein length, L_b , and stretched rate, ε , as expressed [96] by Eq. (3.3):

$$S_s - S_n = L_b \cdot \varepsilon. \quad (3.3)$$

By extrapolating the stretched laminar flame propagation velocity to an infinite flame radius, which is equivalent to setting the flame stretched rate to 0, the unstretched laminar flame propagation velocity can be obtained. The unstretched laminar burning velocity, U_L , was derived from Eq. (3.4):

$$U_L = \frac{\rho_b}{\rho_u} \cdot S_s. \quad (3.4)$$

The stretched laminar burning velocity, U_N , was calculated by Eq. (3.5):

$$U_N = \frac{\rho_b}{\rho_u} \cdot S_n, \quad (3.5)$$

where ρ_u and ρ_b are unburned mixture density and burned mixture density, respectively.

Kelly et al. [97] found that outwardly propagating spherical flames in a constant-volume chamber may exhibit nonlinear relationship between the stretched flame propagation velocity, S_n , and stretched rate, ε . To extrapolate the unstretched laminar propagation velocity and the burned gas Markstein length, they proposed the nonlinear relationship expressed by Eq. (3.6):

$$\left(\frac{S_n}{S_s}\right)^2 \ln \left(\frac{S_n}{S_s}\right)^2 = -2 \frac{L_b \varepsilon}{S_s}. \quad (3.6)$$

The unstretched laminar flame propagation velocity, S_s , and the burned gas Markstein number, L_b , can be measured from linear extrapolation of $\ln(S_n)$ with ε/S_n^2 [10,98]. Okafor et al. [10] concluded that the nonlinear equation was also appropriate for mixtures with Lewis numbers close to unity. In our research, both linear and nonlinear equations were used to obtain the unstretched laminar burning velocity, U_L , and the burned gas Markstein length, L_b .

3.2.2. Evaluation of turbulent burning velocity

The turbulent burning velocity is expressed by Eq. (3.7), the same as for the laminar burning velocity [94,99,100]:

$$U_{tr} = \frac{\rho_b}{\rho_u} \cdot \frac{dr_{sch}}{dt}. \quad (3.7)$$

In the case of turbulent flames, the flame is deformed by turbulent eddies. Because the schlieren image is integrated along the light path, it is impossible to define the three-dimensionally wrinkled flame front by using the schlieren photography. However, Bradley and Kitagawa et al. [99] revealed that such burning velocity could be correlated to the turbulent burning velocity by planer Mie-scattered imagery, and they also came to an important conclusion that the turbulent burning velocity was associated with the entrainment and mass-consumption rate of the unburned mixture.

3.3. Ammonia/oxygen/nitrogen mixture properties

Among the properties of the ammonia/oxygen/nitrogen mixtures (Table 3.1), ρ_b and ρ_u were burned and unburned gas mixture densities were obtained from the Chemical Equilibrium Application (CEA) computer program of the U.S. National Aeronautics and Space Administration [101]. λ , c_p , α , ν and Le were thermal conductivity, specific heat at constant pressure, thermal diffusivity, kinematic viscosity, and the Lewis number which were calculated using the website of the Dandy research group at Colorado State University [102]. The Lewis number is defined [103] by Eq. (3.8):

$$Le_i = \frac{\alpha}{D_{i/N_2}}, \quad (3.8)$$

where D_{i/N_2} is the mass diffusivity of the deficient species “i”.

The effective Lewis number, Le_{eff} , of a single component fuel and an oxidizer can be expressed [104] by Eq. (3.9):

$$Le_{eff} = 1 + \frac{(Le_E - 1) + (Le_D - 1)A}{1 + A}. \quad (3.9)$$

In this equation, the Lewis number Le_E and Le_D are those defined based on the reactant that is relatively in excess and deficient, respectively. A represent a measure of the mixture's strength which can be calculated by Eq. (3.10):

$$A = 1 + Ze(\Phi - 1). \quad (3.10)$$

The constant Φ , which is always >1 , is defined as the mass ratio of excess-to-deficient reactants in the mixture relative to their stoichiometric ratio [104,105]. Ze is Zel'dovich number which can be expressed by Eq. (3.11):

$$Ze = E_a(T_{ad}-T_u)/(R^0 T_{ad}^2), \quad (3.11)$$

where R_0 is the universal gas constant, E_a is the activation energy which can be calculated [95,106] by Eq. (3.12):

$$\frac{E_a}{R_0} = -2 \frac{\partial \ln(\rho_u U_L)}{\partial (1/T_{ad})}. \quad (3.12)$$

As shown in Table 3.1, although the equivalence ratio changes greatly from 0.6 to 1.6 under oxygen content of 0.4, values of the effective Lewis number which change from 0.936 to 1.084, are very close to unity. Thus, the differential diffusion effect (characterized by the effective Lewis number) is comparably small.

Table 3.1. Properties of ammonia/oxygen/nitrogen mixtures [=, can't be defined]

Ω	ϕ	ρ_u [kg/m ³]	ρ_b [kg/m ³]	λ [10 ⁻³ W/m/K]	c_p [J/kg/K]	α [10 ⁻⁵ m ² /s]	ν [10 ⁻⁵ m ² /s]	Le	T_{ad} [K]	Le_{eff}
0.35	0.6	1.0908	0.14938	27.559	1144.6	2.2074	1.560	0.896	2062.14	0.942
	0.8	1.0650	0.12707	27.804	1204.4	2.2034	1.556	0.894	2324.47	0.948
	0.9	1.0527	0.11985	27.911	1204.4	2.2012	1.554	0.883	2412.55	0.965
	1.0	1.0410	0.11483	28.015	1224	2.1987	1.552	=	2460.04	1.000
	1.1	1.0304	0.11249	28.099	1241.5	2.1966	1.550	1.125	2444.05	1.034
	1.2	1.0198	0.11227	28.181	1259.4	2.1943	1.549	1.122	2377.48	1.052
	1.4	1.0002	0.11419	28.337	1294.3	2.1889	1.545	1.119	2293.83	1.070
0.4	0.6	1.0861	0.13940	27.666	1155.2	2.2051	1.559	0.906	2182.39	0.936
	0.8	1.0570	0.11972	27.922	1200.7	2.2002	1.554	0.88	2423.05	0.945
	0.9	1.0440	0.11340	28.030	1221.8	2.1975	1.552	0.868	2497.35	0.963
	1.0	1.0319	0.10893	28.128	1241.9	2.1948	1.550	=	2534.38	0.999
	1.1	1.0206	0.10646	28.216	1261.1	2.1921	1.548	1.138	2521.72	1.033
	1.2	1.0101	0.10575	28.296	1279.5	2.1895	1.546	1.135	2463.98	1.052
	1.4	0.9909	0.107	28.435	1313.8	2.1842	1.543	1.13	2296.3	1.072
	1.6	0.97397	0.10978	28.552	1345.3	2.1791	1.5396	1.125	2122.21	1.084

3.4. Flame observation

Fig. 3.4 shows the sequence of schlieren images of ammonia/oxygen/nitrogen flames from 1 to 6 ms for $\phi = 0.6$ under laminar and four different turbulence intensity cases. It is apparent that as the turbulent flame expands outwardly, the flame becomes more wrinkled and accelerated. In the initial period of turbulent flame propagation, only eddies of a size smaller than the flame size could wrinkle the flame front, but with the development of the flame radius, the flame can be affected by wider range of turbulence wavelength. Also, Kolmogorov and Taylor's length scales become smaller as the turbulence intensity increases. Therefore, as the turbulence intensity

increases, more smaller patterns of flame front deformations can be seen in Fig. 3.4. Also, the nonuniformity of the wrinkling effects of eddies increases with increasing turbulence intensity [107,108]. Accordingly, the flame propagates faster with increasing turbulence intensity.

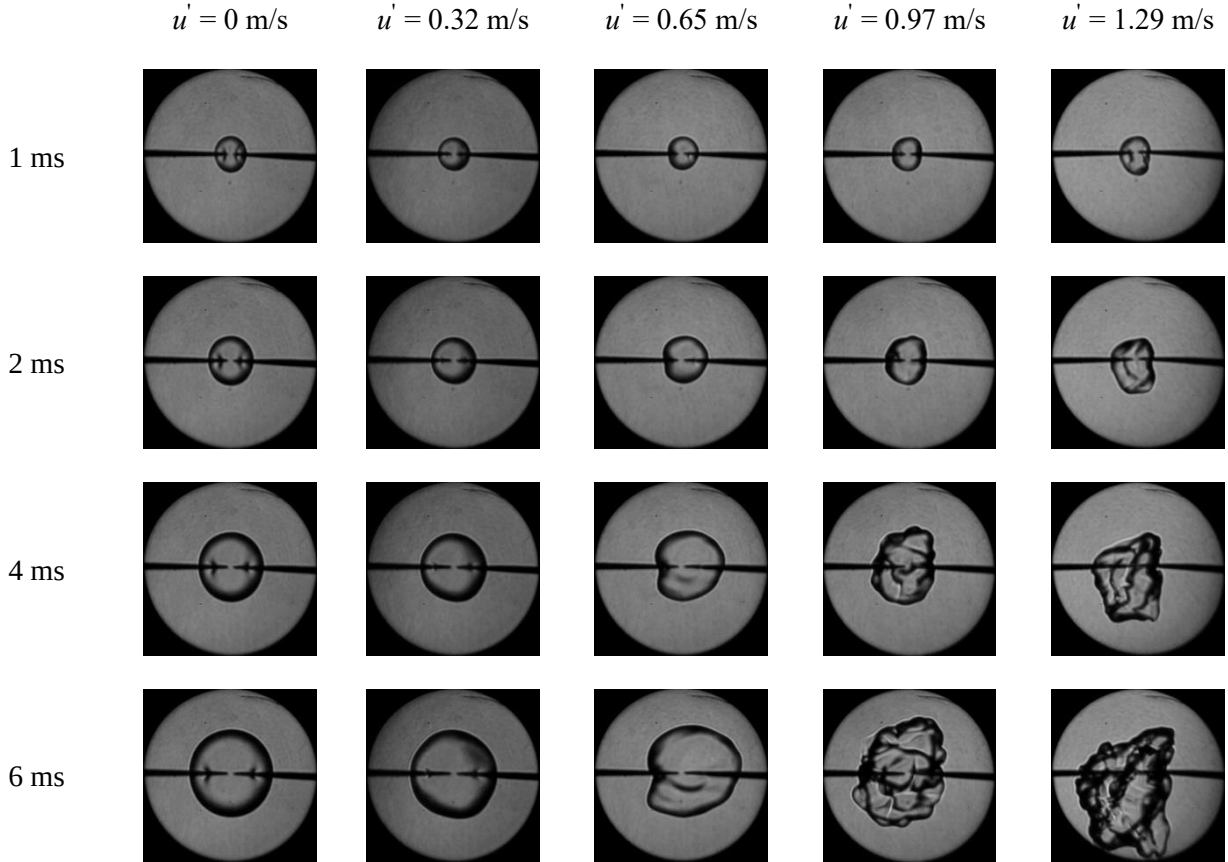


Fig. 3.4. Schlieren images of ammonia/oxygen/nitrogen mixtures under $\phi = 0.6$ at various turbulence intensities.

Fig. 3.5 shows the image processing for the schlieren photography for obtaining the burning characteristics of pure ammonia combustion. The 16-bit images were processed by gray levels from 0 = black (flame) to 255 = white (background). The threshold value was selected based on visual inspection. The range of the threshold value used for processing the images was from 50 to

100 depending on the obtained images. The threshold-value effect on the radius and velocity deviations was within $\pm 2\%$. Then the processed image was transferred to the binary image in which the flame was black and background was white. Subsequently, the flame area was calculated by the number of included pixels of the flame area and the mean flame radius, r_{sch} , was determined by the radius of the equivalent circle area under both laminar and turbulent conditions. This flame radius calculation method is quite different with that method in Chapter 3.1. This is because the flame radius calculation method by direct measuring the flame tips is used to obtain the turbulent flame propagation velocity of pure ammonia flame. However, the radius calculated by flame surface area is used to obtain the burning velocity of pure ammonia flame.

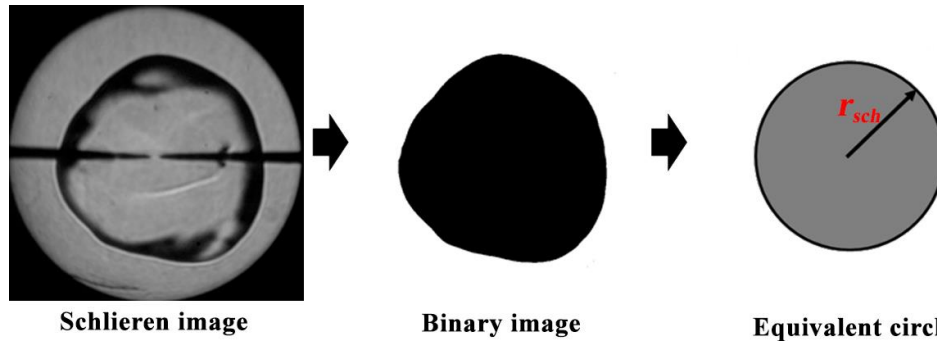


Fig. 3.5. Image processing for obtaining the burning characteristics of ammonia flame

Fig. 3.6 illustrates the flame radius as a function of elapsed time under $\phi = 0.6$ for various turbulence intensities. It is apparent that at the beginning, the flame propagation was affected by the ignition energy, but after the flame developed beyond the ignition affected period, under the same elapsed time, the flame radius increased with the increase of turbulence intensity.

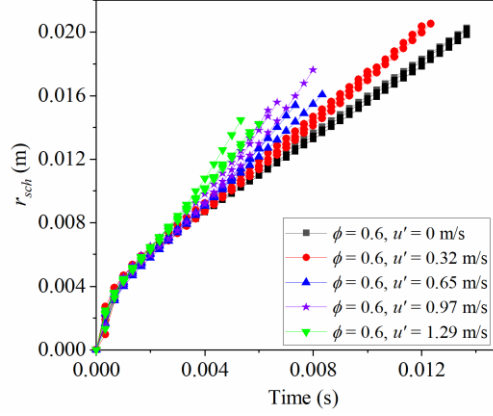


Fig. 3.6. Flame radius as function of time under $\phi = 0.6$ at various turbulence intensities.

3.5. Turbulent burning characteristics of ammonia/oxygen/nitrogen premixed flame

3.5.1. Unstretched laminar burning velocity of the ammonia/oxygen/nitrogen flame

The ignition energy effect is checked by changing ignition energy from 0.3 to 5.5 J, as shown in Fig. 3.7. The critical flame radius, which was used to eliminate the ignition energy affected period, observed by ammonia/oxygen/nitrogen combustion for $\phi = 1.0$ at $\Omega = 0.4$, was ~ 0.008 m. (This method was used by Chen et al.[109] and Huang et al. [110].) So, the radius that was < 0.008 m was not counted in laminar and turbulent studies.

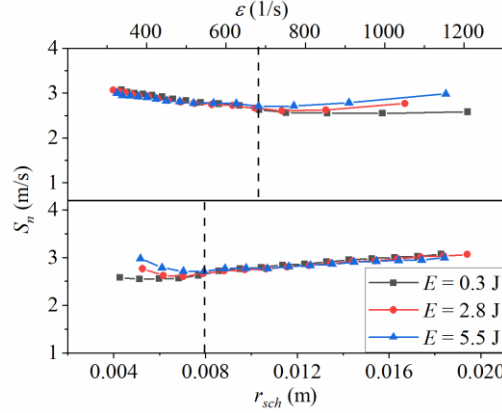


Fig. 3.7. Stretched laminar flame propagation velocity as functions of flame radius and stretch rate for ammonia/oxygen/nitrogen mixture at $\phi = 1.0$ on $\Omega = 0.4$.

In our research, the outwardly propagating spherical flame (OPF) in the constant-pressure method was used to obtain the unstretched laminar burning velocity. Chen et al. [111] had noted that the ignition energy, confinement, buoyancy, flame instability, and nonlinearity of the flame speed-stretch rate relationship can cause inaccuracy of unstretched laminar flame speed measurement. The relation between the stretched laminar flame propagation velocity, S_n , and the flame stretch rate, ϵ , under conditions of $\phi = 0.8$ and $\phi = 1.2$ are shown in Fig. 3.8. According to Kelley [97], flame propagation in a constant-pressure environment can be divided into three distinctive periods: an ignition energy affected period, a quasi-steady period, and a chamber confinement affected period. The ignition energy effected period was determined by the critical radius (Fig. 3.7). The confinement effect was neglected because the observation period was relatively small compared with chamber volume. Mei et al. [69] pointed out that the buoyancy effect on the ammonia/oxygen/nitrogen flame was almost eliminated under oxygen concentrations of 35% and 45% because flames for both were nearly spherical. The same phenomenon was found in present research. Also, the buoyancy effect was ignored because there

was no noticeable change in the flame symmetry under any tested conditions. Besides, because the flames within the observation range in the present study were stable, there was no uncertainty caused by instability. Additionally, linear and nonlinear methods were carefully applied to avoid the uncertainties induced by the nonlinearity of the flame speed-stretch rate relationship.

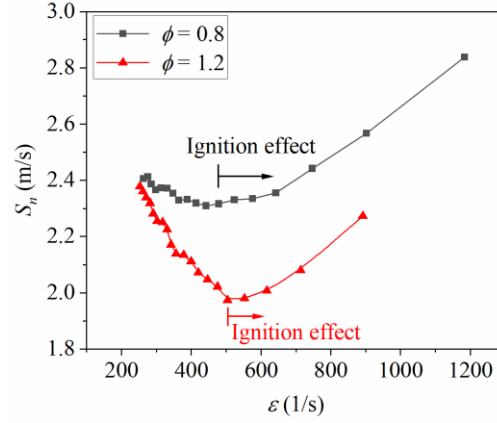


Fig. 3.8. The unstretched laminar propagation velocity as a function of stretch rate.

Fig. 3.9 shows the unstretched laminar burning velocities of the ammonia/oxygen/nitrogen premixture flame, which were obtained by using Eqs. (3.3) and (3.6). The results obtained by Mei et al. [69] by the same experimental method for $\Omega = 0.35$ were similar to those from our current research. Accordingly, the reproducibility of the flame propagation experiments of ammonia O₂-enriched combustion was confirmed.

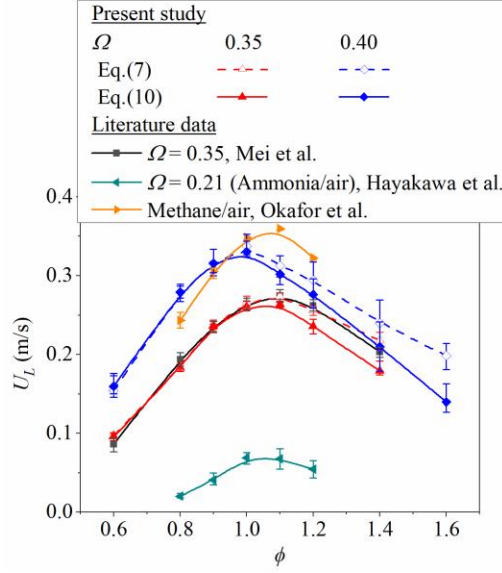


Fig. 3.9. Experimental results of correlation of unstretched laminar burning velocity with equivalence ratio under various oxygen contents in oxidizer.

As indicated in Fig. 3.9, under the same ammonia/oxygen/nitrogen equivalence ratio, the unstretched laminar burning velocity of the ammonia/oxygen/nitrogen mixture increases with increasing Ω from 0.21 to 0.4. The maximum laminar burning velocity was 0.337 m/s at $\phi = 1.0$ under $\Omega = 0.4$ which was approximately 4.9 times the value under the condition $\Omega = 0.21$. From comparing with laminar burning velocity of CH₄/air [2], 40% oxygen content was found to enhance the ammonia laminar burning velocity to the level of methane/air laminar burning velocity.

On the other hand, the unstretched laminar burning velocities obtained from linear and nonlinear equations are approximately same on ammonia-lean and under stoichiometric conditions. However, the disparity increased with the rise of the equivalence ratio in ammonia-rich cases. The disparity between the two methods was considered by Okafor et al. [10] to have been caused by the increasing sensitivity of the flame to stretch.

The sensitivity of the laminar burning velocity to the flame stretch rate can be evaluated by the burned gas Markstein length, L_b . Fig. 3.10 shows the burned gas Markstein length which was obtained by the non-linear equation. Additionally, L_b increases with increase of ammonia equivalence ratio for both $\Omega = 0.35$ and 0.4 cases.

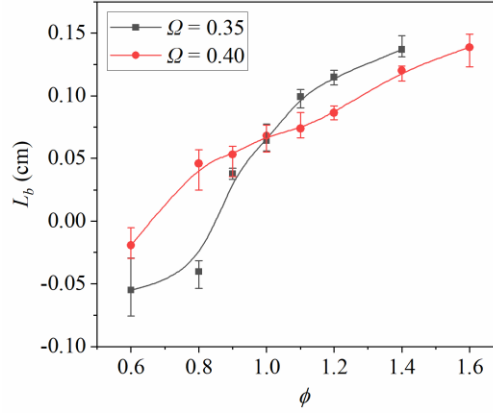


Fig. 3.10. Variation of the burned gas Markstein length with the equivalence ratio and oxygen content.

From the asymptotic analysis of the premixed flame structure, L_b can be expressed [10,96] by Eq. (3.13):

$$L_b = \delta_F [f_1(\sigma) + Ze(Le-1)f_2(\sigma)], \quad (3.13)$$

where the $f_1(\sigma)$ and $f_2(\sigma)$ are functions of the thermal-expansion coefficient and are always positive for realistic coefficient values of σ [10]. In present research, the burned gas Markstein length was dominated by the Zel'dovich number, flame thickness, and Lewis number. Flame thickness, δ_F , is calculated [112] by Eq. (3.14):

$$\delta_F = \frac{\lambda}{c_p \rho_u U_L}. \quad (3.14)$$

Fig. 3.11 shows the Ze and δ_F under different cases. Because Ze promotes the effect of a non-unity Lewis number, the effect of an increase in Ze on the sensitivity of the flames to stretch depends on the value of the Lewis number [10]. In ammonia-lean cases in which $Le < 1$, Ze decreases with increasing L_b , while Ze increases with increasing L_b in ammonia-rich cases.

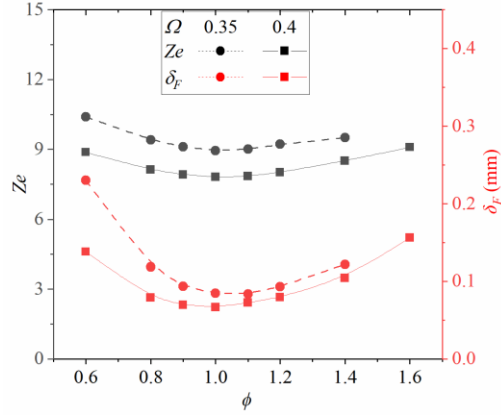


Fig. 3.11. Flame thickness and Zel'dovich number under different equivalence ratios and oxygen contents.

3.5.2. Turbulent flame structure of ammonia/oxygen/nitrogen mixture under conditions of oxygen enrichment

To reveal the turbulence longitudinal integral length scale effect on the flame front, Borghi and Peters proposed four kinds of turbulent flame regimes [70]. As shown in Fig. 3.12, the Peters regime diagram indicates four flame regimes determined by the ratio of longitudinal integral length scale (L_f) to laminar flame thickness (δ_F), with the ratio of turbulence intensity (u') to unstretched laminar burning velocity (U_L), including the wrinkled flamelets regime, the corrugated flamelets regime, the thin reaction zone, and the broken reaction zone.

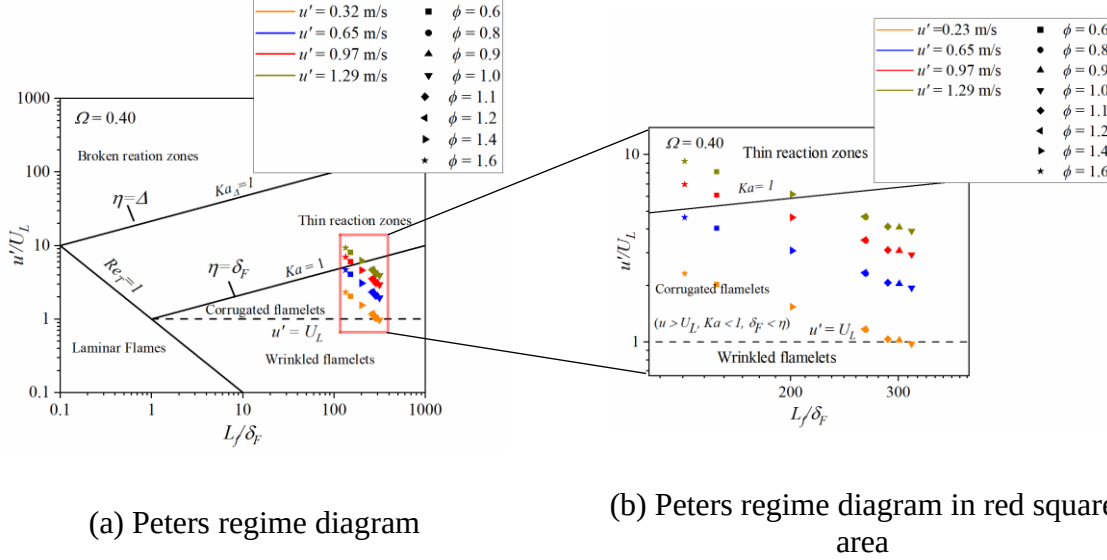


Fig. 3.12. Regimes of present experimental conditions on turbulent combustion diagram.

Most of the ammonia/oxygen/nitrogen turbulent flames were in the corrugated flamelets regime. In this regime, turbulent eddies push the flame front and undergo convolution, which increases the flame surface area, and the chemical reaction time is faster than the turbulent mixing. This means that the turbulent eddies can only wrinkle the laminar flamelets and cannot influence the chemical reaction within the flame front.

The turbulence Karlovitz number, which is the ratio of the chemical time scale to the time scale of turbulent eddies, can be calculated by Eq. (3.15) as a specific value of flame stretch caused by turbulent flow to turbulent flame [113]:

$$Ka = \frac{\delta_F}{U_L} \frac{1}{\lambda_f u'}, \quad (3.15)$$

where U_L is the unstretched laminar burning velocity, λ_f is the longitudinal Taylor microscale of turbulent field, and u' is turbulence intensity, δ_F is the thickness of preheat zone.

As shown in Fig. 3.13, the turbulent Karlovitz number (Ka) increases with increasing turbulence intensity irrespective of the equivalence ratio. Moreover, it decreases with increasing equivalence ratio in ammonia-lean cases but it increases with increasing equivalence ratio in ammonia-rich cases. However, all $Ka < 1$. Thus, compared to the time scale of small eddies, chemical reaction rates were faster enough that turbulence eddies just wrinkled the flamelets and did not affect the chemical reaction within the flame front.

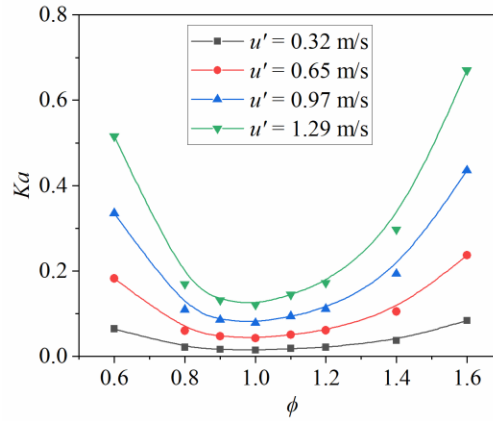


Fig. 3.13. Turbulence Karlovitz number (Ka) under different equivalence ratios and turbulence intensities.

3.5.3. Turbulence burning velocity of ammonia/oxygen/nitrogen mixture under condition of oxygen enrichment

Fig. 3.14 shows the turbulent burning velocity U_{tr} and stretched laminar burning velocity U_N as functions of flame radius, r_{sch} , under various turbulence intensities at $\phi = 0.6$. As the flame radius increased from 0.004 m to 0.008 m, the turbulent burning velocity decreased because of the ignition energy effect. The ignition energy affected period, in which $r_{sch} < 0.008$ m, was ignored, but after the ignition energy affected period, the turbulent burning velocity increased

with increasing flame radius for all turbulence intensity cases. For the same flame radius, the turbulent burning velocity increases with increasing turbulence intensity. The turbulent trends are the same for the other equivalence ratio cases.

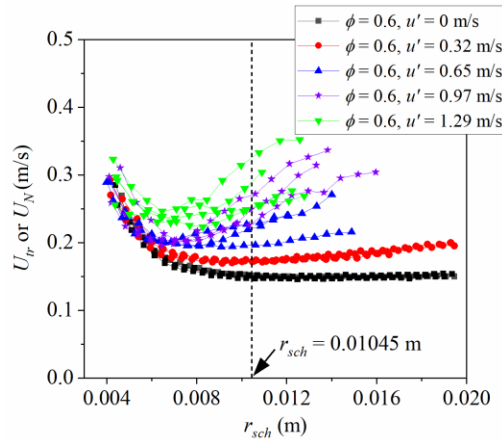


Fig. 3.14. Turbulent burning velocity developing as a function of flame radius for $\phi = 0.6$.

To examine the turbulence intensity effect on burning velocity, the burning velocity at flame diameter of the turbulence longitudinal integral length scale was used for comparison. The method has been used for studying premixed turbulent combustion of methane/air, hydrogen/methane/air, hydrogen/octane/air, hydrogen/air, iso-octane/air, methanol/air [34,91–93,114–116]. Moreover, for the laminar case, the stretched laminar burning velocity at flame diameter of the longitudinal integral length scale was used for comparison.

Fig. 3.15 shows the turbulent burning velocity and stretched laminar burning velocity at flame diameter of L_f under various equivalence ratio, ϕ . It was found that turbulent burning velocity increases with increasing turbulence intensity. The increase of turbulent burning velocity of the ammonia/oxygen/nitrogen mixture is caused by the increase of the turbulent flame surface

area deformed by turbulent eddies. Maximum turbulent burning velocity is at $\phi = 1.0$, the same as for unstretched laminar burning velocity. However, as shown in Fig. 3.15, somewhat large scatter is observed under conditions of high turbulence intensity. One reason for the large scatter is that the flame is highly deformed at relative high turbulence intensities. This phenomenon has also been observed in other instances of gaseous fuel turbulent flame propagation [117,118]. A second reason for the scatter is that the effects of eddies on flame propagation increase with increasing turbulence intensity. There are turbulent eddies of various sizes in the turbulent flow field, and the wrinkling effects differ according to each eddy size [34]. Accordingly, the nonuniformity of wrinkling effects of eddies increases with increasing turbulence intensity.

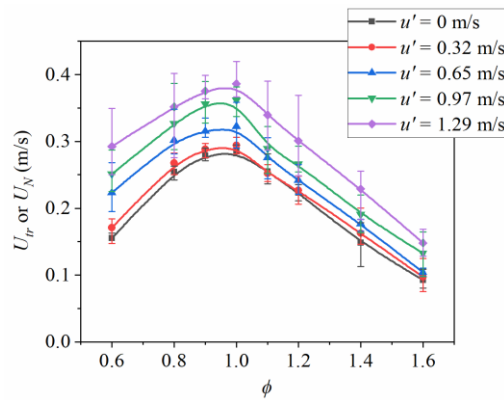


Fig. 3.15. Turbulent burning velocity and stretched laminar burning velocity at flame diameter of longitudinal integral length scale as a function of equivalence ratio.

Fig. 3.16 shows the ratio of turbulent burning velocity to the stretched laminar burning velocity, U_{tr}/U_N , as a function of ϕ . Through using the ratio U_{tr}/U_N , the effect of the global stretch that appears in both the laminar and turbulent cases can be eliminated. Globally, the ratio U_{tr}/U_N decreases with increasing equivalence ratio for ammonia-lean cases but increases with increasing of equivalence ratio for ammonia-rich cases. Also, with increasing turbulence intensity, the ratio

U_{tr}/U_N increases. To examine these tendencies, the turbulence Karlovitz number, Ka , was introduced and the relationship between turbulence Karlovitz number and the ratio of turbulent burning velocity to stretched laminar burning velocity was studied.

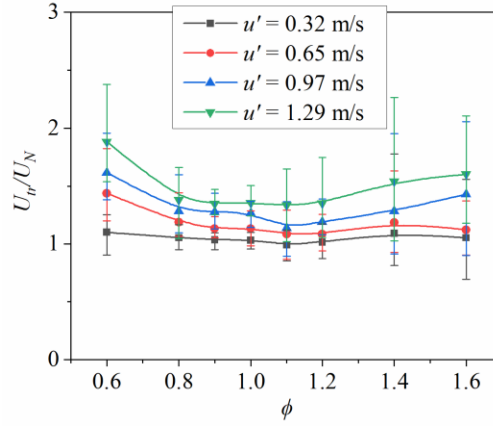


Fig. 3.16. The relation of the ratio of U_{tr}/U_N with ammonia equivalence ratio.

Fig. 3.17(a) shows the relationship between turbulence Ka and U_{tr}/U_N . The ratio, U_{tr}/U_N , increases with increasing turbulence Ka . As shown in Fig. 3.17(b), the ratio U_{tr}/U_N for ammonia-lean cases, is higher than for ammonia-rich cases. This is most likely due to the effect of diffusional–thermal instability. The local burning velocity in the convex structure increases when $Le < 1$, i.e., the mass diffusion of reactants from the unburned area to the burned area excels the thermal diffusion from the burned area to the unburned area, and a convex structure develops. On the other hand, the local temperature and burning velocity in concave areas decrease, and a concave shape develops also. Eventually, overall burning velocity increases due to the increase in flame surface area because of the diffusional–thermal instability effect caused when $Le < 1$. Hence, turbulence eddies and the diffusional–thermal instability effect induced higher turbulent burning velocity in ammonia-lean cases under the same turbulence Ka . These findings indicate

that not only the consideration of the turbulence effect but also the consideration of the diffusional–thermal instability effect is important to predict the turbulent burning velocity of ammonia flame. Consideration of the effect of the diffusional–thermal instability when simulating flame propagation velocity can contribute greatly to the future design of combustor using ammonia as a fuel.

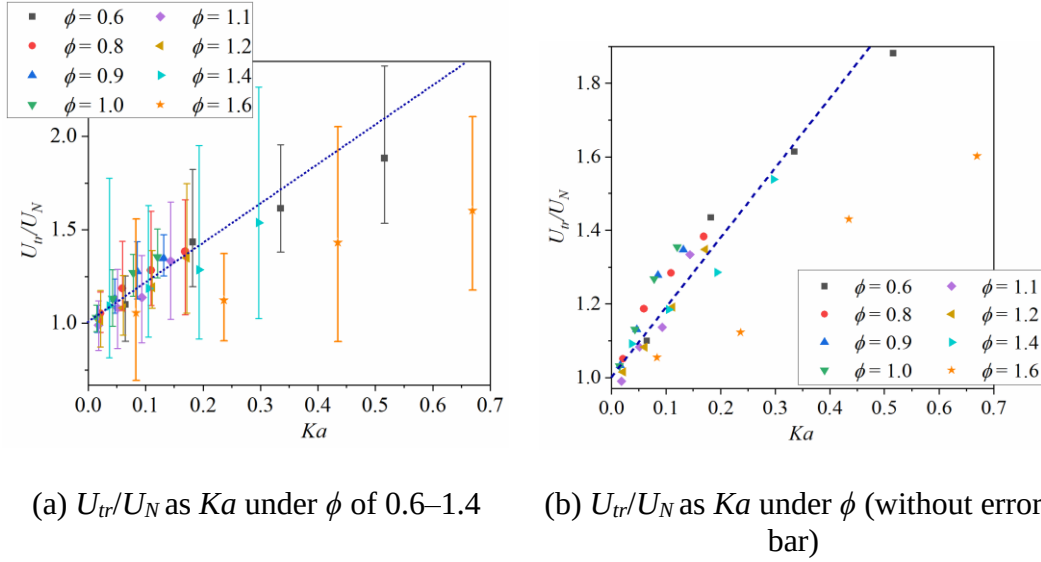


Fig. 3.17. Ratio of turbulent burning velocity to stretched laminar burning velocity (U_{tr}/U_N) in terms of turbulence Karlovitz number (Ka).

However, for the case of $\phi = 0.6$, the U_{tr}/U_N as the turbulence Ka is slightly lower than the average line. This is considered to be caused by the lower adiabatic flame temperature, T_{ad} , which is shown in Table 2. For the case when $\phi = 1.6$, the Lewis number is almost the same as when $\phi = 1.4$. However, because of lower T_{ad} , the ratio of U_{tr}/U_N under the condition of $\phi = 1.6$ is much smaller than that in the case when $\phi = 1.4$. Hence, under the condition of $\phi = 0.6$, the lower adiabatic flame temperature limits the effect of diffusional–thermal instability. There is a possibility that the local quenching happens owing to the lower adiabatic flame temperature even

though the basic diffusional–thermal instability effect is strong for ammonia-lean flame. That is, the contribution of the effect of diffusional-thermal instability to increase flame surface area is limited by local quenching due to the lower adiabatic flame temperature for the case when $\phi = 0.6$. Although the diffusional-thermal instability effect is limited for the $\phi = 0.6$ case, it is still important because the ratio of U_{tr}/U_N under $\phi = 0.6$ is much larger than that under $\phi = 1.6$ even though T_{ad} is almost the same.

3.6. Concluding remarks

The effect of turbulence intensity on the burning characteristics of an ammonia/oxygen/nitrogen mixture was investigated under conditions of oxygen enrichment. The principal findings are as follows:

The turbulent flame propagation velocity of the ammonia/oxygen/nitrogen combustion increased with the increase of the turbulence intensity.

The turbulent burning velocity of the ammonia/oxygen/nitrogen flame increased with the increasing turbulence intensity owing to the increase of flame surface area (due to the increase of turbulence intensity).

Under the same turbulence Karlovitz number, the ratio of turbulent burning velocity to the stretched laminar burning velocity in ammonia-lean cases was larger than that in ammonia-rich cases. This is caused by the effect of diffusional-thermal instability. Consideration of both effects of the diffusional-thermal instability and the turbulence is important for the prediction of turbulent flame propagation velocity in ammonia combustion fields.

Chapter 4. Turbulent flame propagation mechanism of solid particle clouds

4.1. Flame observation

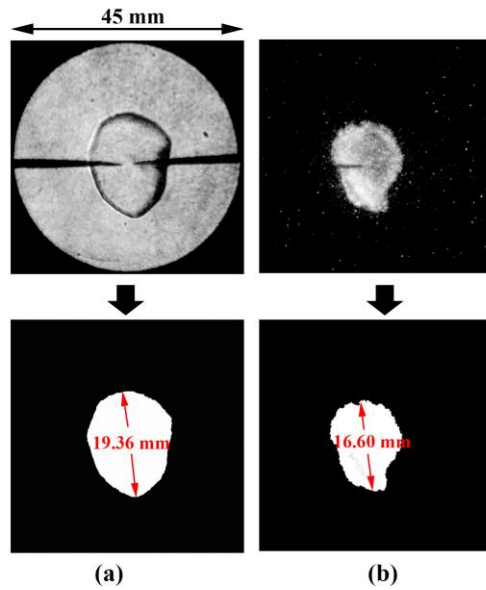


Fig. 4.1. Image processing; (a) Schlieren photography image; (b) OH radical photography image.

Fig. 4.1(a) shows the schlieren image processing procedure for the combustion of 30- μm quasi-monodispersed PMMA particle clouds under a particle concentration of 0.6 kg/m^3 and a turbulence intensity of $u' = 0.32 \text{ m/s}$. The same processing method with that in Chapter 3.1 was used for processing the schlieren image in Fig. 4.1(a). Fig. 4.1(b) shows the OH radical image for the same condition and time shown in Fig. 4.1(a). The border of the OH radical image was considered as the reaction front where the combustion reaction started [15]. Subsequently, the flame radii were calculated by measuring the flame tips. Even though the turbulent flame radius calculated using the flame area method and directly measuring the flame tips are different, the

radius calculation method had little effect on the exact value and basic tendency of the turbulent flame propagation velocity under different turbulence intensities (the comparison of the flame radius and turbulent flame propagation velocity using two different radius calculation methods can be seen in Figs. C and D in Appendix).

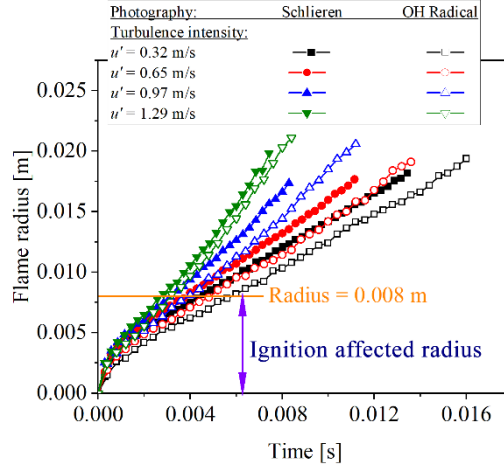


Fig. 4.2. Flame radius histories measured by schlieren photography and OH radical photography for the 30- μm quasi-monodispersed PMMA particles with a particle concentration of 0.6 kg/m^3 .

Fig. 4.2 shows the schlieren image flame and OH radical image flame radii histories for the combustion of the 30- μm quasi-monodispersed PMMA particle clouds at a particle concentration of 0.6 kg/m^3 with different turbulence intensities. The ignition-affected period for the flame propagation was determined in Chapter 3.5. The results showed that the radius affected by the ignition energy is within 0.008 m [63]. Therefore, to eliminate the ignition-affected period, only the flame radii data from 0.008 m to the flame front touching the window edge was used for calculating the flame propagation speed [15]. As shown in Fig. 4.2, the schlieren flame radius is always larger than the OH radical flame radius at the same elapsed time under the same conditions because schlieren photography, which can capture the position of high-density

gradient caused by the rapid change in gas temperature, detects the preheated zone front, while OH radical photography detects the reaction front, which follows the preheated zone, as clarified in our previous studies [15,16]. The pressure inside the chamber was constant at $\pm 5\%$ atmosphere pressure during the flame propagation within the observation period for flame radius measurement for all conditions.

Same analysis method with Chapter 3.1, a polynomial relationship for the measured flame propagation radius as a function of time was applied to obtain the propagation velocity. As shown in Fig. 4.2 and Fig. 4.3, although the radius measured by schlieren photography is always larger than that measured by OH radical photography, both methods gave almost the same flame propagation speed.

Furthermore, for all turbulent combustion experiments, the propagation velocities increased with the increase in flame radius, which was the same as that identified in previous pure coal combustion and the pulverized coal/ammonia co-combustion studies [15,16,34]. Additionally, no constant value was observed within the observation range. The increase in the flame propagation velocity with the flame radius is caused by the wrinkling of the flame front by turbulent eddies. As the turbulent flame expands outwardly, the flame becomes more wrinkled and accelerated. In the initial period of flame propagation, only eddies whose size is smaller than the flame size could wrinkle the flame front, but with the development of the flame radius, the flame can be affected by a wider range of turbulence wavelength. Therefore, the flame propagation velocity increases with the increase of the flame radius. The flame propagation velocities at a flame diameter of 0.02090 m (which is equivalent to the integral length scale (L_f) of the turbulent field) were chosen to compare the flame propagation velocities obtained under different conditions.

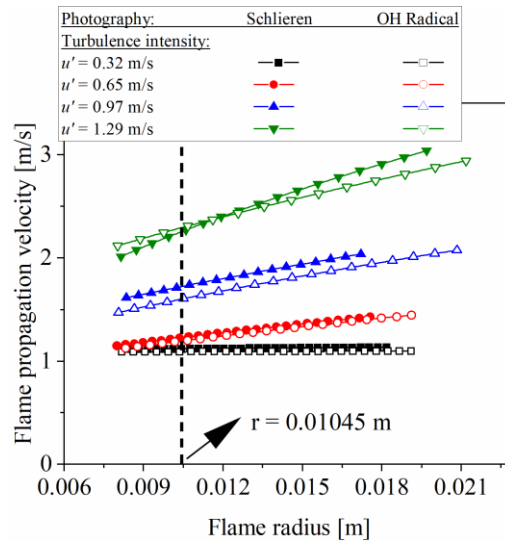


Fig. 4.3. Flame propagation velocity as a function of flame radius for the 30- μ m quasi-monodispersed PMMA particles with a particle cloud concentration of 0.6 kg/m³.

4.2. Turbulence intensity and particle clouds concentration effects on turbulent flame propagation of the quasi-monodispersed particle clouds combustion

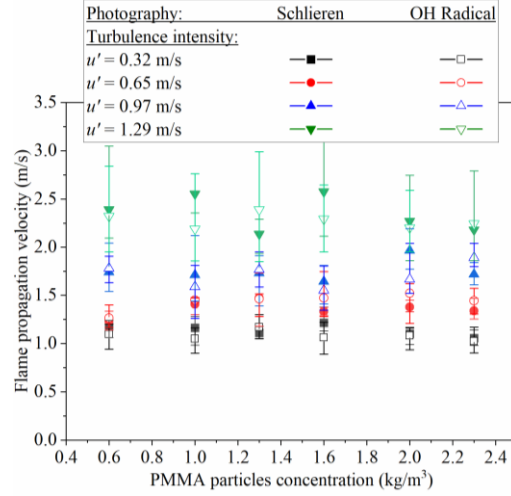


Fig. 4.4. Flame propagation velocity in terms of PMMA particle concentration under different turbulence intensity for the 30- μ m quasi-monodispersed PMMA particles.

Fig. 4.4 shows the relationship of the flame propagation velocity as a function of particle concentration for the 30- μ m quasi-monodispersed particle clouds. To obtain a clear schlieren image even at a high particle concentration, experiments to clarify the particle concentration effect were conducted with the 30- μ m quasi-monodispersed particles. As shown in Fig. 4.4, the turbulent flame propagation velocity of the PMMA particle clouds increased with the increase in turbulence intensity. Two major reasons cause this tendency. First, as the turbulence intensity increases, the turbulence heat and mass transfer can be enhanced. The enhanced turbulence heat and mass transfer can promote the release of the volatile matter. Subsequently, the flame propagation velocity can be increased. Second, the flame surface area can be increased with the increase in turbulence intensity. Consequently, the turbulent flame propagation velocity increased with the increase in turbulence intensity.

Additionally, the PMMA particle cloud concentration has little effect on the turbulent flame propagation velocity. This tendency was also found in the pulverized coal particle cloud combustion, which can be seen in Fig. 1.4(b) [34]. Therefore, in solid particle cloud turbulent

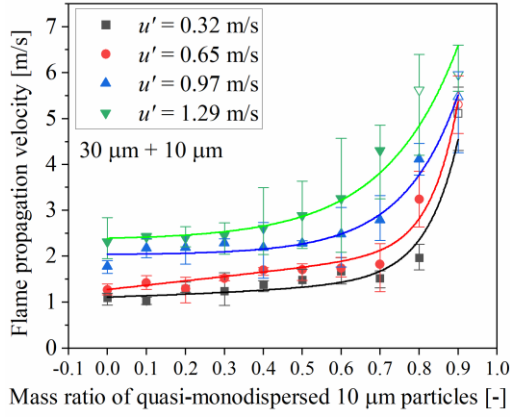
combustion, the particle concentration has a weak effect on the flame propagation velocity. This tendency is different from that in a quiescent environment in which the flame propagation velocity reaches a maximum value for a specific particle concentration [18,26–28]. In a quiescent condition in which no natural convection or buoyancy effect exists, the particle cloud flame propagation velocity is mainly controlled by the heat conduction between gas and particles and radiation between particles [18]. Therefore, the distance between particles plays a key role in the flame propagation phenomenon. Accordingly, the particle concentration dominates the flame propagation phenomenon in a quiescent condition. However, in the turbulent environment (where the buoyancy effect and natural convection are negligible), the turbulent flame propagation velocity is mainly controlled by the turbulent heat and mass transfer. The radiation between particles has little effect on the turbulent flame propagation velocity. Therefore, particle concentration has little effect the turbulent flame propagation velocity. Furthermore, an increase in the turbulent intensity enhances the turbulent heat and mass transfer. Hence, the flame propagation velocity increases with turbulence intensity.

Besides, the PMMA particle cloud flame propagation velocity is larger than that of the pulverized coal particle clouds combustion under the same particle cloud concentration and turbulence intensity because of the differences in the particle size and the fuel materials. First, the average particle size of pulverized coal particle cloud in the past study was 48 μm [34]. On the other hand, the average particle size of the quasi-monodispersed PMMA particle cloud for Fig. 4.4(a) was 30 μm . Second, for different fuel materials, the composition of decomposed gases and their combustion behavior differ. Coal particles contain volatile matter, residual carbon, and ash. When combustion occurs, the volatile matter burns in the gas phase after devolatilization, while

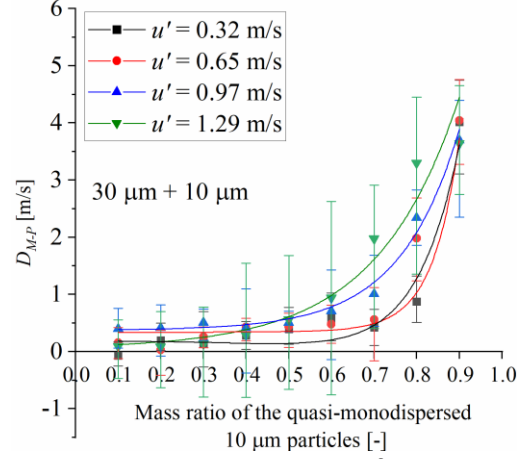
residual carbon in char particles burns heterogeneously and slowly [119]. On the other hand, for the PMMA particles, there is no residual carbon and ash.

However, as shown in Fig. 4.4 and Fig. 1.4(b), although the value of turbulent flame propagation velocity of coal particle clouds is different from that of PMMA particle clouds under the same condition, the turbulent flame propagation velocity of the PMMA particle clouds shows the same tendency with that of coal particle clouds. For particle clouds, the flame propagation velocity increases with the increase in turbulence intensity, and the particles concentration takes a minor role on the flame propagation velocity because, for both particle clouds, the flame propagation velocity is mainly controlled by the devolatilization rate of the particles. The heterogeneous combustion of char particles has little effect on the flame propagation velocity because of its slow combustion process.

4.3. Co-combustion of different size quasi-monodispersed particles



(a) Flame propagation velocity versus the mass ratio of 10- μm quasi-monodispersed particles



(b) D_{M-P} versus the mass ratio of 10- μm quasi-monodispersed particles

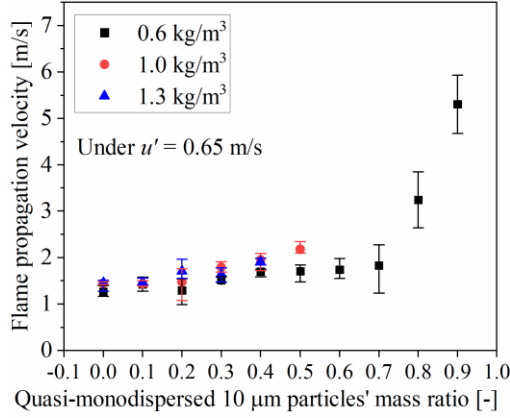
Fig. 4.5. Flame propagation tendency of 30- μm quasi-monodispersed particles mixed with 10- μm quasi-monodispersed particles.

First, combustion experiments were conducted by mixing 30- μm quasi-monodispersed particles with 10- μm quasi-monodispersed particles based on the mass ratio under the constant particle cloud concentration of 0.6 kg/m^3 . Fig. 4.5(a) shows the flame propagation velocity as a function of mass ratio of 10- μm quasi-monodispersed particles under different turbulence intensities. As shown in Fig. 4.5, the turbulent flame propagation velocity has a nonlinear relationship with the mass ratio of the small particles (J-shaped curve). The turbulent flame propagation velocity had a very weak increase at relatively low mass ratios of the small particles, while it sharply increased at high mass ratio of the small particles. This trend is called as the nonlinear convex downward relationship. Moreover, the flame propagation velocity increased with the increase in turbulence intensity for all cases. Further, to examine the turbulent flame propagation velocity difference between the combustions of the mixture of quasi-monodispersed particles of different sizes and pure large quasi-mono-dispersed particles, D_{M-P} was calculated by Eq. (4.1). Based on the turbulent flame propagation velocity difference between the mixtures that

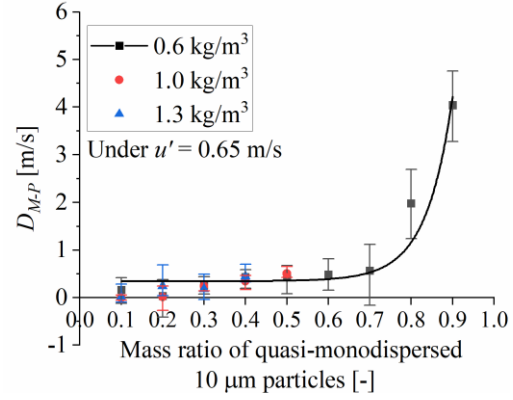
consist of small and large particles and the pure large particles, the increase in the turbulent flame propagation velocity caused by effect of small particles can be estimated under the same turbulence intensity. This methodology is better to obtain the effect of small particles under different turbulence intensities and mixing conditions.

$$D_{M-P} = S_{ws} - S_{wos}, \quad (4.1)$$

where S_{ws} represents the turbulent flame propagation velocity of the mixed particles with different sizes. S_{wos} represents the turbulent flame propagation velocity of pure large quasi-monodispersed particles combustion, which is in the same turbulent condition as the mixing combustion. For all conditions, first, D_{M-P} slightly increased. Then, there was a sharp D_{M-P} increase under a certain mass ratio of the small particles. As shown in Fig. 4.5(b), for lower turbulence intensity conditions, which include 0.32 m/s and 0.65 m/s, when the mass ratio of small particles is lower than 0.7, D_{M-P} slightly increases with the increase in the mass ratio of small particles. However, after mass ratio of small particles exceeds 0.7, there is a sharp increase in D_{M-P} with the rise of the mass ratio of small particles. Contrarily, for higher turbulence intensity conditions which include 0.97 m/s and 1.29 m/s, the sharp increase start at a mass ratio (of small particles) of 0.5.



(a) Flame propagation velocity as a function of the mass ratio of 10-μm quasi-monodispersed particles under different particle cloud concentrations

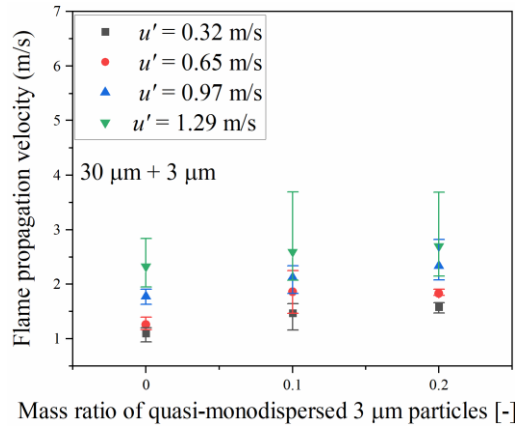


(b) D_{M-P} as a function of the mass ratio of 10-μm quasi-monodispersed particles under different particle cloud concentrations

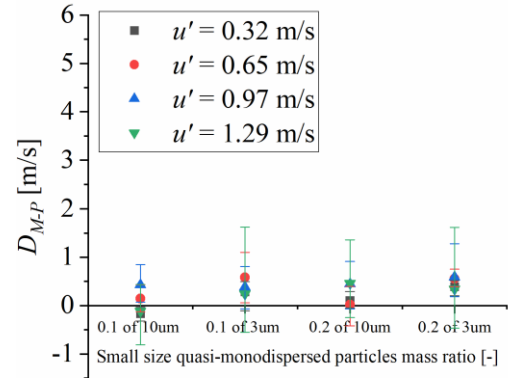
Fig. 4.6. Flame propagation tendency versus the small particle mass ratio for the mixture of the 30-μm quasi-monodispersed particles and 10-μm quasi-monodispersed particles under different concentrations of the mixture.

Second, combustion experiments were conducted by changing the mixture's concentration under the same turbulence intensity ($u' = 0.65$ m/s). Fig. 4.6(a) shows the flame propagation velocity for the mixture of 30-μm quasi-monodispersed particles and 10-μm quasi-monodispersed particles by changing the concentration from 0.6 to 1.3 kg/m³. Under a particle concentration of 1.0 kg/m³, schlieren photography and OH radical photography cannot capture the flame propagation images if the 10-μm quasi-monodispersed particles' mass ratio is larger than 0.5. Similarly, for a particle concentration of 1.3 kg/m³, the two photography methods cannot obtain images if the mass ratio of the 10-μm quasi-monodispersed particles is larger than 0.4. Fig. 4.6(b) shows D_{M-P} in terms of the mass ratio of 10-μm quasi-monodispersed particles. Under the same turbulence intensity and mass ratio of 10-μm quasi-monodispersed particles, the particle clouds concentration had little effect on D_{M-P} .

Further, combustion experiments were conducted for the mixture of the 30- μm quasi-monodispersed particles and 3- μm quasi-monodispersed particles at a particle concentration of 0.6 kg/m^3 . The result can be seen in Fig. 4.7. As shown in Fig. 4.7, when the mass ratio of small particles was lower than 0.2, if the 10- μm quasi-monodispersed particles were substituted with 3- μm particles in the clouds, the flame propagation velocity remained almost unchanged.



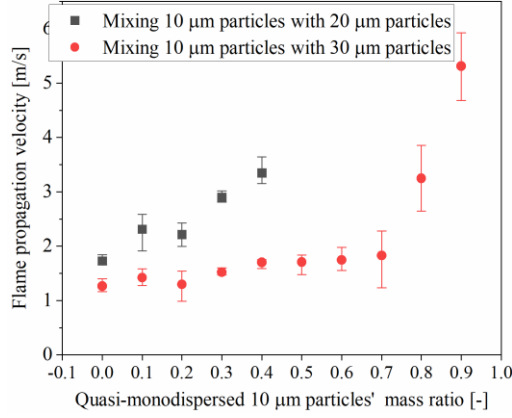
(a) Flame propagation velocity as a function of the 3 μm quasi-monodispersed particles' mass ratio



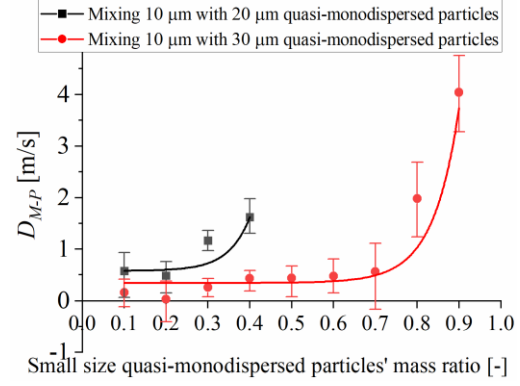
(b) D_{M-P} as a function of the small size quasi-monodispersed particles' mass ratio (comparing with mixing the 30 μm quasi-mono-dispersed particles with the 10 μm quasi-monodispersed particles)

Fig. 4.7. Flame propagation phenomenon under mixing the 30 μm quasi-mono-dispersed particles with the 3 μm quasi-mono-dispersed particles.

Based on the previous findings, to further consider the particle size difference effect in the mixture on the flame propagation phenomenon, combustion experiments were conducted by mixing the quasi-monodispersed 20- μm particles with quasi-monodispersed 10- μm particles. The results are shown in Fig. 4.8. Through mixing 20- μm particles with 10- μm particles, the sharp increase started at a mass ratio (of small particles) of 0.2. However, it started at around 0.7 for the condition of the mixture of the 30- μm particles with 10- μm particles.



(a) Flame propagation velocity as a function of the mass ratio of 10-μm quasi-monodispersed particles



(b) D_{M-P} as a function of the mass ratio of 10-μm quasi-monodispersed particles

Fig. 4.8. Flame propagation tendency of the mixture of 20-μm quasi-monodispersed particles and 10-μm quasi-monodispersed particles.

Thus, under the condition of mixing quasi-monodispersed particles with different diameters based on the mass ratio (the primary particle was a large diameter quasi-monodispersed particle), the nonlinear convex downward relationship (J-shaped curve) was found between the mass ratio of the small particles and flame propagation velocity. The turbulent flame propagation velocity first slightly increased with the increase in the small quasi-monodispersed particles' mass ratio. When the small particles' mass ratio increased to a certain point, the flame propagation velocity sharply increased with the rise of the small particles' mass ratio. The flame propagation velocity did not change upon changing the concentration of the particles under the same mixing condition. Moreover, the starting point of the sharp increase of the flame propagation velocity was advanced by increasing the turbulence intensity and decreasing the size of the primary particles (large particles). The mechanism is proposed to explain these tendencies in Chapter 4.5.

4.4. Particle size effect on turbulent flame propagation of quasi-monodispersed particle cloud

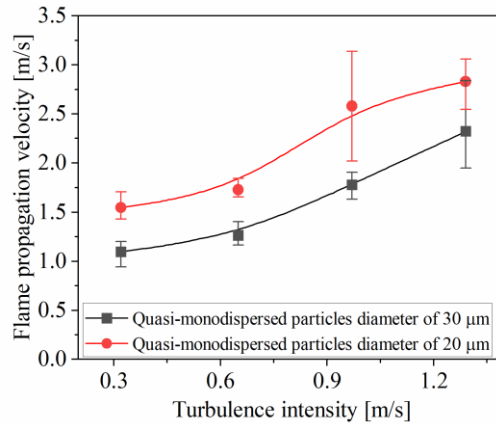
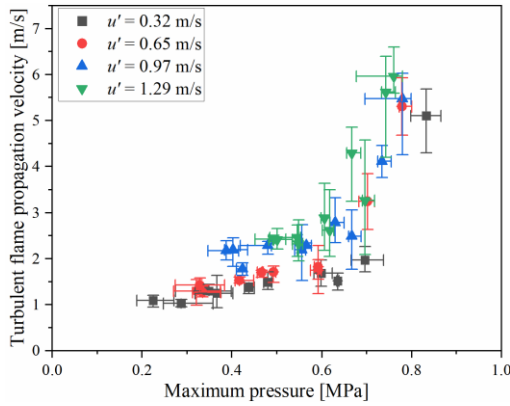


Fig. 4.9. Turbulent flame propagation velocity versus the turbulence intensity under quasi-monodispersed particles with different diameters.

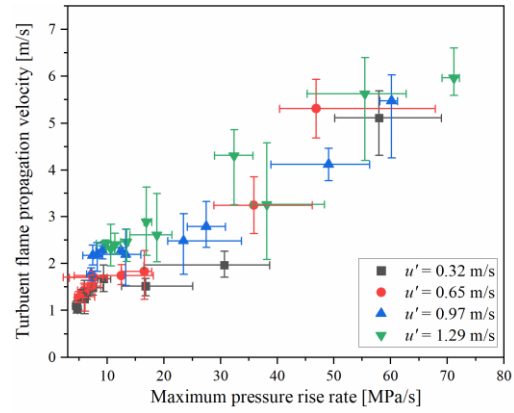
To clarify the particle size effect on the turbulent flame propagation phenomenon, combustion experiments were conducted using different sizes of quasi-monodispersed particles under a constant particle concentration of 0.6 kg/m^3 . As shown in Fig. 4.9, the flame propagation velocity increases with the decrease in the particle diameter (from 30 μm to 20 μm) under the same turbulence intensity.

However, because of the strong light scattering of the 10-μm quasi-monodispersed particles, the flame propagation images cannot be obtained by schlieren photography and OH radical photography. Therefore, to compare the turbulent flame propagation velocity indirectly, the recorded pressure histories were analyzed. Two key pressure-related values exist to describe the combustion behavior of solid particle clouds in the constant-volume combustion chamber, namely, the maximum pressure and maximum pressure rise rate. The maximum explosion

pressure is directly related to the average flame temperature in the vessel. The combustion reaction increases the pressure due to the heat release and temperature rise. Moreover, the maximum pressure rise rate is directly related to the mass burning rate of the fuel. The dust explosion intensity or the maximum rate of the pressure rise is the most direct measurement that best indicates the speed of the deflagration wave [120]. Therefore, the turbulent flame propagation velocity was directly compared with the maximum pressure and maximum pressure rise rate.



(a) Turbulent flame propagation velocity as a function of the maximum pressure



(b) Turbulent flame propagation velocity as a function of the maximum pressure rise rate

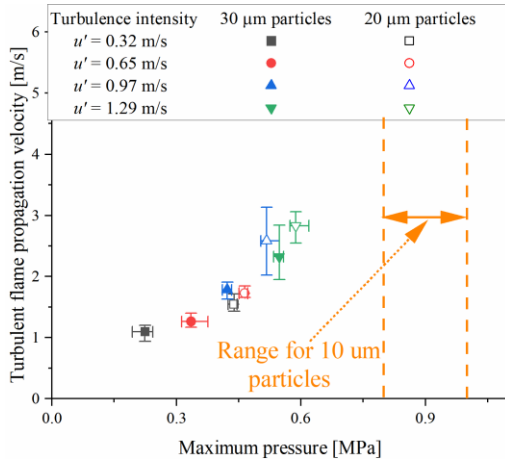
Fig. 4.10. Turbulent flame propagation velocity as functions of the pressure characteristics for the mixture of 30- μm quasi-monodispersed particles and 10- μm quasi-monodispersed particles under different mass ratios of 10- μm particles and turbulence intensities.

Fig. 4.10 shows the turbulent flame propagation velocity as a function of the maximum pressure and the maximum pressure rise rate for the mixture of 30- μm quasi-monodispersed particles and 10- μm quasi-monodispersed particles under different mass ratios of 10- μm particles and turbulence intensities. As shown in Fig. 4.10(a), under approximately the same turbulent flame propagation velocity, maximum pressure decreases with the increase in the turbulence intensity. This is caused by the turbulent flame-wall interactions. The turbulent vortexes push the

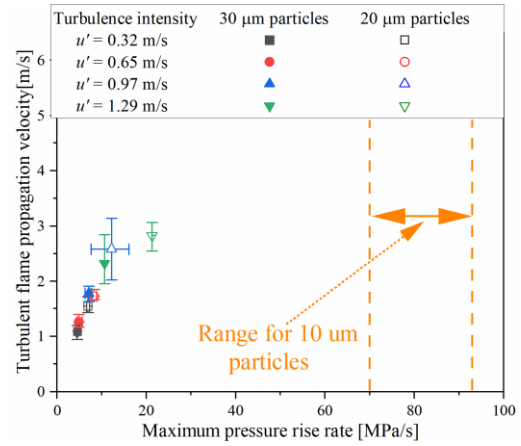
flame close to the wall and take the fresh gases away from the wall creating regions of high wall heat flux [121–123]. In high turbulence intensity, the turbulent vortex effect is enhanced because the size range of the turbulent vortex is enlarged. Therefore, for high turbulence intensity, the wall heat flux is higher than that for the low turbulence intensity to increase the heat transfer between the wall and flame.

However, this tendency is not clearly shown in the relation between the turbulent flame propagation velocity and the maximum pressure rise rate because of the non-uniform turbulent flame–wall interaction. Because the turbulent flame is highly deformed in the turbulent environment, the flame partially contacts the wall, whereas part of the flame is still in a flame propagation process. Therefore, the data shows scattering under different turbulence intensities.

Besides, as shown in Fig. 4.10(b), the turbulent flame propagation velocity increases with the maximum pressure rise rate. The same tendency was found in quasi-monodispersed particle combustion under different particle sizes. Fig. 4.11(a) and (b) show the turbulent flame propagation velocity as functions of the maximum pressure and maximum pressure rise rate, respectively, in quasi-monodispersed particle combustion. Furthermore, the maximum pressure for the 10- μm quasi-monodispersed particles varied in the range 0.8–1.0 MPa, whereas the maximum pressure rise rate varied in the range 70–93 MPa/s under different turbulence intensities. All values of the maximum pressure and the maximum pressure rise rate for 10- μm quasi-monodispersed particles are much larger than the values of plots shown in Fig. 4.10. Therefore, it is considered that the flame propagation velocity increases with the decrease in the particle diameter from 20 μm to 10 μm .



(a) Turbulent flame propagation velocity as a function of the maximum pressure



(b) Turbulent flame propagation velocity as a function of the maximum pressure rise rate

Fig. 4.11. Turbulent flame propagation velocity as a function of pressure characteristics for the combustion of quasi-monodispersed particles under different particle sizes.

For the quasi-monodispersed particles, as the particle size decreased, the ratio of the heat capacity to the surface area of the individual particle decreased. Hence, the time required to heat the particle decreases with decreasing the particle diameter. Accordingly, the small particles can be decomposed and burned within a short period. Consequently, the turbulent flame propagation velocity for the quasi-monodispersed particles with a smaller diameter is faster than that with a larger diameter. Therefore, the maximum pressure rise rate increases with the decrease in the particle size.

Notably, the findings above were based on the turbulent flame propagation velocity at a flame diameter of 0.0209 m, which is equivalent to the integral length scale of the turbulent field. To examine the effect of the choice of the flame diameter on the results, the flame propagation velocities at a flame diameter of 0.0300 m, which is the maximum flame diameter to obtain flame propagation velocity data under various conditions, were measured and compared. All findings

from flame propagation velocities at a flame diameter of 0.0300 m were consistent with those at a flame diameter of 0.0209 m.

4.5. Turbulent flame propagation mechanism of solid particle cloud in quasi-monodispersed particles and the mixture of quasi-monodispersed particles of different size

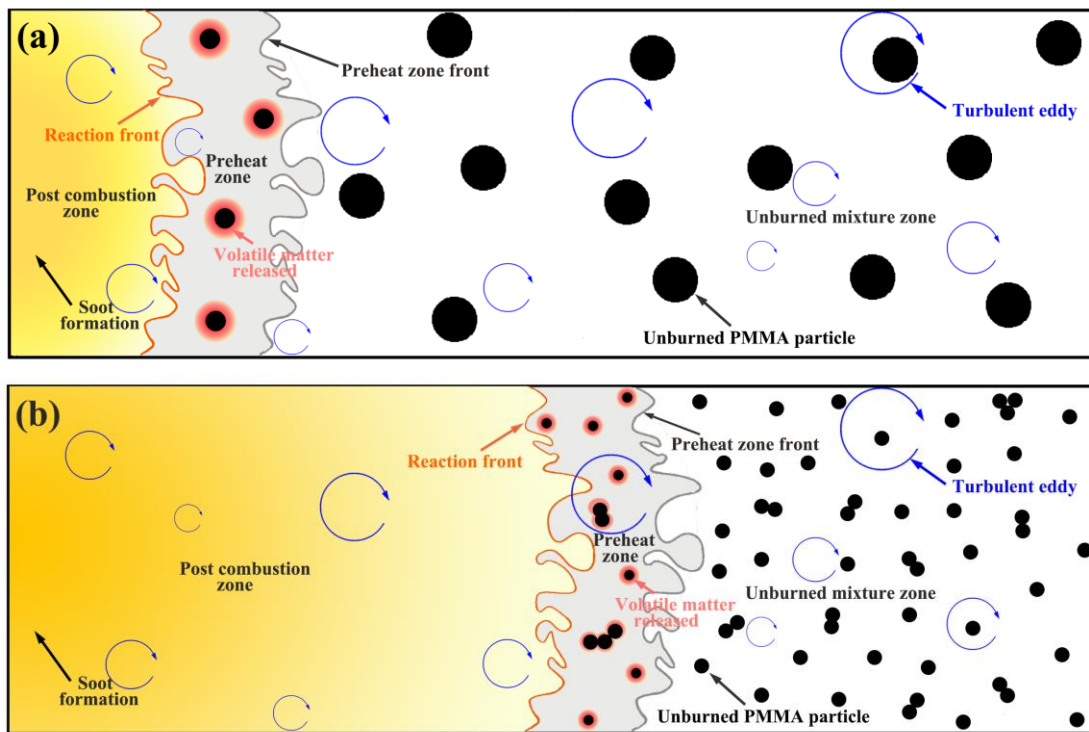


Fig. 4.12. Turbulent flame propagation mechanism for the combustion of (a) 30- μm quasi-monodispersed particle clouds, (b) 10- μm quasi-monodispersed particle clouds.

As illustrated in Fig. 4.12(a–b), the spherical turbulent flame propagation of the PMMA particle cloud combustion can be divided into three zones along the flame propagation direction, including the post-combustion zone, the preheat zone, and the unburned mixture zone. The

reaction front, which is detected by OH photography, indicates the combustion reaction starting point. A PMMA particle's combustion follows the sequential process of heat-up, liquefaction, devolatilization or pyrolysis, and combustion. Soot particles are formed by the secondary pyrolysis of volatile matter evolved from PMMA particles. In the preheat zone, PMMA particles just release volatile matter when heated by the turbulent heat transfer from the reaction front. In the PMMA particle cloud turbulent combustion, the turbulent flame propagation velocity is dominated by turbulent heat and mass transfer.

Fig. 4.12(a) and (b) shows the flame propagation mechanisms for the quasi-monodispersed 30- μm particle clouds and the quasi-monodispersed 10- μm particle clouds, respectively. As described in Chapter 3.4, the flame propagation velocity increased with the decrease in the particle diameter from 30 μm to 10 μm . It can be concluded that the specific surface area has an important effect on the flame propagation phenomenon in particle cloud combustion because the small particle, which has a larger specific surface area, can be devolatilized and burned faster.

Further, for the co-combustion of quasi-monodispersed particles with different sizes, we obtained the relationship between the turbulent flame propagation velocity and the mixture's Sauter mean diameter under $u' = 0.65$ m/s. The Sauter mean diameter, which is generally used to express the mean diameter of the particle cloud, is also called the surface-volume mean diameter. The Sauter mean diameter reflects a collection of spherical objects of different diameters, which is equal to the diameter of identical spherical objects forming an equivalent collection of spheres while both systems have the same total area and total volume [124]. As shown in Fig. 4.13(a), for the mixture of the 30- μm particles and 3- μm particles, even though the Sauter mean diameter of the mixture decreased dramatically from 28.3 μm to 10.0 μm , the turbulent flame propagation was almost the same. Similarly, for the mixture of the 30- μm particles and 10- μm particles, even

though the Sauter mean diameter decreased from 28.3 μm to 10.2 μm , the turbulent flame propagation velocity was almost the same. However, for the mixture of the 20- μm and 10- μm particles, even though the Sauter mean diameter decreased slightly from 18.5 μm to 13.4 μm , the turbulent flame propagation velocity largely increased from 1.729 m/s to 3.348 m/s. Besides, the same tendency was found between the turbulent flame propagation velocity and the specific surface area of the mixture (see Fig. E in Appendix).

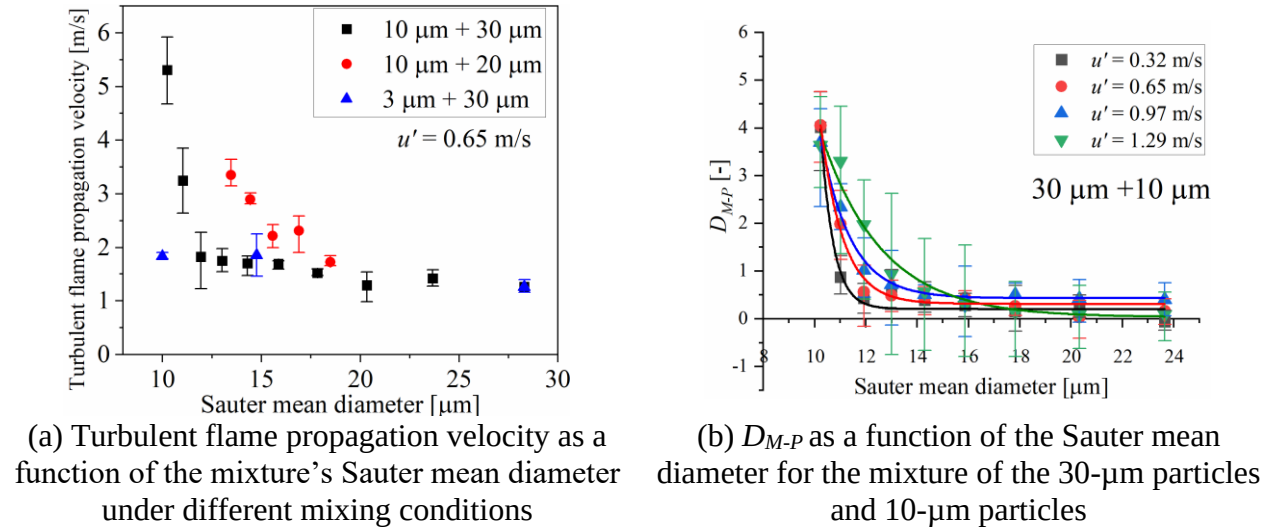


Fig. 4.13. Turbulent flame propagation characteristics as a function of the Sauter mean diameter under different mixing conditions.

Based on the above discussions, it can be concluded that the flame propagation behavior of mixing different sizes of quasi-monodispersed PMMA particles is not dominated by the total surface area of the particle cloud. Under different mixing conditions, the effective specific surface area and the effective Sauter mean diameter of the mixture are affected by different combinations of particle diameters and mass ratios. Further, for the present research, all experiments were carefully conducted by following the same experimental procedure which was explained in Chapter 2.3. Therefore, considering the factors affecting the mixtures' effective

specific surface area and the effective Sauter mean diameter in the chamber, the turbulent motion of the particles, and the turbulent particle–particle interactions (agglomeration) in turbulent flow are the dominant factors.

Further, for the mixture of the 30- μm particles and 10- μm particles and the mixture of 20- μm particles and 10- μm particles, under the same mixture's mass and mass ratio of 10- μm particles, the number of 10- μm particles is the same. However, the overall surface area of the 20- μm particles is larger than that of the 30- μm particles. Moreover, the interparticle force is enhanced in the mixture as the large particle size decreases [43,46,56]. This means that the interaction effect should be stronger for the mixture of the 20- μm particles and 10- μm particles. However, based on the experimental data in Fig. 4.5 and Fig. 4.13(a), under the same small particles' mass ratio and turbulence intensity, for the mixture of the 30- μm particles and 10- μm particles, the effect of small–large particle interaction is much stronger compared to the mixture of the 20- μm particles and 10- μm particles. By considering the agglomeration effect, this means that most of the small particles are in isolated status for the mixture of 20- μm particles and 10- μm particles. However, for the mixture of the 30- μm and 10- μm particles, most of the small particles are in agglomeration status. Therefore, in turbulent flow, compared to the agglomeration formed by 30- μm with 10- μm particles, the agglomeration formed by the 20- μm with 10- μm particles is easy to be broken up to cause an increase of the mixture's effective specific surface area. Further, under the same turbulence intensity and small particles' mass ratio, even though the effect of small–large particle interaction is stronger for the mixture of 20- μm and 10- μm particles, why the agglomeration formed by them is easy to be broken up? Taking into consideration the agglomeration turbulent break-up mechanism (This mechanism will be

explained in detail in the following part), the structure of the agglomeration must be considered (the turbulence effect is the same because the turbulence intensity is the same).

Besides, Fig. 4.13(b) shows D_{M-P} as a function of the Sauter mean diameter for the mixture of the 30- μm and 10- μm particles under different turbulence intensities. If do not consider the turbulent effect on the agglomeration structure, the value of D_{M-P} should be approximately the same under a certain small particles' mass ratio with different turbulence intensities because the small particles' effect is the same under a certain small particles' mass ratio. However, for lower turbulence intensity conditions, which include 0.32 m/s and 0.65 m/s, the sharp increase starts from the calculated Sauter mean diameter of 12 μm . However, for higher turbulence intensity conditions, which include 0.97 m/s and 1.29 m/s, the sharp increase trend starts from the calculated Sauter mean diameter of 16 μm . Therefore, the small-large particle interaction is different under different turbulence intensity conditions.

To understand the above turbulence flame propagation behavior in the co-combustion of different size quasi-monodispersed particles, we proposed a mechanism based on small-large particle interactions (see Fig. 4.14). The agglomeration effect on the combustion phenomenon has been studied for many years in the combustion filed [51,52,54]. Based on previous studies and above discussions, we believe that agglomeration has a dominant effect on the turbulent flame propagation phenomenon under the mixing of particles of different sizes.

After the particles are dispersed into the chamber, they are in motion, caused by the surrounding turbulent gas flow (The Brownian motion and gravitational settling are negligible compared to turbulence-induced motion [125]). The turbulence-induced particle motion can cause collisions between particles [46]. During the process of the collision between the particles,

the particles can agglomerate together to form the agglomerate caused by the interparticle force [46,125].

After the particles collide and agglomerate together, they form irregular shapes or fractals [126–131]. The morphology structure of the agglomerates is characterized by the fractal dimension, which also indicates the spatial mass distribution of the particles. Depending on the agglomeration structure, the agglomerate may have a fractal dimension between 1 (straight line) and 3 (compact spherical solid body) [46]. Generally, strong random motions of particles form irregular agglomerates with a small fractal dimension; in contrast, strong centripetal force favors the formation of spherical agglomerates [132].

In the turbulent flow field, the individual agglomerates can interact with turbulent structures, which may cause them to segregate to break through the high shearing of the flow or continue to grow with the enhanced collision rate [132–134]. Besides, the break-up of the agglomerates in turbulent flow is mainly controlled by shear flow induced by turbulent eddies and the fractal dimension of the agglomerate [126,132]. The break-up frequency can be increased by decreasing the fractal dimension of the agglomerate since the agglomeration's mechanical strength greatly increases with the increase in the fractal dimension. Moreover, increasing the turbulence intensity can enhance the turbulent shear force to increase the break-up frequency [132].

The agglomeration effect is enhanced with the decrease in the quasi-monodispersed PMMA particle size from 30- μm to 10- μm since the interparticle force is more significant for the small particle with a small mass [43,46,56]. However, the 10- μm quasi-monodispersed particles have the largest flame propagation velocity. It is considered that, for the 10- μm quasi-monodispersed particles, the effective diameter of the agglomerates is smaller than that of the larger-diameter quasi-monodispersed particles.

Compared to the agglomerates formed by 10- μm particles in quasi-monodispersed 10- μm particles combustion and the agglomerates formed by 10- μm and 20- μm particles in co-combustion of 10- μm and 20- μm quasi-monodispersed particles, the agglomerates formed by the 10- μm with 30- μm particles in co-combustion of 10- μm and 30- μm quasi-monodispersed particles are considered to have a larger fractal dimension. There are two major reasons: First, the single 30- μm particle has a large surface area to adhere small particles. Therefore, the small particles tend to adhere to the surface of the large particles to form the near-spherical-shaped agglomerates. It was confirmed by past studies that the more the dust particles in a dust cloud deviate from monodispersity, the faster the cloud coagulates [43,45]. Second, in the polydispersed particle clouds, the particles in the agglomerate are packed closer than that in the quasi-monodispersed particles since the small particles tend to fill the voids in the agglomerate [135].

Further, the agglomerates which have a small fractal dimension are easy to be broken up by the shear flow. Accordingly, the large agglomerates in 10- μm quasi-monodispersed particle clouds and the mixture of 10- μm and 20- μm quasi-monodispersed particle clouds are easy to be broken up to form isolated particles and small agglomerates.

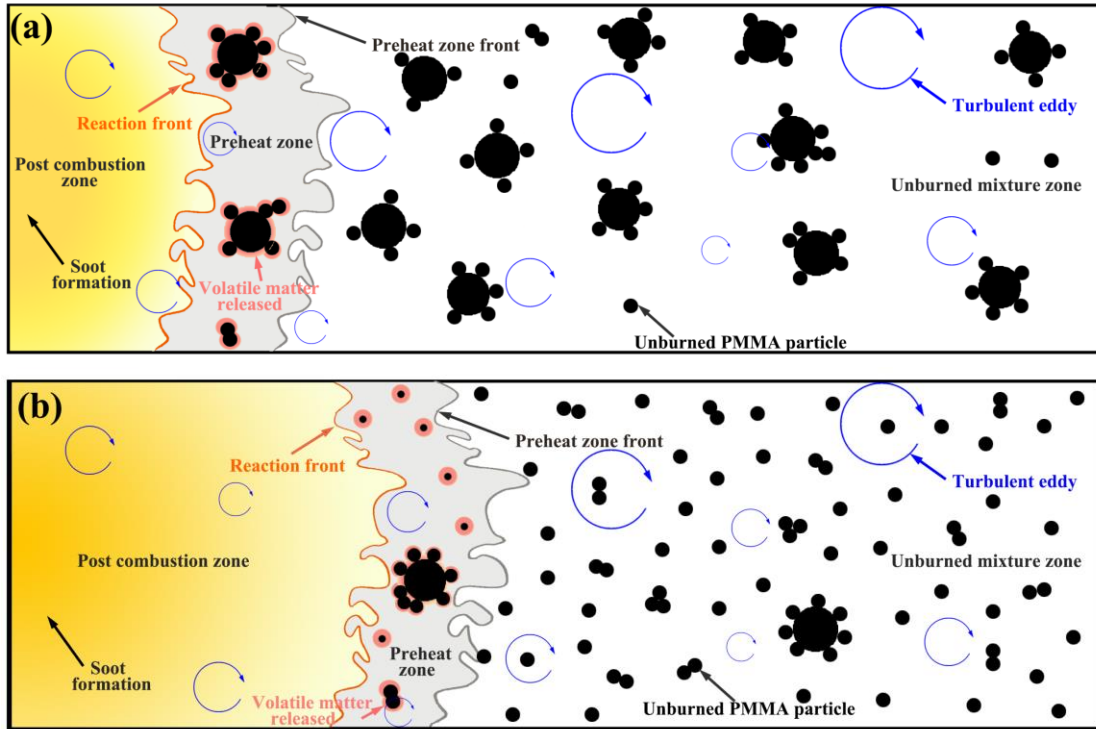


Fig. 4.14. Proposed turbulent flame propagation mechanism considering polydispersed interparticle interactions; (a) mixture of 30- μm quasi-monodispersed particles and 10- μm quasi-monodispersed particles with a small mass ratio of 10- μm particles, (b) mixture of 30- μm quasi-monodispersed particles and 10- μm quasi-monodispersed particles with a large mass ratio of 10- μm particles.

Fig. 4.14(a) and (b) show the flame propagation mechanism for the mixed 30- μm and 10- μm quasi-monodispersed particles. When the 10- μm quasi-monodispersed particle concentration is low, most of these small particles adhere to the surface of the large particles to form large agglomerates. As elucidated previously, this types of agglomerates with large fractal dimensions are hard to be broken up by the turbulent shear force. Furthermore, the devolatilization rate of these large agglomerates is low because of the small effective specific surface area compared to that of the isolated particles. The small particles which do not adhere to the large particles in the mixture remain isolated or in the small agglomerate. The isolated small particles or small agglomerates have a large effective specific surface area, which can be devolatilized faster than

large agglomerates. The number of isolated small particles or agglomerates increase with the increase in the mass ratio of the small-diameter particles because the increase of mass of the small particles can increase the collision possibility between small particles. However, when the concentration of small particles is low, most of the small particles adhere to the surface of large particles to form large agglomerates. Accordingly, although there are a small amount of isolated small particles or small agglomerates to increase the mixture's effective specific surface area, the overall effective specific surface area of the mixture is mainly controlled by large agglomerates. Therefore, the flame propagation velocity slightly increases when the small particles with a small mass ratio are added under different turbulence intensities. Furthermore, after the mass ratio of small particles reaches a certain value, the overall effective specific surface area of the mixture is controlled by the isolated small particles or small agglomerates. Therefore, the flame propagation velocity abruptly increases as the mass ratio of small particles exceeds a certain value.

Additionally, as the turbulence intensity increases, the starting point of the sharp increase of the flame propagation velocity is advanced. As the turbulence intensity increases, the break-up frequency can be increased because of the strong shear flow induced by turbulent eddies [132]. The intensive break-up events can cause large agglomerates to be separated to form more isolated small particles or small agglomerates. Accordingly, under the same small particle mass ratio, more isolated small particles or small agglomerates are included in the mixture to increase the overall effective specific surface area of the mixture. Finally, the starting point is advanced under high turbulence intensity.

Moreover, the starting point of the sharp increase of flame propagation velocity is advanced under mixing 10- μm quasi-monodispersed particles with 20- μm quasi-monodispersed particles. As elucidated previously, compared to the agglomerates formed by 10- μm and 30- μm particles in

the mixture of 10- μm quasi-monodispersed particles with 30- μm quasi-monodispersed particles, the agglomerates formed by 10- μm and 20- μm in mixture of 10- μm quasi-monodispersed particles with 20- μm quasi-monodispersed particles are considered to have a small fractal dimension. The agglomerates having small fractal dimensions are easy to be broken up by the shear force. Consequently, under the same mass ratio of small quasi-monodispersed particles, a larger number of the isolated small particles or small agglomerates are formed in the mixture of 10- μm quasi-monodispersed particles and 20 μm quasi-monodispersed particles compared to the case of mixing 10 μm and 30 μm particles. Therefore, the starting point of the sharp increase in flame propagation velocity is advanced.

Besides, the experiments by using the polydispersed particles and quasi-monodispersed particles having approximately the same volume-weighted mean diameter (30 μm) were conducted. The particle size properties of mixtures can be seen in Table B in Appendix. The particle size distribution data for the polydispersed particles can be seen in Table E in Appendix. Moreover, the size range of the polydispersed particles varies between 10 μm and 60 μm . The result (which can be seen in Fig. F in the Appendix) shows that, the turbulent flame propagation velocity of polydispersed particles is slightly larger than (or almost same with) that of the quasi-monodispersed particles. If considering the agglomeration effect on the turbulent flame propagation phenomenon, the small particles with large particles, which have a large particle size difference, will form the agglomerates having a large fractal dimension. However, for the particles which have a small size difference, the agglomerate will have a small fractal dimension. Finally, the overall effective specific surface area of the polydispersed particles is slightly larger than (or almost same with) that of the quasi-monodispersed particles.

4.6. Concluding marks

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. The findings can be summarized as follows:

For the combustion of quasi-monodispersed PMMA particle clouds, the flame propagation velocity increases with the increase in the turbulence intensity, and the particle concentration has little effect on the flame propagation velocity. The same tendency has been observed in our previous study for the coal particle cloud combustion [14]. The consistency of the current and previous results suggest that the heterogeneous combustion of char particles has little effect on the turbulent flame propagation velocity of the combustion of solid particle clouds because of its slow combustion process.

Decreasing the quasi-monodispersed PMMA particles' diameter from 30 μm to 10 μm increases the turbulent flame propagation velocity because the small quasi-monodispersed particles have a large specific surface area and can be devolatilized and burned faster.

Under mixing different size quasi-monodispersed particles, the nonlinear convex downward relationship (J-shaped curve) between the turbulent flame propagation velocity and the small particle mass ratio was found. The turbulent flame propagation velocity first slightly increases with the increase in the small particle mass ratio; then the turbulent flame propagation velocity sharply increases after a certain small particle mass ratio. The rise of the turbulence intensity and the decrease in the size of the primary particle (large particle) in the clouds can advance the

starting point of sharp increase. In the mixture, the agglomeration between small and large particles forms large agglomerates, which have a lower effective specific surface area than the isolated large particles. The isolated small particles or small agglomerates have a large effective specific surface area. When the concentration of small particles is low, most of the small particles adhere to the surface of large particles to form large agglomerates and dominate the mixture's overall effective specific surface area. After reaching a certain small particle mass ratio (the starting point of sharp increase), the overall effective specific surface area of the mixture is mainly controlled by isolated small particles or small agglomerates. Additionally, increasing the turbulence intensity can increase the shear force and, in turn, the agglomeration break-up frequency to form more isolated small particles or small agglomerates and further advance the starting point of the sharp increase. Decreasing the primary particle (large particles) size in the mixture can decrease the fractal dimension of agglomerates. Further, agglomerates having a small fractal dimension are easy to be broken up by the shear flow to increase the number of small agglomerates or isolated small particles.

Chapter 5. Solid particle fuel/ammonia co-combustion

turbulent flame propagation mechanism

5.1. Flame observation

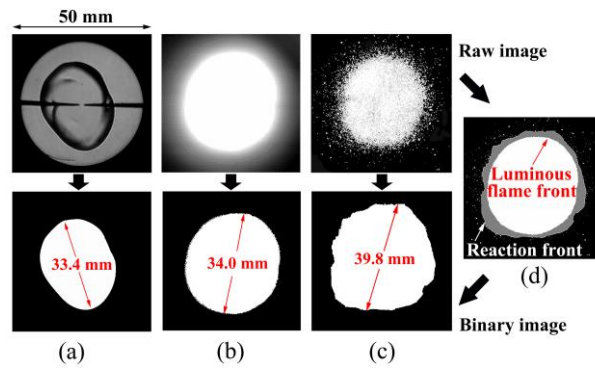


Fig. 5.1. Images processing; (a) ammonia/oxygen/nitrogen flame; (b) luminous flame in co-combustion; (c) OH radical image in co-combustion; (d) OH radical image processing.

Fig. 5.1(a) shows the schlieren image of ammonia/oxygen/nitrogen flames for $\phi = 0.8$ at $u' = 0.32$ m/s. ϕ represents the ammonia/oxygen/nitrogen equivalence ratio of pure ammonia combustion. Fig. 5.1(b) shows the direct camera image of co-combustion on the condition of $\phi_{\text{Ammonia}} = 0.8$ at $u' = 0.32$ m/s. ϕ_{Ammonia} represents the ammonia/oxygen/nitrogen equivalence ratio in co-combustion. The glow surrounding the luminous flame was not considered as part of luminous flame to maintain consistency with the pure coal combustion research that was previously conducted [34]. The luminous flame front comprises only the white border of the original image. When the number density of the soot particles, which are formed by the secondary pyrolysis of volatile matter evolved from coal particles, becomes sufficient, the

luminous flame front was formed. Fig. 5.1(c) illustrates the OH radical image at same condition and time considered for Fig. 5.1(b). As shown in Fig. 5.1(d), the diameter of the reaction front (the border of OH radical image) is larger than the luminous flame front (the border of direct image). Finally, the flame radii were measured by counting the dimension between the farthest of the flame fronts, which was an approach that was similar to that used with pure coal combustion [34].

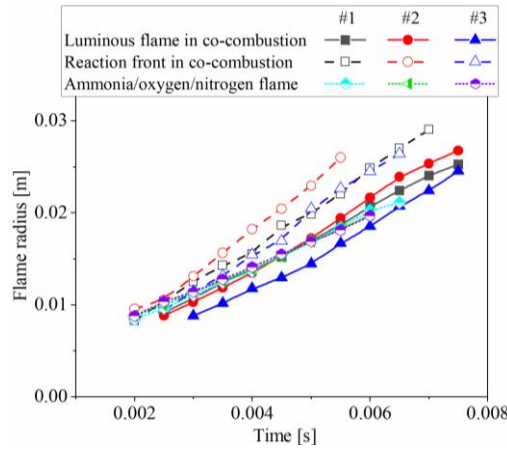


Fig. 5.2. Flame radii histories of the luminous flame and reaction front of co-combustion at $\phi_{\text{Ammonia}} = 0.8$ as well as ammonia/oxygen/nitrogen flame at $\phi = 0.8$ under the same turbulence intensity of $u' = 0.32$ m/s.

Fig. 5.2 shows the flame radii histories of the luminous flame, reaction front and ammonia/oxygen/nitrogen flame under the same equivalence ratio and turbulence intensity. Three trajectories of every flame in the same experimental condition are displayed here. The flame radius was measured from 0.008 m to the flame front touching the window edge for eliminating the ignition effect [63]. The pressure during observation range was constant at $\pm 5\%$ atmosphere pressure for all the conditions, which was a trend that was similar to previous studies [9,34,63]. As shown in Fig. 5.2, the luminous flame radius is always smaller than reaction front at the same

time. This phenomenon was observed for all cases of co-combustion in the study. In addition, the reaction front radius was greater than that of ammonia/oxygen/nitrogen flame in this condition.

A polynomial relationship for the measured propagation radius as a function of time was applied to obtain the propagation velocity. For all turbulent combustion experiments, the propagation velocities of the luminous flame, reaction front and ammonia/oxygen/nitrogen flame increased with the increase of the flame radii, which was the same as that identified in previous pure PMMA particle cloud combustion. Additionally, no constant value was observed within the observation range. Therefore, to examine turbulence intensity effect, the flame propagation velocities at a flame radius of $0.01045 \text{ m } (L_f/2)$ were chosen for comparison [34]. Additionally, to compare the luminous flame propagation velocity of co-combustion with that of pure coal combustion and to compare the propagation velocities of the gas phase in co-combustion with that of ammonia/oxygen/nitrogen flame, the luminous flame, reaction front and ammonia/oxygen/nitrogen flame propagation velocities were separately analyzed and compared.

5.2. Luminous flame propagation characteristics in turbulent co-combustion under various ammonia equivalence ratios

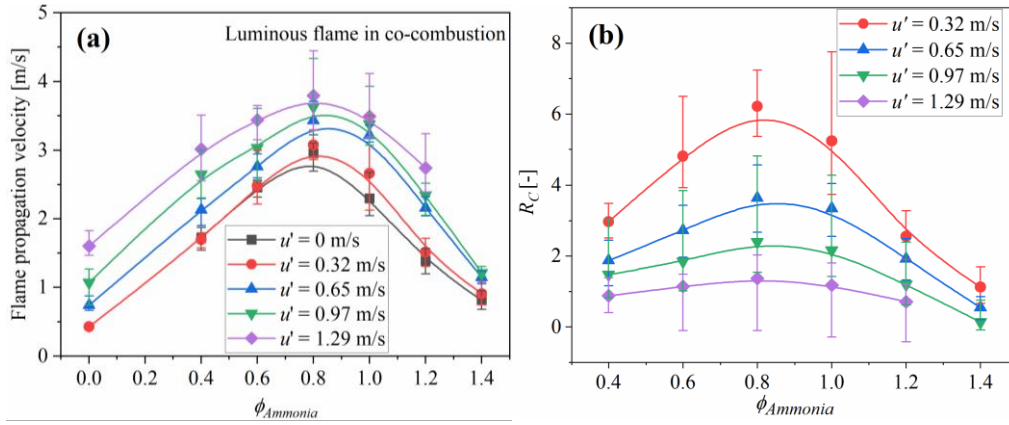


Fig. 5.3. (a) Luminous flame propagation velocities as functions of $\phi_{Ammonia}$ under different u' ; (b) $Ratio_{Coal}$ in terms of $\phi_{Ammonia}$.

Fig. 5.3(a) shows the luminous flame propagation velocities as functions of $\phi_{Ammonia}$ in co-combustion under various turbulence intensities. In addition, $\phi_{Ammonia} = 0$ represents pure coal combustion [34]. As shown in this figure, the propagation velocity increases with the increase of turbulence intensity. As clarified in pure PMMA particle cloud combustion, this was considered to be caused by the enhanced turbulent transport of heat and mass and the increased total surface area of the wrinkled flamelets by increasing turbulence intensity.

To examine the difference of luminous flame propagation velocities between co-combustion and pure coal combustion relative to the luminous flame propagation velocity of pure coal combustion, $ratio_{Coal}$ (R_C) was used which was calculated by Eq. (5.1):

$$R_C = \frac{S_{LCO} - S_{LC}}{S_{LC}}, \quad (5.1)$$

$S_{Luminous\ co-combustion\ flame}$ (S_{LCO}) represents the luminous flame propagation velocity in co-combustion. $S_{Luminous\ pure\ coal\ flame}$ (S_{LC}) represents the luminous flame propagation velocity of pure coal combustion, which is in same turbulent condition as with co-combustion. As shown in

Fig. 5.4, all values of R_C are positive. This means the luminous flame propagation velocity of co-combustion is larger than that of pure coal combustion. In addition, R_C increased with the increase of the ammonia equivalence ratio $\phi_{Ammonia}$ from 0.4 to 0.8. Then, a decreasing trend was observed with the increase of $\phi_{Ammonia}$ from 0.8 to 1.4. Vertically, under the same $\phi_{Ammonia}$, R_C decreased with the rise of the turbulence intensity.

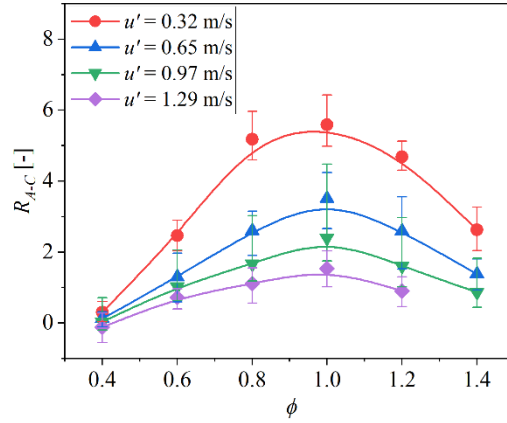


Fig. 5.4. $Ratio_{Ammonia-Coal}$ as a function of ϕ under various u' .

The disparity between propagation velocities of ammonia/oxygen/nitrogen flame with pure coal flame relative to the flame propagation velocity of pure coal combustion was examined by $ratio_{Ammonia-Coal}$ (R_{A-C}) that was expressed by Eq. (5.2):

$$R_{A-C} = \frac{S_A - S_{LC}}{S_{LC}}, \quad (5.2)$$

$S_{Ammonia/oxygen/nitrogen\ flame}$ (S_A) represents ammonia/oxygen/nitrogen flame propagation velocity, which is under the same turbulence intensity as with pure coal combustion. The relation of S_A as ϕ is shown in Fig. 3.3.

As shown in Fig. 5.4(b), all the values of R_{A-C} under ϕ from 0.6 to 1.4 are positive, which is the same observed with R_C . Furthermore, under the same equivalence ratio, ϕ , R_{A-C} decreased

with an increase of the turbulence intensity, which was the same trend with R_C as $\phi_{Ammonia}$. Under the condition of $\phi_{Ammonia}$ from 0.4 to 1.2, the R_C at each $\phi_{Ammonia}$ is approximately the same with the R_{A-C} at $\phi = \phi_{Ammonia} + 0.2$ at the same turbulent condition. This was considered as the equivalence ratio increment by the volatile matter.

5.3. Reaction front propagation features in turbulent co-combustion under various ammonia equivalence ratios

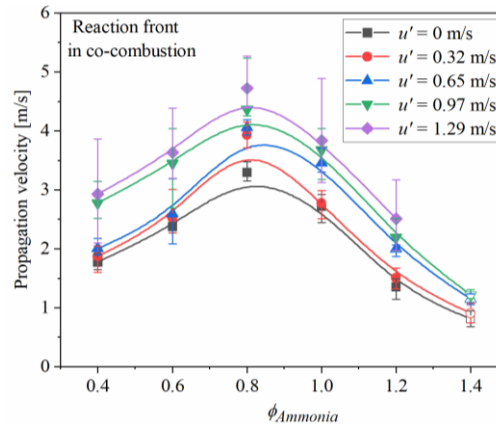


Fig. 5.5. Reaction front propagation velocities as $\phi_{Ammonia}$ under various u' .

Fig. 5.5 shows reaction front propagation velocities as functions of $\phi_{Ammonia}$ under various turbulence intensities. In the case of $\phi_{Ammonia} = 1.4$, the OH radical photography could not capture the OH radical because of weak light intensity. Therefore, for comparison with pure ammonia combustion, the propagation velocity of luminous flame front is used only for this condition ($\phi_{Ammonia} = 1.4$). This was because the propagation velocities of the reaction front in condition of $\phi_{Ammonia} = 0.4, 0.6, 1.0, 1.2$ at various turbulence intensities were approximately the same as those of the luminous flame. As shown in this figure, the propagation velocity increases with increase

of the turbulence intensity, which is the same as the luminous flame propagation in co-combustion. By conducting a comparison with ammonia/oxygen/nitrogen combustion, the maximum propagation velocity for each turbulence intensity shifted to $\phi_{Ammonia} = 0.8$. This was because of the equivalence ratio increment by the volatile matter as explained in the last section. The released volatile matter increased the local equivalence ratio of the flame front.

To examine the coal particles' effect on ammonia/oxygen/nitrogen flame, $ratio_{Reaction\ front}$ (R_R) is used and is expressed by Eq. (5.3):

$$R_R = \frac{S_R - S_A}{S_A}, \quad (5.3)$$

$S_{Reaction\ front}(S_R)$ represents the reaction front propagation velocity in co-combustion which is shown in Fig. 5.6. In this equation, the parameters were in the same turbulence intensity and ammonia equivalence ratio.

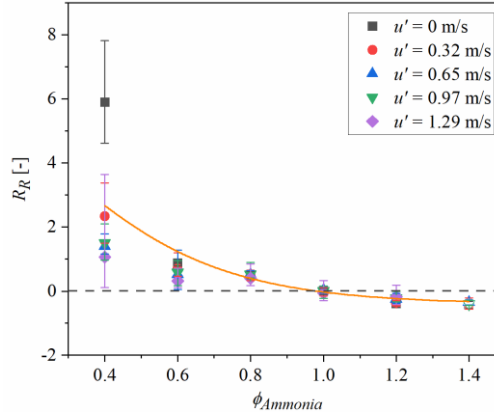


Fig. 5.6. $Ratio_{Reaction\ front}$ in terms of $\phi_{Ammonia}$ under various u' .

As illustrated in Fig. 5.6, in ammonia lean conditions, the propagation velocity of the reaction front in the co-combustion case is greater than that of pure ammonia combustion. On the other hand, in ammonia rich conditions, the propagation velocity of reaction front in the co-combustion case is lower than that of pure ammonia combustion. However, on ammonia stoichiometric co-combustion, both are almost same. To explain this tendency, mechanism of pulverized coal/ammonia co-combustion has been proposed, as shown in Fig. 5.7.

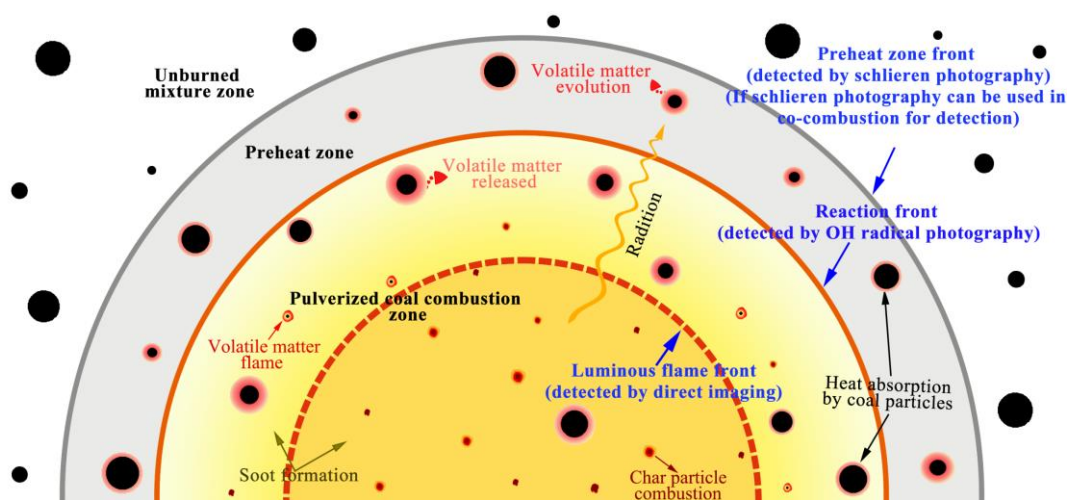


Fig. 5.7. One dimensional assumption of co-combustion flame structure.

The pulverized coal/ammonia co-combustion flame can be divided into three zones according to the flame propagation direction, including the pulverized coal combustion zone, preheat zone, and unburned mixture zone. The reaction front is the border between the pulverized coal combustion zone and preheat zone. Most of the ammonia is considered to be completely combusted in a thin area of this reaction front in ammonia lean cases. In ammonia rich cases, most of oxygen is consumed by the reaction with ammonia and volatile matter in the reaction front. Some reactions including the devolatilization of coal particles and formation of soot particles proceed after the reaction front passing by. In the pulverized coal combustion zone, the

single coal particle combustion follows the sequential process of heat-up, volatile matter release and combustion, and char combustion. Soot particles are formed by the secondary pyrolysis of volatile matter evolved from coal particles. Small diameter coal particles generally tend to combust faster than larger ones because of larger specific surface area [136]. Therefore, volatile matter release and combustion, soot formation, and char combustion simultaneously occur in this area. As defined previously, the luminous flame front is the white border of the original image, which indicates the existence of a high density of soot particles with high temperature. Furthermore, the luminous flame has a strong radiation effect to surrounding area [137]. In the preheat zone, coal particles with smaller diameter release volatile matter when the particles are heated up by the heat transfer from the reaction front and also by the heat transfer from the luminous flame in the pulverized coal combustion zone through the radiation. Before the reaction front passing by, the local equivalence ratio in the preheat zone was already changed by addition of volatile matter. Moreover, the unburned mixture zone is just a mixture of unburned gases and coal particles.

Clearly, the effects on the difference of flame propagation velocities between pulverized coal/ammonia co-combustion and pure ammonia combustion are of three types. First, the heat sink effect of the unburned coal particles in the preheat zone has a negative effect on the flame propagation velocity of the co-combustion. During the preheat of coal particles, the sensible heat as well as the heat required for the devolatilization are absorbed by the particles. Second, the strong radiation from the luminous flame to the unburned coal particles in the preheat zone has a positive effect on the flame propagation velocity of the co-combustion. This strong radiation is mainly caused by the soot particles with high temperature in the luminous flame [10] with a small contribution towards the radiation by the coal particles themselves. Indeed, the strong radiation

between the solid particles in the pulverized coal combustion field is a unique additional heat transfer path [139], which is absent in the gaseous fuel combustion fields without soot formation. Third, the increment of local equivalence ratio in the preheat zone by addition of volatile matter can induce positive or negative effects, depending on $\phi_{Ammonia}$. This effect is positive in the ammonia lean condition because of the increase in the amount of fuel species that causes an increase in the flame temperature, while the increase in the amount in fuel has a negative effect in the ammonia rich condition because the addition of the fuel amount causes a decrease in the flame temperature. These three effects compete to determine the propagation velocity of the reaction front in co-combustion.

In the ammonia lean co-combustion condition, the propagation velocity of reaction front is larger than that of pure ammonia combustion. This is because the positive effects, which are the strong radiation from the luminous flame and the increment of local equivalence ratio by the addition of volatile matter, are larger than negative effect, which is the heat absorption by the coal particles. On the other hand, in ammonia rich condition, the negative effects, which are the heat absorption by coal particles and a very high equivalence ratio under a rich $\phi_{Ammonia}$ condition, overcome the positive effect of the strong radiation. In the ammonia stoichiometric condition, the propagation velocity of the reaction front is almost the same as that of the ammonia/oxygen/nitrogen flame. This is because the negative effect is offset by the positive effect.

The present research revealed the fundamental mechanism of the pulverized coal particle clouds/ammonia co-combustion. From a micro perspective, the single coal particle combustion phenomenon differs under conditions of different particle size, atmosphere gases composition, and ambient temperature [140–142]. The unique phenomenon of the single coal particle/ammonia

co-combustion is considered to contribute to reveal the mechanism of pulverized coal/ammonia co-combustion. However, it is beyond the scope of the present study.

5.4. Concluding marks

Because ammonia is one of the most promising candidates for energy carrier in the future, various applications of ammonia as a fuel are currently considered. One medium for utilizing ammonia is by introducing it to coal-fired boilers. To the best of our knowledge, this paper is the first to report the fundamental mechanism of the flame propagation phenomenon for pulverized coal/ammonia co-combustion. The effects of the equivalence ratio of the ammonia-oxidizer mixture on the flame propagation velocity of pulverized coal/ammonia co-combustion in turbulent fields were clarified by the experiments employing a unique fan-stirred constant volume chamber. The flame propagation velocities of pulverized coal/ammonia co-combustion, pure ammonia combustion, and pure pulverized coal combustion were compared. As expected, the flame propagation velocity of pulverized coal/ammonia was higher than that of the pure pulverized coal combustion for all conditions. However, the comparison of the flame propagation velocities of pulverized coal/ammonia co-combustion and that of the pure ammonia combustion, revealed that whether the flame propagation of the pulverized coal/ammonia was higher than that of the pure ammonia combustion was dependent on the equivalence ratio of the ammonia-oxidizer. This unique feature was explained by a mechanism including three competing effects proposed by the authors. In the ammonia lean condition, the positive effects, which are the strong radiation from the luminous flame and the increment of local equivalence ratio by the addition of volatile matter, are larger than the negative effect, which is the heat absorption by coal particles in preheat zone. In the ammonia rich condition, the effect of an increment of the local

equivalence ratio by the addition of volatile matter turns into a negative effect. Consequently, the negative effects overcome the positive effect in the ammonia rich condition resulting in a lower flame propagation velocity of pulverized coal/ammonia co-combustion.

Chapter 6. Validation of the solid particle cloud/ammonia co-combustion turbulent flame propagation mechanism

6.1. Heat sink negative effect of unburned particles on solid particle cloud/ammonia/oxygen/nitrogen co-combustion

To validate the heat sink negative effect from the unburned particle on solid particle cloud/ammonia co-combustion, the silica particle cloud/ammonia/oxygen/nitrogen mixing-combustion experiments were conducted under various turbulence intensities (The mass of the silica particles in the silica particle cloud/ammonia/oxygen/nitrogen mixing-combustion was the same as that of the PMMA particles in the PMMA particle cloud/ammonia co-combustion under a same ammonia equivalence ratio). The same image processing and data analysis procedure with the PMMA particle cloud combustion was used for the silica particle cloud/ammonia/oxygen/nitrogen mixing-combustion experiments.

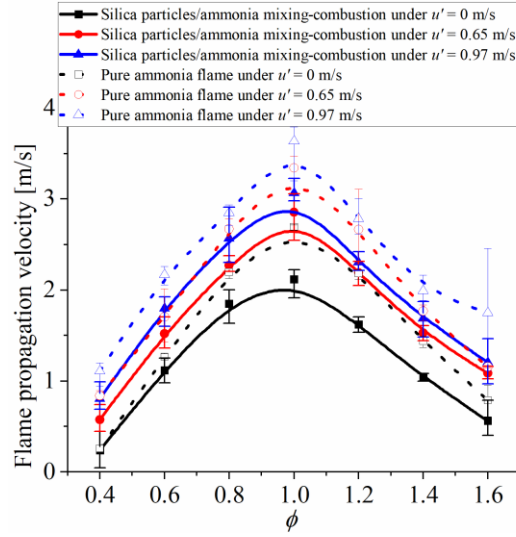


Fig. 6.1. Turbulent fame propagation in silica particle cloud/ammonia/oxygen/nitrogen mixing-combustion under various ammonia equivalence ratios and turbulence intensities.

Fig. 6.1 shows the silica particle cloud/ammonia/oxygen/nitrogen mixing-combustion turbulent flame propagation velocity as a function of ammonia equivalence ratio under various turbulence intensities. The turbulent flame propagation velocity obtained in pure ammonia combustion was also included in Fig. 6.1.

To examine the silica particles effect on pure ammonia/oxygen/nitrogen combustion, the R was used which was calculated by Eq. (6.1):

$$R = \frac{S_{Mix} - S_A}{S_A}, \quad (6.1)$$

Where S_{Mix} represents the turbulent flame propagation velocity in the mixing-combustion which is shown in Fig. 6.1. S_A represents the pure ammonia/oxygen/nitrogen turbulent flame propagation velocity, which is under a same turbulence intensity and ammonia equivalence ratio as with the mixing-combustion. The relation of S_A as ϕ is shown in Fig. 3.3 [15].

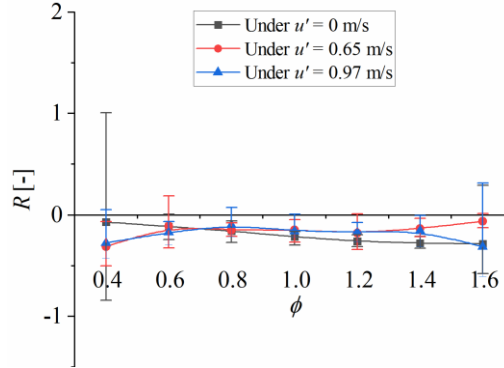


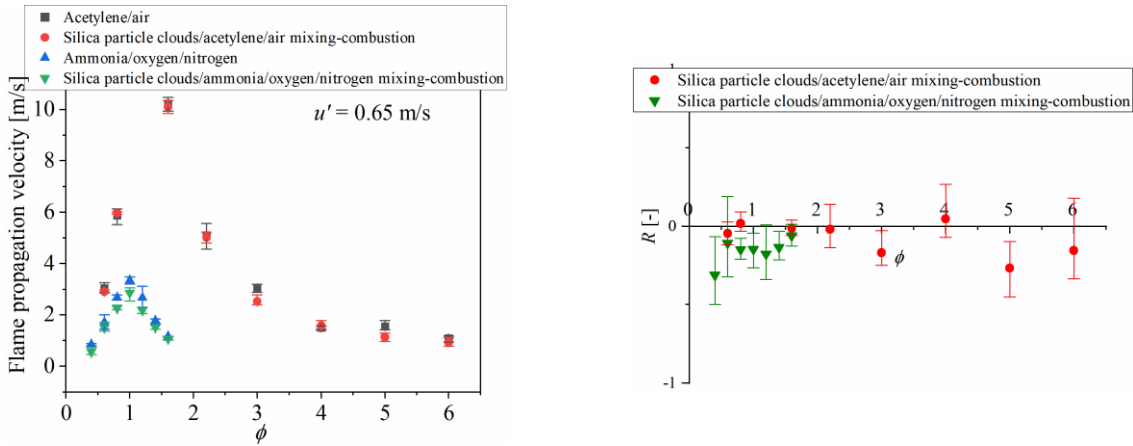
Fig. 6.2. R as a function of ϕ in silica particle cloud/ammonia/oxygen/nitrogen mixing-combustion.

As shown in Fig. 6.2, all values of R are lower than 0 which means that turbulent flame propagation velocity of silica particle cloud/ammonia/oxygen/nitrogen mixing-combustion is lower than that of pure ammonia/oxygen/nitrogen combustion under a same ammonia equivalence ratio and turbulence intensity. Therefore, in silica particle cloud/ammonia/oxygen/nitrogen mixing-combustion, the silica particles extract the heat from the flame to decrease the flame temperature to decrease the turbulent flame propagation velocity.

In the solid-particle-fuel/ammonia/oxygen/nitrogen co-combustion, on the one hand, the unburned particles in the preheat zone of flame front will absorb the heat from the flame because the heat transfer between the high temperature flame and the lower temperature unburned particles induces the thermal heat sink effect (sensible heat). On the other hand, the heat required for the devolatilization of the particle is absorbed by the particles to release the volatile matter. Finally, in solid-particle-fuel/ammonia/oxygen/nitrogen co-combustion, the unburned particles in

the preheat zone of flame front induce the negative heat sink effect on the turbulent flame propagation.

6.2. Soot particles radiation effect on solid particle cloud/ammonia co-combustion turbulent flame propagation



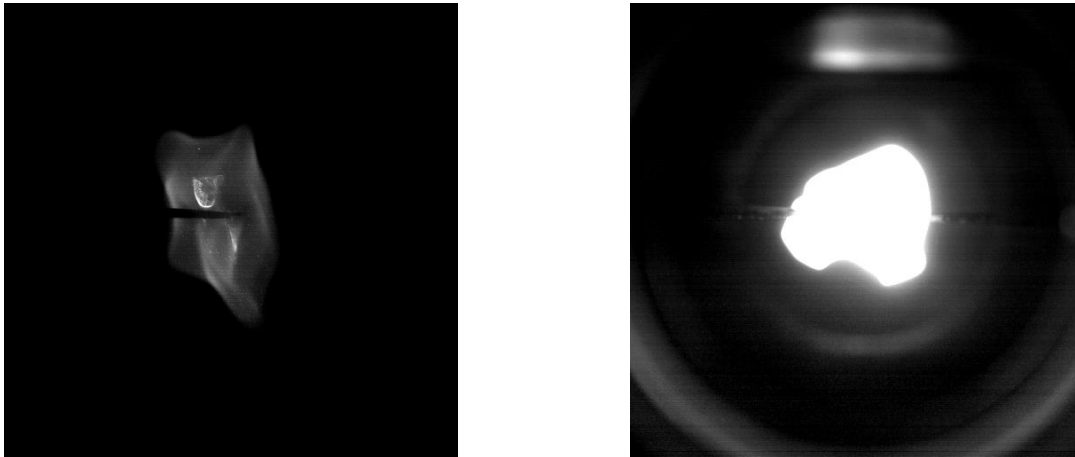
(a) Turbulent flame propagation velocity as a function of acetylene equivalence ratio in silica particle cloud/acetylene/air mixing-combustion and pure acetylene/air combustion

(b) R in silica particle cloud/acetylene/air mixing-combustion and silica particle cloud/ammonia/oxygen/nitrogen mixing-combustion

Fig. 6.3. Turbulent flame propagation in silica particle cloud/acetylene/air mixing-combustion and silica particle cloud/ammonia/oxygen/nitrogen mixing-combustion.

Fig. 6.3(a) shows turbulent flame propagation velocity of silica particle cloud/acetylene/air mixing-combustion and pure acetylene/air combustion as a function of acetylene equivalence ratio under a turbulence intensity of 0.65 m/s. R was used to obtain the turbulent flame propagation velocity difference between silica particle cloud/acetylene/air mixing-combustion and pure acetylene/air combustion. Fig. 6.3(b) shows the R as a function of acetylene equivalence ratio. To compare with silica particle cloud/ammonia/oxygen/nitrogen mixing-combustion, the data obtained in silica particle cloud/ammonia/oxygen/nitrogen mixing-combustion were also

included in Fig. 6.3(a) and (b). Fig. 6.4(a) shows the direct flame image of ammonia/oxygen/nitrogen combustion under ammonia equivalence ratio of 1.6 and turbulence intensity of 0.65 m/s. Fig. 6.4(b) shows the direct flame image of acetylene/air combustion under acetylene equivalence ratio of 4.0 and turbulence intensity of 0.65 m/s. As pointed out by Hayakawa et al. [7], the flame observed in pure ammonia combustion is caused by the NH_2 ammonia α band spectra and the superheated H_2O vapor spectra. NH_2 increases as the equivalence ratio increases. However, in acetylene/air combustion, there are large density soot particles formed. Therefore, as shown in Fig. 6.4, the luminous flame formed in acetylene rich combustion.



(a) ammonia/oxygen/nitrogen flame under $\phi = 1.6$ and $u' = 0.65$ m/s (b) acetylene/air flame under $\phi = 4.0$ and $u' = 0.65$ m/s

Fig. 6.4. Direct image of ammonia/oxygen/nitrogen flame and acetylene/air flame

As shown in Fig. 6.3(a) and (b), in silica particle cloud/ammonia/oxygen/nitrogen mixing-combustion and silica particle cloud/acetylene/air mixing-combustion, turbulent flame propagation velocity shows the same tendency that the turbulent flame propagation velocity of pure gas combustion is lower than that of the mixing-combustion. Even though the acetylene/air

flame forms large density soot particles in acetylene-rich cases, the turbulent flame propagation velocity in silica particle cloud/acetylene/air mixing-combustion is lower than that of pure acetylene/air combustion. Therefore, the radiation from the soot particles takes a minor role on the solid-particle-fuel/ammonia/oxygen/nitrogen co-combustion turbulent flame propagation for the small-scale flame.

This phenomenon is considered to be caused by the thin thickness of the flame in the study. As suggested by Hashimoto et al. [143], for the small scale burners, the flame thickness is thinner than the large scale burner. Furthermore, particles in a large-scale burner tend to easily obtain the heat by radiation heat transfer from the large thick flame compared to that in the small test burner. Therefore, in present study, the radiation takes a minor role to enhance the co-combustion turbulent flame propagation velocity.

6.3. Solid particle cloud/ammonia co-combustion turbulent flame propagation mechanism

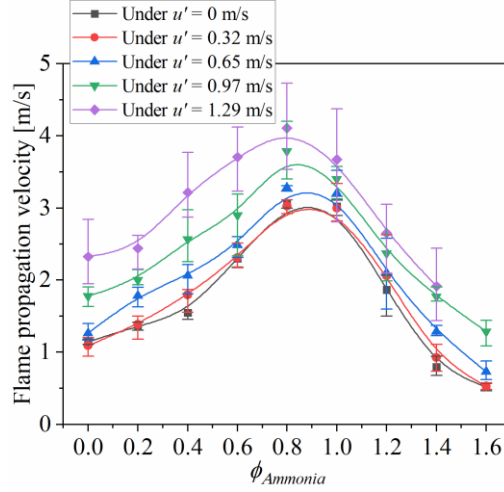


Fig. 6.5. PMMA particle cloud/ammonia/oxygen/nitrogen co-combustion turbulent flame propagation velocity as a function of $\phi_{Ammonia}$ under various turbulence intensities.

Fig. 6.5 shows the PMMA particle cloud/ammonia/oxygen/nitrogen co-combustion turbulent flame propagation velocity in terms of the $\phi_{Ammonia}$ under various turbulence intensities. As shown in Fig. 6.5, the turbulent flame propagation velocity increases with the increase of the turbulence intensity. As clarified in our previous study, the increase of the turbulence flame propagation velocity is caused by the enhanced turbulent heat and mass transfer in particle cloud/ammonia/oxidizer mixture and the increased total surface area of the wrinkled flame front by increasing turbulence intensity. Moreover, the turbulent flame propagation velocity first increased and then decreased with the increase of the $\phi_{Ammonia}$ from 0 to 1.6. This tendency was also observed in pulverized coal particle cloud/ammonia/oxygen/nitrogen co-combustion [15].

The R_P was used to characterize the effect of PMMA particles on pure ammonia/oxygen/nitrogen combustion, which was calculated by Eq. (6.2),

$$R_P = \frac{S_{CO} - S_A}{S_A}, \quad (6.2)$$

S_{CO} represents the turbulent flame propagation velocity in PMMA particle cloud/ammonia/oxygen/nitrogen co-combustion which is shown in Fig. 6.5. S_A represents the pure ammonia/oxygen/nitrogen turbulent flame propagation velocity, which is under a same turbulence intensity and ammonia equivalence ratio as with the mixing-combustion. The relation of S_A as ϕ is shown in Fig. 3.3.

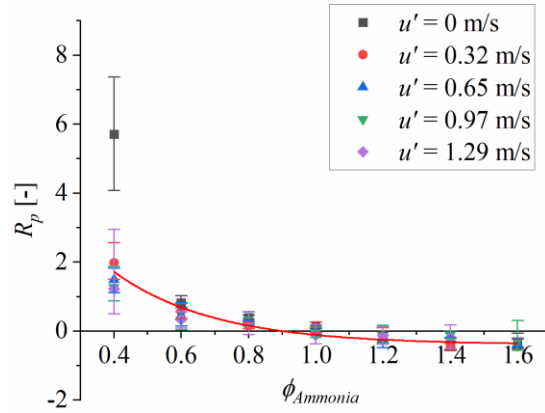


Fig. 6.6. R_P as a function of the $\phi_{Ammonia}$ in PMMA particle cloud/ammonia/oxygen/nitrogen co-combustion under various turbulence intensities.

Fig. 6.6 shows the R_P as a function of the $\phi_{Ammonia}$ in PMMA particle cloud/ammonia/oxygen/nitrogen co-combustion under various turbulence intensities. The R_P decreased with the increase of the $\phi_{Ammonia}$. In ammonia-lean cases, the R_P was larger than 0 which meant that the turbulent flame propagation velocity of the co-combustion was larger than that of pure ammonia/oxygen/nitrogen combustion. However, in ammonia-rich cases, the turbulent flame propagation velocity of the co-combustion was lower than that of pure ammonia/oxygen/nitrogen combustion. As shown in Fig. 5.6, the same phenomenon is observed by pulverized coal particle cloud/ammonia/oxygen/nitrogen co-combustion.

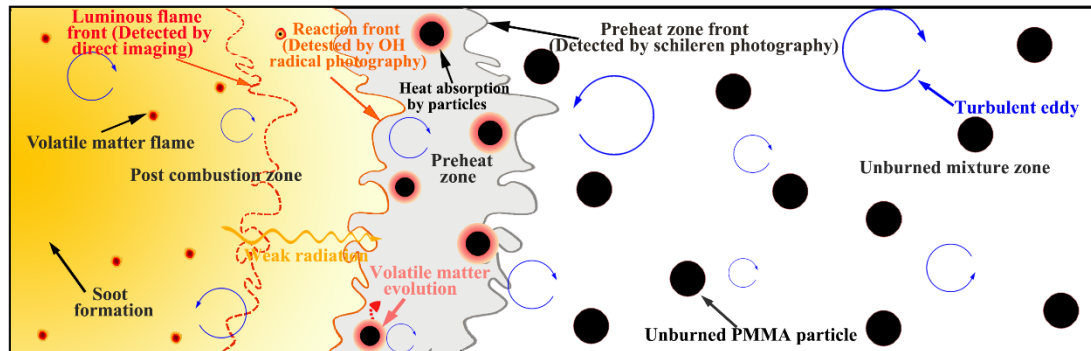


Fig. 6.7. PMMA particle cloud/ammonia/oxygen/nitrogen co-combustion flame structure (Modified from [13]).

Therefore, for two types of different material particles, in an ammonia lean case, the propagation velocity of co-combustion was larger than that of the pure ammonia combustion, while it was lower than that of pure ammonia combustion in an ammonia rich case. Based on the consistency result between the present study and previous study involving pulverized coal particle cloud/ammonia/oxygen/nitrogen co-combustion, the turbulent flame propagation mechanism of solid-particle-fuel/ammonia/oxygen/nitrogen co-combustion, which is shown in Fig. 6.7, is clarified. The flame of solid particle cloud/ammonia/oxygen/nitrogen turbulent co-combustion can be divided into three zones based on flame propagation direction, including the particles combustion zone, preheat zone, and unburned mixture zone. There are two major factors affecting the co-combustion turbulent flame propagation, including the unburned particles heat sink negative effect and the local equivalence ratio increment effect in preheat zone by addition of volatile matter. In ammonia-lean cases, turbulent flame propagation velocity of co-combustion was larger than that of the pure ammonia combustion. This is because the positive effect, which is the increment of local equivalence ratio by the addition of volatile matter, is larger than the

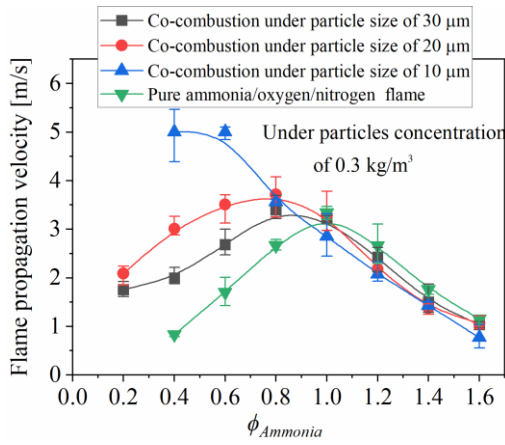
negative effect, which is the heat sink effect by the unburned particles in the preheat zone of the flame front. On the other hand, in ammonia rich cases, the local equivalence ratio increment effect by addition of volatile matter becomes negative because the addition of the fuel species in an ammonia-rich condition causes a decrease in the flame temperature. Consequently, the turbulent flame propagation velocity of the co-combustion was lower than that of the pure ammonia/oxygen/nitrogen combustion in ammonia rich cases. In the ammonia stoichiometric condition, the turbulent flame propagation velocity of the co-combustion was almost the same as that of the pure ammonia/oxygen/nitrogen combustion. This is because the negative effect is offset by the positive effect.

In solid particle cloud/ammonia/oxygen/nitrogen co-combustion turbulent flame propagation, first, the unburned particles in preheat zone of the flame front have a heat sink negative effect on the turbulent flame propagation. Second, the local equivalence ratio increment effect by addition of volatile matter in preheat zone can induce positive or negative effects, which decided by the ammonia equivalence ratio. Third, the radiation from the soot particles in luminous flame has little effect on co-combustion turbulent flame propagation in this study. For small-scale flame, the radiation takes a minor role on the turbulent flame propagation. However, for the large-scale flame, because of the thick flame thickness, particles tend to be easily obtained the heat by radiation heat transfer. Therefore, the radiation may have a large effect on the flame propagation for large-scale flame.

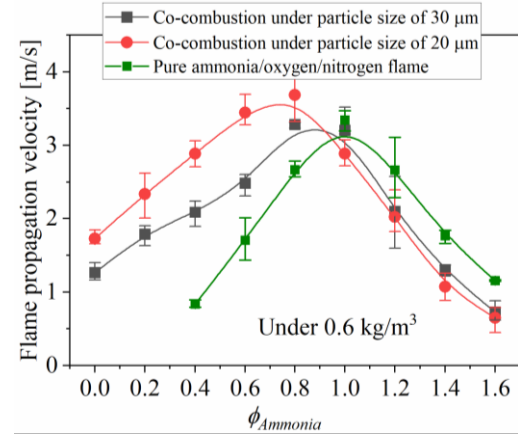
Furthermore, from the consistency of the result between the current study for the PMMA particle cloud/ammonia/oxygen/nitrogen co-combustion and the previous study for pulverized coal particle cloud/ammonia/oxygen/nitrogen co-combustion, it was confirmed that the

heterogeneous combustion of char particles has little effect on co-combustion turbulent flame propagation velocity because of its slow combustion process.

6.4. Particle size effect on solid particle cloud/ammonia co-combustion



(a) co-combustion turbulent flame propagation velocity as a function of the $\phi_{Ammonia}$ under particles concentration of 0.3 kg/m^3



(b) co-combustion turbulent flame propagation velocity as a function of the $\phi_{Ammonia}$ under the particles concentration of 0.6 kg/m^3

Fig. 6.8. Turbulent flame propagation behaviors of the PMMA particle clouds/ammonia/oxygen/nitrogen co-combustion under different particles sizes with the same turbulence intensity of $u' = 0.65 \text{ m/s}$.

Fig. 6.8(a) and (b) shows the turbulent flame propagation velocity of PMMA particle cloud/ammonia/oxygen/nitrogen co-combustion as functions of the $\phi_{Ammonia}$ under particle concentration of 0.3 kg/m^3 and 0.6 kg/m^3 respectively. As shown in Fig. 6.8, for the co-combustion under a quasi-monodispersed PMMA particles size of $30\text{-}\mu\text{m}$, the maximum turbulence flame propagation velocity is obtained approximately at $\phi_{Ammonia} = 0.8$. However, with the decrease of the quasi-monodispersed particles size from $30\text{-}\mu\text{m}$ to $10\text{-}\mu\text{m}$, the maximum turbulence flame propagation velocity was shifted to $\phi_{Ammonia} = 0.4$.

On the one hand, as decreasing of the particle size, the ratio of the heat capacity to the surface area of the individual particle is reduced. Hence, time delay for the heat transfer between particles and flame decreases with decreasing the particle diameter. Accordingly, the small particles can be decomposed within a short period. For the co-combustion under different particles sizes with a same $\phi_{Ammonia}$, if giving the assumption that all particles under all conditions in Fig. 6.8 are devolatilized in the preheat zone of the flame front before the reaction front passing by, it can be concluded that decreasing the particles size just can increase the turbulent flame propagation velocity because the small particles can obtain a same local equivalence ratio with a short period. However, with this kind of assumption, the maximum turbulent flame propagation velocity cannot be shifted from 0.8 to 0.4 because the local equivalence ratio in the preheat zone of the flame front is a constant value under a same ammonia equivalence ratio with different size particles. Therefore, in the co-combustion, for the small particles, large amount of volatile matter will be released in the preheat zone of the flame front. However, for the large particles, small amount of the volatile matter released. Consequently, there is a shift of the maximum turbulent flame propagation velocity with decreasing the quasi-monodispersed PMMA particle size from 30- μm to 10- μm .

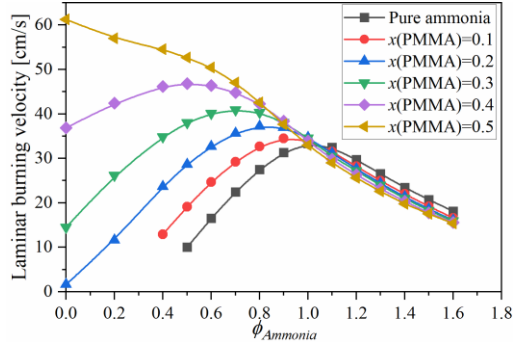
Further, as shown in Fig. 6.8, in an ammonia lean case, the co-combustion turbulent flame propagation velocity largely increased with the decrease of the particle size. In the ammonia rich case, the co-combustion turbulent flame propagation velocity slightly decreased with the decrease of the particle size. This phenomenon is considered to be caused by the chemical kinetic reaction effect of the MMA/ammonia/air mixture on the PMMA particle cloud/ammonia/oxidizer co-combustion.

To validate the effect of the different pyrolysis ratio of different size particles and the chemical kinetic reaction effect of the MMA(gas)/ammonia/oxygen/nitrogen mixture on the co-combustion, the CHEMKIN simulation [144] for the MMA/ammonia/oxygen/nitrogen co-combustion was conducted under particle concentration of 0.3 kg/m^3 to obtain the tendency of the laminar burning velocity of the MMA/ammonia/oxygen/nitrogen mixture under different PMMA particles pyrolysis ratios and ammonia equivalence ratios. In this simulation, the unburned particles thermal heat sink effect and heat required for the devolatilization are not examined.

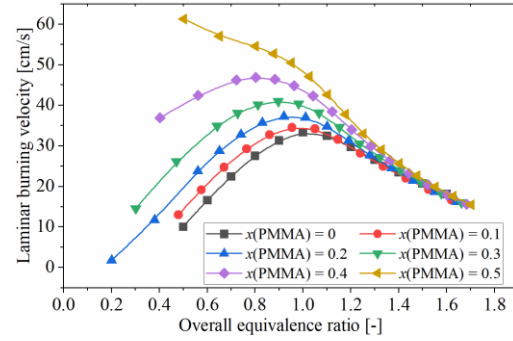
A freely propagating adiabatic, premixed, laminar flame speed calculation model was used. The mechanism for methyl methacrylate oxidation is from Yang et al. [145]. The mechanism for ammonia oxidation is from Okafor et al. [10]. The methyl methacrylate oxidation mechanism and ammonia oxidation mechanism were combined to simulate the MMA/ammonia/oxygen/nitrogen co-combustion. The steady-state mass, species and energy conservation equations of the flame were solved using the hybrid time-integration/Newton-iteration technique with adaptive meshes and mixture-averaged transport parameters [2]. With-draw differencing on both the convective and diffusion terms were used in the simulation. To control the adaptive grid mesh, the values of the adaptive grid control based on the solution gradient and curvature were set to be 0.1 and 0.4, respectively [146]. At the cold boundary, the initial temperature and pressure were set as 297 K and 1atm, respectively.

The simulation was conducted under different PMMA particles pyrolysis ratio under particle concentration of 0.3 kg/m^3 . The PMMA particles' pyrolysis ratio, χ_{PMMA} , was defined as the ratio of devolatilized PMMA particles mass to the overall mass of the PMMA particles. Fig. 6 (a) shows the laminar burning velocity as functions of the $\phi_{Ammonia}$ under different pyrolysis ratio of PMMA particles. Same tendency is found with Fig. 6.8(a). The maximum laminar burning

velocity for the MMA/ammonia/oxygen/nitrogen mixture is shifted to the ammonia leaner side with the increase of the PMMA particles' pyrolysis ratio. Therefore, we can conclude that, before the reaction front passing by, in the preheat zone of the flame front, with the decrease of the particle size, the pyrolysis ratio for PMMA particles is increased.



(a) Laminar burning velocity as a function of ϕ_{Ammonia} in MMA/ammonia/oxygen/nitrogen co-combustion based on different PMMA particles pyrolysis ratio



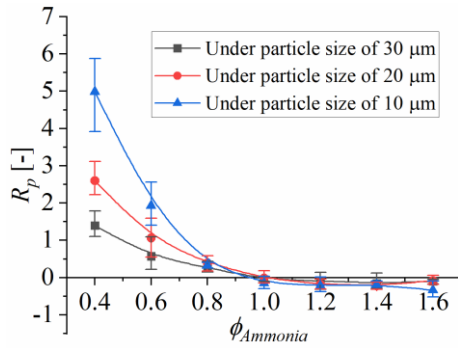
(b) Laminar burning velocity as a function of the overall equivalence ratio based on different PMMA particles pyrolysis ratio

Fig. 6.9. Laminar burning velocity of the MMA/ammonia/oxygen/nitrogen premixture based on different PMMA particles pyrolysis ratio.

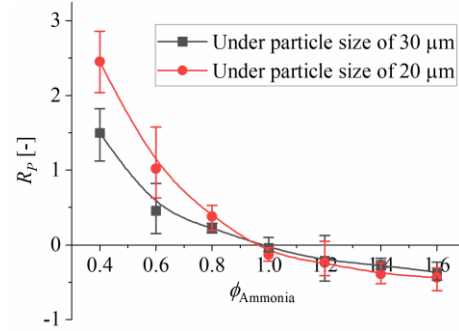
Further, as shown in Fig. 6.9(a), with the increase of the PMMA particles pyrolysis ratio, there is a largely increase of the laminar burning velocity in an ammonia-lean co-combustion. However, in ammonia-rich cases, there is a slightly decrease of the laminar burning velocity with increase of the pyrolysis ratio. The Same tendency has been found with Fig. 6.7(a). To explain this tendency, the laminar burning velocity as functions of the overall equivalence ratio of the MMA/ammonia/oxidizer under different PMMA particles pyrolysis ratio is plot in Fig. 6.9(b). As shown in Fig. 6.9(b), with the increase of the pyrolysis ratio, the laminar burning velocity of the MMA/ammonia/oxygen/nitrogen mixture increases largely in fuel-lean cases. However, there is a slight increase of the laminar burning velocity of the MMA/ammonia/oxygen mixture in fuel-rich

cases. Therefore, it can be concluded that, the chemical reaction of the MMA/ammonia/oxygen/nitrogen mixture has essential effect on PMMA particle cloud/ammonia co-combustion.

To obtain the PMMA particles' effect on pure ammonia combustion under different particle size, the R_p was used which was calculated by Eq. (6.2).



(a) R_p in terms of the $\phi_{Ammonia}$ under the PMMA particles concentration of 0.3 kg/m^3 for different sizes PMMA particles



(b) R_p in terms of the $\phi_{Ammonia}$ under the PMMA particles concentration of 0.6 kg/m^3 for different sizes PMMA particles

Fig. 6.10. R_p as functions of the $\phi_{Ammonia}$ under different particles sizes and concentration with the same $u' = 0.65 \text{ m/s}$.

Fig. 6.10(a) and (b) shows the R_p as functions of the $\phi_{Ammonia}$ in the co-combustion for different sizes of PMMA particles. As shown in Fig. 6.10(a) and (b), R_p was larger than 0 in ammonia lean cases, while it was smaller than 0 in ammonia rich cases. This is because, in an ammonia lean condition, the positive effects, which is the increment of local equivalence ratio by the addition of volatile matter, are larger than the negative effect, which is the heat absorption by PMMA particles in preheat zone. In the ammonia rich condition, the effect of an increment of the local equivalence ratio by the addition of volatile matter turns into a negative effect.

Consequently, the negative effects in the ammonia rich condition resulting in a lower flame propagation velocity of PMMA particles/ammonia co-combustion.

6.5. Concluding remarks

In this chapter, the fundamental turbulent flame propagation mechanism of solid particle cloud/ammonia/oxidizer co-combustion were investigated. Three types of experiments were conducted. The silica particle cloud/ammonia/oxygen/nitrogen mixing-combustion experiments were conducted to investigate the unburned particle heat sink negative effect on solid particle cloud/ammonia/oxidizer co-combustion turbulent flame propagation. The silica particle cloud/acetylene/air mixing-combustion experiments were conducted to investigate the soot particles radiation effect on turbulent flame propagation of solid particle cloud/ammonia/oxidizer co-combustion. Moreover, the PMMA particle cloud/ammonia/oxygen/nitrogen co-combustion experiments were carried out to validate previous co-combustion mechanism and clarify the char reaction effect on co-combustion turbulent flame propagation. The principal findings are as follows:

In silica particle cloud/ammonia/oxygen/nitrogen mixing-combustion, the turbulent flame propagation velocity of the mixing-combustion was lower than that of pure ammonia/oxygen/nitrogen combustion. Therefore, the unburned particles in preheat zone of the flame front in solid particle cloud/ammonia/oxidizer co-combustion has a heat sink negative effect on the turbulent flame propagation. Further, in silica particle cloud/acetylene/air mixing-combustion, the turbulent flame propagation velocity of the mixing-combustion was lower than that of the acetylene/air combustion. Therefore, the radiation effect from the soot particles has

little effect on turbulent flame propagation in solid particle cloud/ammonia/oxidizer co-combustion for small scale flame.

The consistent results between the current study for the quasi-monodispersed PMMA particle cloud/ammonia/oxygen/nitrogen co-combustion and the previous study for the pulverized coal particle cloud/ammonia/oxygen/nitrogen co-combustion were observed. In ammonia lean cases, the turbulent flame propagation velocity of the co-combustion was larger than that of the pure ammonia combustion. This is because the positive effect, which is the increment of local equivalence ratio by addition of volatile matter, is larger than the negative effect, which is the heat sink effect by the unburned particles in preheat zone of flame front. However, in ammonia-rich cases, the turbulent flame propagation velocity of the co-combustion was lower than that of the pure ammonia combustion because the increment of local equivalence ratio by the addition of volatile matter turns to be negative effect. Further, from the consistency of the results between the PMMA particle cloud/ammonia/oxygen/nitrogen co-combustion and the pulverized coal particle cloud/ammonia/oxygen/nitrogen co-combustion, it was confirmed that the heterogeneous combustion of char particles weakly affected the turbulent flame propagation velocity of the co-combustion because of its slow combustion process.

Further, in PMMA particle cloud/ammonia/oxygen/nitrogen co-combustion, it was found that decreasing the particle size advanced the maximum turbulent flame propagation velocity to ammonia leaner side because decreasing the particles size can increase the amount of volatile matter devolatilized from the particles. Moreover, decreasing the particle size can largely increase the turbulent flame propagation velocity in ammonia-lean co-combustion, where it can slightly decrease the turbulent flame propagation velocity in ammonia-rich cases. This

phenomenon is mainly caused by the chemical reaction effect of the MMA/ammonia/oxygen/nitrogen mixture.

Chapter 7. Conclusions

Application of ammonia in thermal power plant for co-combustion is considered an efficient and feasible method to reduce CO₂ emissions from the viewpoint to step into a carbon free society. Flame propagation velocity is a fundamental property for evaluating the flame stability performance of combustion of fuels in combustors. The present research aims to clarify the turbulent flame propagation characteristics and mechanism of solid particle cloud/ammonia/oxidizer co-combustion. Therefore, the experiments on pure solid particle cloud turbulent flame propagation and pure ammonia/oxidizer turbulent flame propagation were conducted. The mechanism for pure solid particle cloud turbulent flame propagation and pure ammonia/oxidizer turbulent flame propagation were proposed respectively. Based on above two mechanisms, the solid particle cloud/ammonia co-combustion experiments were conducted, and the results were compared with results obtained in pure ammonia combustion and pure solid particle cloud combustion. Based on the comparison, the turbulent flame propagation mechanism of co-combustion was proposed. Further, to validate the proposed mechanism, the silica particle cloud/ammonia/oxidizer mixing-combustion, silica particle cloud/acetylene/air mixing-combustion, and PMMA particle cloud/ammonia/oxidizer co-combustion experiments were conducted. The principal findings are as follows.

In pure ammonia turbulent combustion experiments, the turbulent flame propagation velocity and turbulent burning velocity of the ammonia/oxygen/nitrogen flame increased with the increasing turbulence intensity owing to the increase of flame surface area (due to the increase of turbulence intensity). Under the same turbulence Karlovitz number, the ratio of turbulent burning velocity to the stretched laminar burning velocity in ammonia-lean cases was larger than that in

ammonia-rich cases. This is caused by the effect of diffusional-thermal instability. Consideration of both effects of the diffusional-thermal instability and the turbulence is important for the prediction of turbulent flame propagation velocity in ammonia combustion fields.

In pure solid particle combustion, the effects of the particle's concentration and 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 combustion of quasi-monodispersed PMMA particle clouds, the flame propagation velocity increases with the increase in the turbulence intensity, and the particle concentration takes a minor role on the flame propagation velocity. The consistency of the current and previous results suggest that the heterogeneous combustion of char particles has a little effect on the turbulent flame propagation velocity of the combustion of solid particle clouds because of its slow combustion process. Decreasing the quasi-monodispersed PMMA particles diameter from 30 μm to 10 μm increases the turbulent flame propagation velocity because the small quasi-monodispersed particles can be devolatilized and burned faster.

Under mixing different size quasi-monodispersed particles, the nonlinear convex downward relationship (J-shaped curve) between the turbulent flame propagation velocity and the small particle mass ratio was found. The turbulent flame propagation velocity first slightly increases with the increase in the small particle mass ratio; then the turbulent flame propagation velocity sharply increases after a certain small particle mass ratio. The rise of the turbulence intensity and the decrease in the size of the primary particle (large particle) in the clouds can advance the starting point of sharp increase. The above flame propagation behavior of mixing different size of

quasi-monodispersed PMMA particles is not dominated by the total surface area of the particle cloud. The mechanism considering the polydispersed interparticle interaction was suggested to explain above results. In the mixture, the agglomeration between small and large particles forms large agglomerates, which have a lower effective specific surface area than the isolate large particles. The isolated small particles or small agglomerates have a large effective specific surface area. When the concentration of small particles is low, most of the small particles adhere to the surface of large particles to form large agglomerates and dominate the mixture's overall effective specific surface area. After reaching a certain small particle mass ratio (the starting point of sharp increase), the overall effective specific surface area of the mixture is mainly controlled by isolated small particles or small agglomerates. Additionally, increasing the turbulence intensity can increase the shear force and, in turn, the agglomeration break-up frequency to form more isolated small particles or small agglomerates and furtherly advance the starting point of the sharp increase. Decreasing the primary particle (large particles) size in the mixture can decrease the fractal dimension of agglomerates. Further, agglomerates having a small fractal dimension are easy to be broken up by the shear flow to increase the number of small agglomerates or isolated small particles.

In pulverized coal particle cloud/ammonia/oxygen/nitrogen co-combustion, it was discovered the flame propagation velocity of pulverized coal/ammonia co-combustion is higher than that of pure ammonia combustion in the ammonia lean condition. Conversely, the flame propagation velocity of pulverized coal/ammonia co-combustion is lower than that of pure ammonia combustion in the ammonia rich condition. In the stoichiometric condition, the flame propagation velocities between co-combustion and pure ammonia combustion are approximately the same. The mechanism including three types of effects was suggested to explain the above

results. In the ammonia lean condition, the positive effects, which are the strong radiation from the luminous flame and the increment of local equivalence ratio by the addition of volatile matter, are larger than the negative effect, which is the heat absorption by coal particles in the preheat zone. In the ammonia rich condition, the effect of increment of the local equivalence ratio by the addition of volatile matter becomes negative. Consequently, the negative effects overcome the positive effect in the ammonia rich condition resulting in the lower flame propagation velocity of pulverized coal/ammonia co-combustion compared with that of pure ammonia combustion. In the ammonia stoichiometric condition, the positive and the negative effects are comparable resulting in a flame propagation velocity that is almost same between co-combustion and pure ammonia combustion.

To furtherly validate the proposed three effects, the silica particle cloud/ammonia/oxygen/nitrogen mixing-combustion and silica particle cloud/acetylene/air mixing-combustion, and PMMA particle cloud/ammonia/oxidizer co-combustion experiments were conducted. It was found that the turbulent flame propagation velocity of the silica particle cloud/ammonia/oxygen/nitrogen mixing combustion is 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 particles on the co-combustion takes a minor role on the flame propagation of co-combustion for small scale flame. However, it may have important effect in the practical large-scale flame. Further, in PMMA particle cloud/ammonia/oxygen/nitrogen co-combustion, the same turbulent flame propagation phenomenon with pulverized coal particle cloud/ammonia/oxygen/nitrogen co-combustion was

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.

Further, in PMMA particle cloud/ammonia/oxygen/nitrogen co-combustion, it was found that decreasing the particle size advanced the maximum turbulent flame propagation velocity to ammonia leaner side because decreasing the particles size can increase the amount of volatile matter devolatilized from the particles. Moreover, decreasing the particle size can largely increase the turbulent flame propagation velocity in ammonia-lean co-combustion, where it can slightly decrease the turbulent flame propagation velocity in ammonia-rich cases. This phenomenon is mainly caused by the chemical reaction effect of the MMA/ammonia/oxygen/nitrogen mixture. Therefore, for solid particle cloud/ammonia co-combustion, particle size and chemical reaction of volatile matter/ammonia have essential effect on the turbulent flame propagation.

Based on results from present research, the turbulent flame propagation mechanism of solid particle cloud/ammonia/oxidizer co-combustion was clearly clarified.

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Appendix

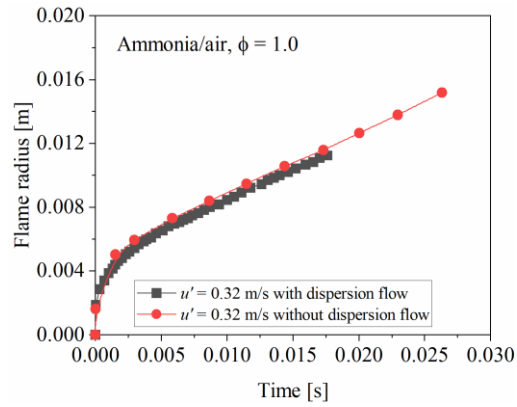


Fig. A Flame radius as a function of elapsed time for quiescent mixture, and mixture with dispersion flow [20]

Table A Turbulent flame propagation velocity error caused by the dispersion [20]

Experimental condition	Flame propagation velocity [m/s]
Ammonia/air with dispersion flow	0.36202
Ammonia/air without dispersion flow	0.37873
Ammonia/oxygen/nitrogen with dispersion flow	2.9642
Ammonia/oxygen/nitrogen without dispersion flow	3.02912

Table B Particle size characteristic parameters for the quasi-monodispersed particles which were manufactured by the Soken chemical Ltd

Particle size characteristic parameters	MX-300 (Quasi-monodispersed 3 μm)	MX-1000 (Quasi-monodispersed 10 μm)	MX-2000 (Quasi-monodispersed 20 μm)	MX-3000 (Quasi-monodispersed 30 μm)	MZ-30H (Polydispersed 30 μm)
Volume weighted mean D [4,3] (μm)	2.879	9.821	18.854	28.813	27.354
Surface weight mean D [3,2] (μm)	2.783	9.564	18.476	28.297	25.224
D _v (10) (μm)	2.249	7.910	15.522	23.814	18.128
D _v (50) (μm)	2.879	9.656	18.654	28.521	26.361
D _v (90) (μm)	3.619	12.109	22.322	34.114	37.898
Specific surface area [m^2/g]	2.16	0.627	0.325	0.212	0.238
COV (The coefficient of variation) [-]	0.152	0.137	0.121	0.117	0.233

Table C The size distribution data for the 46.1 μ m polydispersed silica particles

Size (μ m)	Volume under (%)	Size (μ m)	Volume under (%)	Size (μ m)	Volume under (%)	Size (μ m)	Volume under (%)	Size (μ m)	Volume under (%)
2000	100	176	96.51	15.56	17.25	1.375	0	0.122	0
1826	100	161.4	96.1	14.27	15.66	1.261	0	0.111	0
1674	100	148	95.68	13.08	14.19	1.156	0	0.102	0
1535	100	135.7	95.25	12	12.82	1.06	0	0.094	0
1408	100	124.5	94.79	11	11.55	0.972	0	0.086	0
1291	100	114.1	94.28	10.09	10.38	0.892	0	0.079	0
1184	100	104.7	93.69	9.25	9.31	0.818	0	0.072	0
1086	100	95.96	92.98	8.482	8.35	0.75	0	0.066	0
995.6	100	88	92.1	7.778	7.49	0.688	0	0.061	0
913	100	80.7	90.98	7.133	6.73	0.63	0	0.056	0
837.2	100	74	89.52	6.541	6.06	0.578	0	0.051	0
767.7	100	67.86	87.59	5.998	5.46	0.53	0	0.047	0
704	100	62.23	85.05	5.5	4.93	0.486	0	0.043	0
645.6	100	57.06	81.73	5.044	4.45	0.446	0	0.039	0
592	100	52.33	77.56	4.625	4.01	0.409	0	0.036	0
542.9	100	47.98	72.47	4.241	3.6	0.375	0	0.033	0
497.8	100	44	66.63	3.889	3.22	0.344	0	0.03	0
456.5	99.95	40.35	60.25	3.566	2.86	0.315	0	0.028	0
418.6	99.84	37	53.71	3.27	2.52	0.289	0	0.026	0
383.9	99.66	33.93	47.4	2.999	2.2	0.265	0	0.023	0
352	99.42	31.11	41.59	2.75	1.89	0.243	0	0.021	0
322.8	99.15	28.53	36.53	2.522	1.59	0.223	0		
296	98.85	26.16	32.21	2.312	1.31	0.204	0		
271.4	98.51	23.99	28.61	2.121	1.04	0.187	0		
248.9	98.14	22	25.61	1.945	0.79	0.172	0		
228.2	97.74	20.17	23.08	1.783	0.56	0.158	0		
209.3	97.33	18.5	20.9	1.635	0.35	0.145	0		
191.9	96.92	16.96	18.98	1.499	0.14	0.133	0		

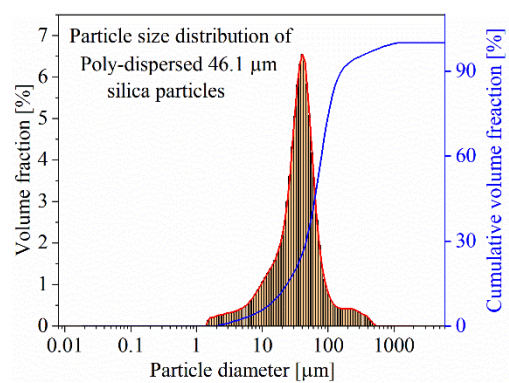
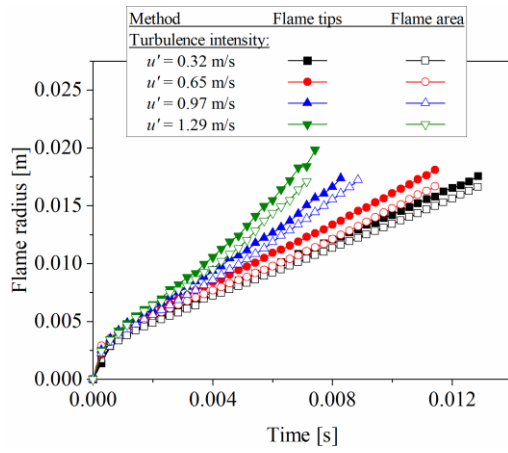


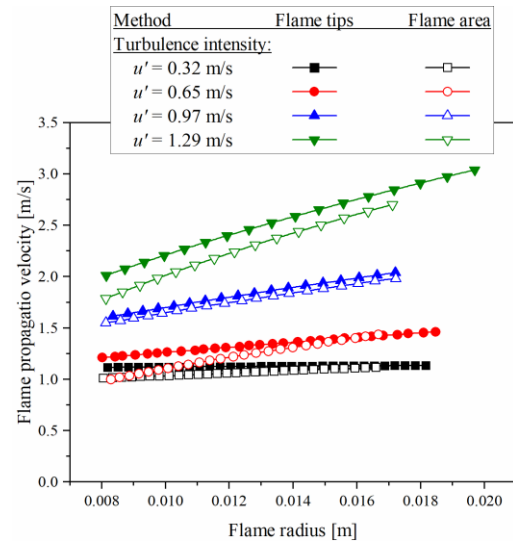
Fig. B Particle size distribution of the 46.1 μm polydispersed silica particles.

Table D The size distribution data for the polydispersed silica particles

Parameter	Value
Mean volume diameter (μm)	46.08
Mean number diameter (μm)	2.6426
Mean area diameter (μm)	19.146
Specific surface area	0.31338
Standard deviation (μm)	22.961



(a) Flame radius measured by different method



(b) Flame propagation velocity obtained by different radius measuring method

Fig. C Flame radii and flame propagation velocity obtained by different radius measuring method

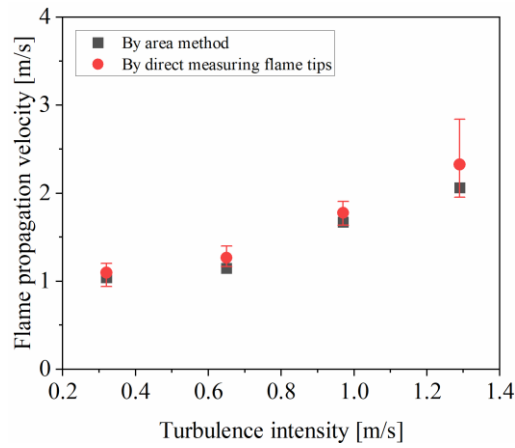


Fig. D Turbulent flame propagation velocity at $r = 0.01045$ m by using different radius measuring method

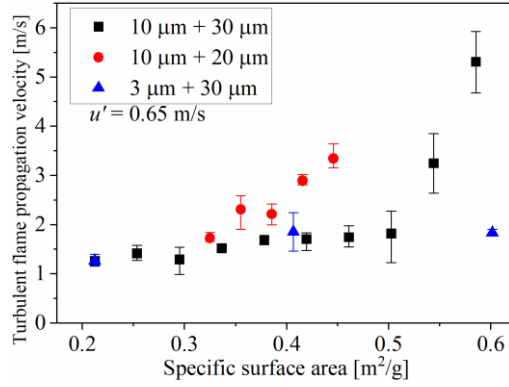


Fig. E Turbulent flame propagation velocity as functions of the specific surface area under different mixing condition

Table E The size distribution data for the 30 µm polydispersed PMMA particles

Size (µm)	Volume under (%)	Size (µm)	Volume under (%)	Size (µm)	Volume under (%)	Size (µm)	Volume under (%)	Size (µm)	Volume under (%)
0.01	0	0.182	0	2.98	0	60.256	100	1096.478	100
0.011	0	0.209	0	3.802	0	69.183	100	1258.925	100
0.013	0	0.24	0	4.365	0	79.433	100	1445.44	100
0.015	0	0.275	0	5.012	0	91.201	100	1659.587	100
0.017	0	0.316	0	5.754	0	104.713	100	1905.461	100
0.02	0	0.363	0	6.607	0	120.226	100	2187.762	100
0.023	0	0.417	0	7.586	0	138.038	100	2511.886	100
0.026	0	0.479	0	8.71	0	158.489	100	2884.032	100
0.03	0	0.55	0	10	0	181.97	100	3311.311	100
0.035	0	0.631	0	11.482	0.06	208.93	100	3801.894	100
0.04	0	0.724	0	13.183	0.57	239.883	100	4365.158	100
0.046	0	0.832	0	15.136	2.57	275.423	100	5011.872	100
0.052	0	0.955	0	17.378	7.59	316.228	100	5754.399	100
0.06	0	1.03	0	19.953	17.19	363.078	100	6606.934	100
0.069	0	1.259	0	22.909	31.72	416.869	100	7585.776	100
0.079	0	1.445	0	26.303	49.7	478.63	100	8709.636	100
0.091	0	1.66	0	30.2	67.94	549.541	100	10000	100
0.105	0	1.905	0	34.674	82.99	630.957	100		
0.12	0	2.188	0	39.811	92.92	724.436	100		
0.138	0	2.512	0	45.709	97.9	831.764	100		
0.158	0	2.884	0	52.481	99.65	954.993	100		

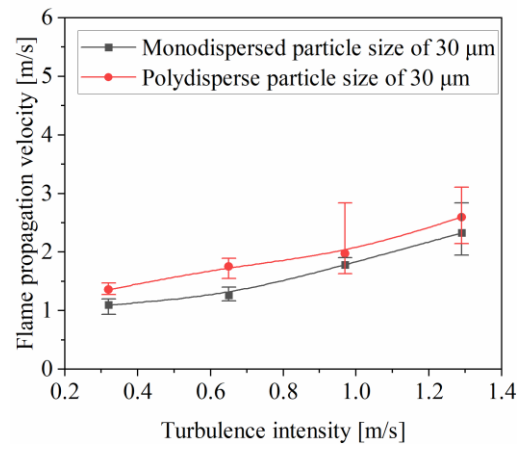


Fig. F Flame propagation velocity under the 30 μm quasi-monodispersed particles and the 30 μm polydispersed particles

Achievements

Journal publications:

1. **Yu Xia**, Nozomu Hashimoto, Osamu Fujita, Turbulent flame propagation of polymethylmethacrylate particle clouds in an O₂/N₂ atmosphere, *Combustion and Flame* (I.F.2019=4.57), Vol. 234, 111616 (2021). doi: 10.1016/j.combustflame.2021.111616.
2. **Yu Xia**, Khalid Hadi, Genya Hashimoto, Nozomu Hashimoto, Osamu Fujita, “Effect of ammonia/oxygen/nitrogen equivalence ratio on spherical turbulent flame propagation of pulverized coal/ammonia co-combustion”, *Proceedings of the Combustion Institute* (I.F.2019=5.627), Vol. 38, pp. 4043–4052 (2021). doi: 10.1016/j.proci.2020.06.102.
3. Genya Hashimoto, Khalid Hadi, **Yu Xia**, Nozomu Hashimoto, Akihiro Hayakawa, Hideaki Kobayashi, Osamu Fujita, “Turbulent flame propagation limits of ammonia/methane/air premixed mixture in a constant volume vessel”, *Proceedings of the Combustion Institute* (I.F.2019=5.627), Vol. 38, pp. 5171–5180 (2021). doi: 10.1016/j.proci.2020.08.055.
4. Khalid Hadi, Ryo Ichimura, Genya Hashimoto, **Yu Xia**, Nozomu Hashimoto, Osamu Fujita, “Effect of fuel ratio of coal on the turbulent flame speed of ammonia/coal particle cloud co-combustion at atmosphere pressure”, *Proceedings of the Combustion Institute* (I.F.2019=5.627), Vol. 38, pp. 4043–4052 (2021). doi: 10.1016/j.proci.2020.06.358.
5. **Yu Xia**, Genya Hashimoto, Khalid Hadi, Nozomu Hashimoto, Akihiro Hayakawa, Hideaki Kobayashi, Osamu Fujita, “Turbulent burning velocity of ammonia/oxygen/nitrogen premixed flame in O₂-enriched air condition”, *Fuel* (I.F.2019=5.578), Vol. 268, 117383 (2020). doi: 10.1016/j.fuel.2020.117383.

Conference publications:

1. **Yu Xia**, Nozomu Hashimoto, Osamu Fujita, Experimental study of the turbulent flame propagation behavior of solid particle fuel/ammonia/oxygen/nitrogen co-combustion within a fan-stirred vessel, The 25th National Symposium on Power and Energy System, Sapporo (Japan), July 2021.
2. **Yu Xia**, Khalid Hadi, Genya Hashimoto, Nozomu Hashimoto, Osamu Fujita, Effect of ammonia/oxygen/nitrogen equivalence ratio on spherical turbulent flame propagation of pulverized coal/ammonia co-combustion, The 38th International Symposium on Combustion, Adelaide, Australia. (2021.01, Oral presentation)
3. Genya Hashimoto, Khalid Hadi, **Yu Xia**, Nozomu Hashimoto, Akihiro Hayakawa, Hideaki Kobayashi, Osamu Fujita, Turbulent flame propagation limits of ammonia/methane/air premixed mixture in a constant volume vessel, The 38th International Symposium on Combustion, Adelaide, Australia. (2021.01, Oral presentation)
4. Khalid Hadi, Ryo Ichimura, Genya Hashimoto, **Yu Xia**, Nozomu Hashimoto, Osamu Fujita, Effect of fuel ratio of coal on the turbulent flame speed of ammonia/coal particle cloud co-combustion at atmosphere, The 38th International Symposium on Combustion, Adelaide, Australia. (2021.01, Oral presentation)
5. **Yu Xia**, Genya Hashimoto, Nozomu Hashimoto, Osamu Fujita, Spherical turbulent flame propagation behavior of the polymethylmethacrylate particle clouds combustion in an O₂/N₂ atmosphere within a fan-stirred closed vessel, The 58th Symposium (Japanese) on Combustion, Ehime, Japan. (2020.12, Oral presentation)
6. Genya Hashimoto, Khalid Hadi, **Yu Xia**, Nozomu Hashimoto, Akihiro Hayakawa, Hideaki Kobayashi, Osamu Fujita, Effect of diffusive-thermal instability on the turbulent flame

- propagation limit of $\text{NH}_3/\text{CH}_4/\text{air}$ premixed gas, The 58th Symposium (Japanese) on Combustion, Ehime, Japan. (2020.12, Oral presentation)
7. **Yu Xia**, Khalid Hadi, Genya Hashimoto, Nozomu Hashimoto, Osamu Fujita, Experimental study of the turbulent flame propagation behavior of pulverized coal/ammonia co-combustion in an O_2/N_2 atmosphere within a fan-stirred closed vessel, 2020 Japan Thermal Engineering Conference, Sapporo, Japan. (2020.10, Oral presentation)
 8. Genya Hashimoto, Khalid Hadi, **Yu Xia**, Nozomu Hashimoto, Akihiro Hayakawa, Hideaki Kobayashi, Osamu Fujita, Experimental study of turbulent flame propagation limits of $\text{NH}_3/\text{CH}_4/\text{air}$ premixed gas in a constant volume combustion chamber, 2020 Japan Thermal Engineering Conference, Sapporo, Japan. (2020.10, Oral presentation)
 9. Nozomu Hashimoto, Khalid Hadi, Ryo Ichimura, **Yu Xia**, Genya Hashimoto, Osamu Fujita, Experimental study on turbulent spherical flame propagation characteristics of ammonia / coal particle cloud mixture in a fan stirred closed vessel, The 2nd Pacific Rim Thermal Engineering Conference (PRTEC2019), PRTEC-24016, Lahaina, Maui, USA, 2019/12/14.
 10. **Yu Xia**, Nozomu Hashimoto, Genya Hashimoto, Khalid Hadi, Osamu Fujita, Spherical turbulent flame propagation behaviors of pulverized coal/ammonia co-combustion in an O_2/N_2 atmosphere, The 57th Symposium (Japanese) on Combustion, Sapporo, Japan. (2019.11, Oral presentation)
 11. Nozomu Hashimoto, Khalid Hadi, **Yu Xia**, Ryo Ichimura, Genya Hashimoto, Osamu Fujita, Flame propagation characteristics of ammonia and coal particle cloud mixture in turbulent field: Experimental investigation using a fan stirred constant volume vessel, The 16th International Conference on Flow Dynamics 2019, Sendai, Japan. (Keynote lecture, 2019.11)

12. **Yu Xia**, Genya Hashimoto, Khalid Hadi, Nozomu Hashimoto, Akihiro Hayakawa, Hideaki Kobayashi, Osamu Fujita, Turbulent burning velocity of ammonia/oxygen/nitrogen premixed flame in oxygen-enriched environment, The 16th International Conference on Flow Dynamics 2019, Sendai, Japan. (2019.11, Oral presentation)
13. Genya Hashimoto, Khalid Hadi, **Yu Xia**, Nozomu Hashimoto, Akihiro Hayakawa, Hideaki Kobayashi, Osamu Fujita, Experimental study of flame propagation limits of ammonia/methane/air mixture in turbulent field, The 16th International Conference on Flow Dynamics 2019, Sendai, Japan. (2019.11, Oral presentation)
14. Nozomu Hashimoto, **Yu Xia**, Khalid Hadi, Genya Hashimoto, Osamu Fujita, Study on the flame propagation velocity of the ammonia/pulverized coal mixing combustion in a turbulent field of a constant volume vessel, 56th Coal Science Conference, No. 2-7, Wink Aichi, Nagoya, 2019/10/30.
15. Nozomu Hashimoto, Genya Hashimoto, Ryo Ichimura, Khalid Hadi, **Yu Xia**, Akihiro Hayakawa, Hideaki Kobayashi, Osamu Fujita, Turbulent flame propagation limit of $\text{NH}_3/\text{CH}_4/\text{air}$ mixture in a fan-stirred closed vessel, The Fifth International Symposium on Innovative Materials and Processes in Energy Systems (IMPRES2019), D113, Kanazawa Chamber of Commerce and Industry, Kanazawa, 2019/10/21.
16. Genya Hashimoto, Ryo Ichimura, Khalid Hadi, **Yu Xia**, Nozomu Hashimoto, Akihiro Hayakawa, Hideaki Kobayashi, Osamu Fujita, Flame propagation limit of premixed gas of ammonia and methane in turbulent field in a constant volume vessel, The 24th National Symposium on Power and Energy System, Tokyo, Japan. (2019.06, Oral presentation)