様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９　（共通）

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研究課題名（和文）Turbulent flame propagation and extinction behaviors and mechanisms of solid particle fuel/ammonia co-combustion

研究課題名（英文）Turbulent flame propagation and extinction behaviors and mechanisms of solid particle fuel/ammonia co-combustion

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研究成果の概要（和文）：本研究ではアンモニア／空気，アンモニアと固体粒子群の混焼，固体粒子群における乱流球状火炎の伝播・消炎とそのメカニズムを明らかにした．これらの知見はカーボンニュートラル社会の実現および，固体粒子の生産・貯蔵において懸念される粉じん爆発等の事故を避けるために役立つものである．

研究成果の学術的意義や社会的意義
The findings can help our society transition to a carbon-neutral with safety-production society. First,results can be used to optimize burner design and operation for co-combustion. Besides, result can be used to evaluate explosion hazard of particles-gas. New safety strategies can be developed.

研究成果の概要（英文）：Ammonia is a promising hydrogen energy carrier and carbon-free fuel. Co-combustion of ammonia within an existing particle-fueled thermal power plant is one of the most promising ways to step into a carbon neutral society. However, turbulent flame extinction is a significant challenge for its utilization. Therefore, through a unique self-designed turbulent combustion system, experiments on turbulent flame propagation and extinction in pure ammonia, pure particle cloud and ammonia-particle cloud co-combustion were conducted. The results showed that, in co-combustion, the particle can enhance turbulent flame propagation velocity and extend the turbulent flame extinction limits of pure ammonia combustion at ammonia-lean cases.
Through further analysis, it was found that, in co-combustion, particles have two dominant effects on the turbulent flame propagation and extinction of pure ammonia combustion, including the particle heat sink and volatile matter decomposed from the particles.

研究分野：熱工学，安全工学，燃焼

キーワード：Ammonia combustion　Particle combustion　Flame propagation　Flame extinction　Turbulent combustion　co-combustion

様　式　Ｃ－１９、Ｆ－１９－１（共通）

１．研究開始当初の背景

The reduction of carbon dioxide ($CO_2$) emission is a critical issue for humankind to curb the impacts of climate change. The use of alternative carbon-free fuels in combustion systems is essential for achieving a carbon-neutral society. Ammonia ($NH_3$) is a promising hydrogen energy carrier and carbon-free fuel [1]. $NH_3$ combustion does not emit $CO_2$, $SO_x$, or soot. $NH_3$ has a hydrogen weight of 17.7%, can be synthesized from renewable energy sources, and is easier to store and transport than hydrogen. Therefore, various applications of ammonia as a fuel are currently considered [1]. $NH_3$ co-combustion within the existing thermal power plant is a practical near-term way while minimizing the equipment requirements, maintaining energy demand, and reducing $CO_2$ emissions [1, 2].

In a real burner, a turbulent environment is used. Turbulent flame extinction is a major challenge for energy generation systems [3]. Owing to the weak combustion intensity and corresponding ease of being extinguished by turbulence of premixed $NH_3$–air flames, many studies have been conducted to clarify the flame stability characteristics of gaseous $NH_3$ combustion [4, 5]. Although the solid particle fuel–$NH_3$ co-combustion is a promising solution to move toward a carbon-neutral society, no fundamental research has been conducted to clarify its turbulent flame propagation and extinction characteristics.

Therefore, while introducing $NH_3$ to the particle-fueled thermal power plant, what is the turbulent flame stability performance of $NH_3$ combustion by addition of solid particle cloud?　What is the turbulent flame stability performance of solid particle cloud combustion by addition of $NH_3$? To clarify this issue, the fundamental turbulent flame propagation and extinction experiments were conducted in this work.

[1] H. Kobayashi et al., Proc. Combust. Inst., Vol. 37, pp.109–133, 2019.
[2] Y. Xia et al., Proc. Combust. Inst., Vol. 38, pp. 4043–4052, 2021.
[3] M.K. Geikie et al., Fuel, Vol. 194, pp. 239–256, 2017.
[4] A. Hayakawa et al., Int J Hydrogen Energy, Vol. 42, pp. 14010–14018, 2017.
[5] S. Wiseman et al., Proc. Combust. Inst., Vol. 38, pp.2869–2876, 2021.

２．研究の目的

The purpose of this study is to investigate turbulent flame stability behaviors and mechanisms of solid particle cloud–$NH_3$ co-combustion. Furthermore, turbulent flame propagation velocity is a key physical quantity for evaluating turbulent flame stability performance. Turbulent flame extinction limit is an indicator of the turbulent flame extinction phenomenon.

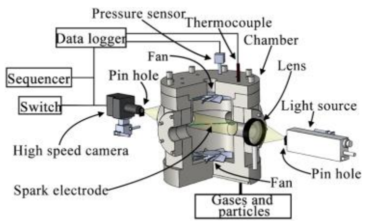


Fig. 1 Schematic of the experimental apparatus [8].

To study the turbulent flame propagation and extinction in co-combustion, a near homogeneous and isotropic turbulent flow field is required. However, most solid particle cloud combustion studies employ dispersion-induced turbulence to create a turbulent flow field [6]. However, near-homogeneous turbulence cannot be sustained in the flame propagation process using this method.

Therefore, the applicant and co-workers [2, 7] developed a unique turbulent combustion apparatus. Figure 1 shows the schematic of the self-designed turbulent combustion apparatus [8]. Through the particle image velocimetry experiments [2, 7], the generation of near-homogeneous turbulence using this apparatus is confirmed.

[6] X.Y. Zhang et al., J. Loss Prev. Process Ind., Vol. 44, pp. 119–124, 2016.
[7] K. Hadi et al., Proc. Combust. Inst., Vol. 37, pp. 2935–2942, 2019.
[8] Y. Xia et al., Proc. Combust. Inst., Vol. 39, pp. 3519–3528, 2023.

## ３．研究の方法

The target of this research is to investigate the turbulent flame propagation and extinction phenomena in solid particle cloud–ammonia co-combustion. Based on this purpose, the turbulent flame propagation and extinction of single fuel combustion were first conducted for the comparison. Then, the turbulent combustion experiments were conducted on hybrid mixtures. Finally, through further analysis, the turbulent flame propagation and extinction mechanism in solid particle cloud–ammonia co-combustion were clarified.

First, to obtain turbulent flame propagation velocity and turbulent flame extinction limits in pure $NH_3$ and pure particle cloud combustion, experiments on turbulent flame propagation and extinction of pure solid particle cloud combustion and pure $NH_3$ combustion were conducted under various conditions.

Second, to obtain the turbulent flame propagation velocity and turbulent flame extinction limits in solid particle cloud–ammonia co-combustion, the experiments were conducted by varying the particle property and equivalence ratio of $NH_3$–oxidizer.

Third, turbulent flame propagation velocity and extinction limits between single fuel combustion and co-combustion were compared and the interaction mechanism was proposed.

Finally, based on the proposed mechanism, the validation analysis was conducted. The mechanism was validated with respect to the two aspects. On the one hand, the chemical reaction simulation of $NH_3$–volatile matter was conducted by Ansys CHEMKIN pro. Second, a theoretical analysis of particle devolatilization parameters and $NH_3$ chemical reaction properties was conducted.

## ４．研究成果

Based on the turbulent flame propagation and extinction experiments in pure solid particle cloud combustion, it was found that the particle size has a significant effect on the turbulent flame propagation velocity and turbulent flame extinction limits. However, the particle concentration has negligible effect on the turbulent flame propagation velocity and extinction limits. Further theoretical analysis validated that the turbulent heat transfer and particle decomposition behavior are the dominant factors for the turbulent flame propagation and extinction phenomena. At the moment, one paper based on these experiments is under-reviewed for journal.

Besides, the turbulent flame propagation and extinction experiments in solid particle cloud–ammonia co-combustion were conducted. The turbulent flame propagation and extinction phenomena in co-combustion can be seen in Fig. 2. As shown in Fig. 2, under the condition of turbulence intensity of 0.32 m/s, the co-combustion flame can travel outward of the window’s edge. However, under turbulence intensity of 3.55 m/s, the flame is finally extinguished by the turbulence eddies.

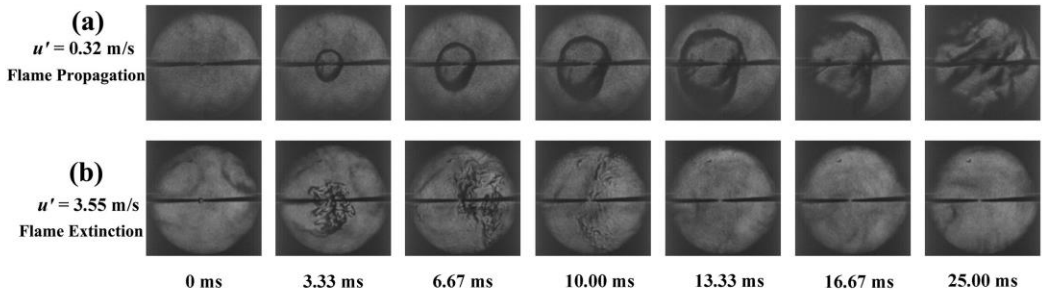


Fig. 2 Turbulent flame propagation and extinction in co-combustion under $\phi_{Ammonia}$ = 0.4; (a) for flame propagation case; (b) for extinction case [8].

Figure 3 shows the turbulent flame propagation probability map on the turbulence intensity as a function of $\phi_{Ammonia}$ in the PMMA particle cloud–ammonia–air two-phase hybrid-mixture co-combustion. In this study, turbulent flame propagation probabilities were categorized into four groups: (1) Blue circles represent 100% propagation; (2) Green squares represent 50%–99% propagation; (3) Orange triangles represent 1%–49% propagation; (3) Black cross-marks represent 0% propagation. Figure 3 illustrates these categories along with various boundary lines. The black dashed line shows the turbulent flame propagation limits for silica particle cloud–ammonia–air mixing combustion [8]. The red dashed line indicates the turbulent flame propagation limits for premixed ammonia–air combustion [9]. Additionally, the purple dotted line represents the turbulent flame propagation limits for PMMA particle cloud–ammonia–air co-combustion. When the ammonia equivalence ratio increases from 0 to 1.2, the turbulent flame propagation limits of premixed ammonia–air mixture initially expand and then contract upon adding PMMA particles. Specifically, when ammonia equivalence ratio equals 0.4, the turbulent flame in PMMA particle cloud–ammonia–air co-combustion exhibits the highest turbulence intensity. In ammonia-lean co-combustion, except for when ammonia equivalence ratio is 0.9, adding PMMA particles expands the turbulent flame propagation limits of premixed ammonia–air mixture. Conversely, in ammonia stoichiometric and rich conditions, adding PMMA particles significantly reduces these limits. Interestingly, the turbulent flame propagation limits of PMMA particle cloud–ammonia–air co-combustion match those of silica particle cloud–ammonia–air mixture under ammonia stoichiometric and rich conditions.

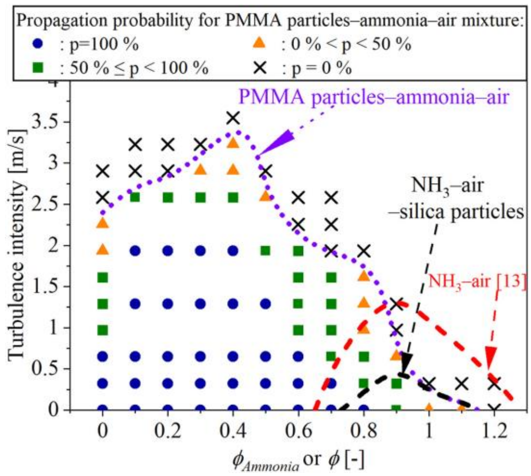


Fig. 3 Schematic of the experimental apparatus [8].

Therefore, by introducing reactive particles into the mixtures of ammonia–air, the turbulent flame propagation limits of premixed ammonia–air mixture first widen and then narrow as the ammonia equivalence ratio shifts from lean to rich conditions. Comparing the turbulent flame propagation velocity between PMMA particle cloud–ammonia–air co-combustion and pure premixed ammonia–air combustion reveals that the dynamics of turbulent flame propagation and extinction in solid particle cloud–ammonia–oxidizer co-combustion are primarily influenced by two factors: (1) Local Equivalence Ratio Increment Effect: This effect stems from the addition of volatile matter released from the particles, altering the local equivalence ratio near the flame front. Depending on the specific conditions, this effect can either enhance or impede flame propagation; (2) Heat Sink Negative Effect: Unburned particles in the preheat zone of the flame front act as a heat sink, dampening flame propagation.

It's noteworthy that the impact of the local equivalence ratio increment can vary, either positively or negatively, depending on the specific value of the ammonia equivalence ratio.

Furthermore, for the validation of the turbulent flame propagation and extinction mechanism, the theoretical analysis and CHEMKIN simulation were conducted. It was found that the particle decomposition behavior and chemical reaction of volatile matter–ammonia mixture has essential effect on the turbulent flame propagation and extinction phenomena (shown in Fig. 3). At the moment, one paper based on this result is under review for journal publication.

The findings from this research would help our society transition to a carbon-neutral with safety-production society. First, the results can be directly used to optimize the burner design and operation to obtain a stable flame for co-combustion. The greenhouse gas emissions from the traditional thermal power plant will be dramatically decreased. Besides, the result can be used to evaluate the explosion hazard of flammable gas, combustible solid particle cloud, and the hybrid mixture of combustible solid particles/flammable gas by considering the turbulence effect. New safety strategies can be developed.

[9] R. Ichimura et al., Fuel, Vol. 246, pp. 178–186, 2019.

５．主な発表論文等

〔雑誌論文〕　計2件（うち査読付論文　2件／うち国際共著　0件／うちオープンアクセス　0件）

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|---|---|
| １．著者名<br>Xia Yu, Hashimoto Nozomu, Fujita Osamu | ４．巻<br>39 |
| ２．論文標題<br>Turbulent flame propagation limits of polymethylmethacrylate particle cloud-ammonia-air co-combustion | ５．発行年<br>2023年 |
| ３．雑誌名<br>Proceedings of the Combustion Institute | ６．最初と最後の頁<br>― |
| 掲載論文のDOI（デジタルオブジェクト識別子）<br>10.1016/j.proci.2022.08.098 | 査読の有無<br>有 |
| オープンアクセス<br>オープンアクセスではない、又はオープンアクセスが困難 | 国際共著<br>― |

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| １．著者名<br>Xia Yu、Hashimoto Nozomu、Fujita Osamu | ４．巻<br>241 |
| ２．論文標題<br>Turbulent flame propagation mechanism of polymethylmethacrylate particle cloud?ammonia co-combustion | ５．発行年<br>2022年 |
| ３．雑誌名<br>Combustion and Flame | ６．最初と最後の頁<br>112077～112077 |
| 掲載論文のDOI（デジタルオブジェクト識別子）<br>10.1016/j.combustflame.2022.112077 | 査読の有無<br>有 |
| オープンアクセス<br>オープンアクセスではない、又はオープンアクセスが困難 | 国際共著<br>― |

〔学会発表〕　計7件（うち招待講演　0件／うち国際学会　4件）

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| １．発表者名<br>Yu Xia, Nozomu Hashimoto, Osamu Fujita |
| ２．発表標題<br>Turbulent flame propagation limits of polymethylmethacrylate particle cloud/ammonia/air co-combustion |
| ３．学会等名<br>39th International Symposium on Combustion（国際学会） |
| ４．発表年<br>2022年～2023年 |

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|---|
| １．発表者名<br>Yu Xia, Nozomu Hashimoto, Osamu Fujita |
| ２．発表標題<br>Experimental study on particle size effect on turbulent flame propagation of solid particle cloud/ammonia co-combustion |
| ３．学会等名<br>The 60th Symposium (Japanese) on Combustion |
| ４．発表年<br>2022年～2023年 |

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|---|
| 1．発表者名<br>Seungmin Song, Yu Xia, Nozomu Hashimoto, Osamu Fujita |
| 2．発表標題<br>Application of PAHs-LIF and OH radical chemiluminescence simultaneous measurement to pulverized coal/ammonia co-combustion propagation flame in a constant volume chamber |
| 3．学会等名<br>The 60th Symposium (Japanese) on Combustion |
| 4．発表年<br>2022年～2023年 |

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| 1．発表者名<br>Yu Xia, Nozomu Hashimoto, Osamu Fujita |
| 2．発表標題<br>Turbulent flame extinction behavior in solid particle cloud-ammonia-air co-combustion within a fan-stirred closed vessel |
| 3．学会等名<br>The 26th National Symposium on Power and Energy System |
| 4．発表年<br>2022年～2023年 |

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| 1．発表者名<br>Yu Xia, Nozomu Hashimoto, Osamu Fujita |
| 2．発表標題<br>Experimental research on turbulent flame propagation of solid particle cloud-gaseous fuel two-phase hybrid mixture co-combustion |
| 3．学会等名<br>14th Asia-Pacific Conference on Combustion（国際学会） |
| 4．発表年<br>2023年～2024年 |

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| 1．発表者名<br>Yu Xia, Nozomu Hashimoto, Osamu Fujita |
| 2．発表標題<br>Turbulent flame propagation and extinction behaviors in solid particle cloud combustion under air condition |
| 3．学会等名<br>3rd Asian Conference on Thermal Sciences（国際学会） |
| 4．発表年<br>2024年～2025年 |

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| **1．発表者名**<br>Yu Xia, Nozomu Hashimoto, Osamu Fujita |
| **2．発表標題**<br>Turbulent flame propagation limits in polymethylmethacrylate particle cloud combustion |
| **3．学会等名**<br>CI ’s 40th International Symposium-Emphasizing Energy Transition（国際学会） |
| **4．発表年**<br>2024年～2025年 |

〔図書〕　計0件

〔産業財産権〕

〔その他〕

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**6．研究組織**

| | 氏名<br>（ローマ字氏名）<br>（研究者番号） | 所属研究機関・部局・職<br>（機関番号） | 備考 |
|---|---|---|---|
| 研究協力者 | 橋本　望<br><br>(Hashimoto Nozomu) | | |

**7．科研費を使用して開催した国際研究集会**

〔国際研究集会〕　計0件

**8．本研究に関連して実施した国際共同研究の実施状況**

| 共同研究相手国 | 相手方研究機関 |
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