2024年度共同利用研究報告書

2025年02月11日

所属・職名 東京理科大学大学院　創域理工学研究科　国際火災科学専攻・博士課程２年生

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整理番号	2024a039

1.研究計画題目	Quantitative prediction of transition phenomena in combustion processes			
2.新規・継続	新規			
3.種別	若手・学生研究			
4.種目	短期共同研究			
5.開催方法	対面開催			
6.研究代表者	氏名	Pichayaporn Viriya-amornkij		
	所属	東京理科大学大学院　創域理工学	職名	博士課程２年生
7.研究実施期間	2024年11月12日(火曜日)～2024年11月13日(水曜日)			
8.キーワード	Transition to flaming, Extinction, Mathematical model, Smoldering, Critical threshold			
9.参加者人数	11人			

10.本研究で得られた成果の概要

This research collaboration led to key advancements in fire safety and combustion science. A reduced theoretical model was developed to predict the transition from smoldering to flaming combustion, with stability analysis confirming stable solutions. A method using bifurcation theory and stochastic differential equations was proposed for early detection of runaway reactions, improving accuracy. The study on flame spread in polyester-cotton materials highlighted the impact of gap width. Premixed flame stability under diffusive-thermal instability was revisited, extending classical theories. Additionally, bifurcation theory was applied to flame ignition, showing how small parameter changes can significantly shift flame behavior. This collaboration analyzed these issues mathematically, aiming to share insights for ongoing combustion and fire safety research.

Report (Short-term Collaborative Research)

Research Theme: Quantitative prediction of transition phenomena in combustion processes

Research Period: 12 November (非公開) -13 November (公開) 2024

Host Institution: Joint Research Center for Advanced and Fundamental Mathematics-for-Industry

Presenters: Pichayaporn Viriya-amornkij, Kazunori Kuwana, Takuya Yamazaki, Zhang Yihong, Yasuhide Fukumoto, and Kaname Matsue

1. Background and Objectives

Transition phenomena in combustion processes, such as the shift from smoldering to flaming combustion, thermal runaway in batteries, and flashover, play a crucial role in fire safety and energy applications. Despite extensive research, quantitatively predicting these transitions remains challenging due to the intricate interplay of thermal and chemical reactions, as well as the influence of environmental factors.

This short-term collaborative research aimed to develop a predictive framework by integrating theoretical modeling and experimental validation. Specifically, we investigated the impact of external heat flux, oxygen concentration, and material properties on combustion transition behavior. By addressing key mechanisms governing these processes, we sought to enhance our understanding of critical limits and provide insights for fire hazard assessment and combustion control strategies.

2. Research Activities

- ビリヤアモンキジュ ピチャヤポーン（東京理科大学）： **Modeling limit conditions of smoldering combustion**

This study proposes a theoretical reduced model to predict the transition from smoldering to flaming combustion. The conservation equations of energy, mass, and species, along with surface and gas-phase reactions, are considered. The auto-ignition assumption of gaseous products by the hot char surface reported in the previous study (Bar-Ilan et al, 2005) is adopted in this study. The results indicate a transition from smoldering combustion, characterized by a higher surface temperature, to flaming combustion, which exhibits a higher gas-phase temperature, occurring at the oxygen mass fraction of approximately 0.17. This finding confirms the model's simple yet effective predictive capability.

Since the model yields two distinct solutions: the upper and lower branches, the stability of these solutions was a critical focus of discussion among the participants. To assess the stability, a detailed stability analysis was performed based on the eigenvalues of the Jacobian matrix derived from the system of governing equations. The eigenvalue analysis provides insights into the system's response to small perturbations, revealing the stability of the solutions. After conducting the analysis, it was confirmed that the upper branch solutions exhibit stable eigenvalues, indicating that they represent a physically realizable state.

- 桑名 一徳（東京理科大学）: 火災時の一酸化炭素発生に関する危険予測

Smoke and CO detectors are required in every compartment due to the role smoke plays in early fire detection. These detectors work by sensing light reflected off particles in a chamber, with the presence of smoke triggering an alarm when the light intensity exceeds a certain threshold. However, conventional smoke detectors face issues with sensitivity, requiring a long time for accumulated smoke to trigger the sensor, and the inability to differentiate between smoke from real fires and particles from dust or water vapor, leading to false alarms. To avoid these false alarms, alarm thresholds are set higher, increasing response time and delaying emergency actions.

This study explores saddle-node bifurcation in dynamical systems and its application to early warning detection for runaway reactions, using an ordinary differential equation model based on Semenov's thermal explosion theory. The study converts the model into stochastic differential equations to assess the influence of noise and applies time-series analysis for early detection of critical transitions. Through numerical simulations, the conventional thermal runaway scenario was tested multiple times to validate the effectiveness of the proposed early detection method.

- 山崎 拓也（弘前大学）： 周期的な構造が固体の燃焼に及ぼす影響の検討

This study explores the flame spread rate of the polyester-cotton mixed material, as more than 30% of building fires involve textile fibers. The experiment was conducted using fabrics with different weaves (twill and plain) and varying gap widths between materials. The flame spread rate for 0 mm gap width (only cotton) was the lowest, while the rates for gap widths from 0.5 to 2 mm were relatively similar and higher than that of 0 mm.

The laminar diffusion flame spread model proposed by De Ris (1969) is applied to represent the experimental data. This model assumes that the hot flame heats the unburned fuel bed, causing it to vaporize. The resulting fuel vapor reacts with oxygen supplied by the incoming air, generating heat to sustain the flame spread process. The model incorporates energy and species conservation equations to describe the phenomenon. During the collaboration research, discussions were held regarding the use of a moving coordinate system and the homogenization method for modeling the behavior of heterogeneous materials.

- 張　一弘（九州大学大学院数理学府)、福本　康秀（九州大学　マス・フォア・インダストリ研究所）：平面および円筒状予混合火災の拡散・熱不安定性再訪

This study focuses on analyzing the stability of premixed flames in both flat (planar) and cylindrical configurations. The study examines the effects of diffusive-thermal instability, which occurs when there is an imbalance between the diffusion of heat and the transport of fuel and oxidizer in the flame. By revisiting and extending classical theories, the research aims to better understand how these instabilities affect flame propagation and stability. The work combines mathematical modeling and numerical simulations to explore the conditions under which these instabilities occur.

- 松江　要（九州大学　マス・フォア・インダストリ研究所）：着火・火炎対応の分岐理論による新（しくない）描像

The study explores ignition and flame dynamics using bifurcation theory to understand how small changes in parameters can cause significant shifts in flame behavior. By analyzing the bifurcation points, the study identifies the critical thresholds where flames transition between stable and unstable states. The research revisits previous theories on flame behavior while providing new insights into ignition and response dynamics in combustion systems.

3. Conclusions

The research collaboration developed and validated models for predicting transitions in combustion dynamics, including the shift from smoldering to flaming combustion and the stability of premixed flames under diffusive-thermal instability. Key findings include the identification of critical bifurcation points and the applicability of theoretical models in improving flame spread predictions and early detection of combustion runaway reactions. The discussions on stability analysis, moving coordinate systems, and homogenization methods contributed valuable insights into the behavior of heterogeneous materials and their fire-related dynamics. We hope that this discussion will help share the mathematical approach for ongoing research in combustion and address fire safety issues within society and industry perspectives.

…開催日：2024/11/13〜2024/11/13

Quantitative prediction of transition phenomena in combustion processes｜2024a039

カテゴリー：イベント　タグ：若手研究 短期共同研究

プログラム

11月12日（火）【非公開】15:00〜18:00

11月13日（水）【公開】

- 13:00-13:40

ビリヤアモンキジュ ピチャヤポーン（東京理科大学）
Modeling limit conditions of smoldering combustion

- 13:40-14:20

桑名 一徳（東京理科大学）
火災時の一酸化炭素発生に関する危険予測

- 14:20-15:00

山崎 拓也（弘前大学）
周期的な構造が固体の燃焼に及ぼす影響の検討

- 15:30-16:10

張 一弘（九州大学大学院数理学府）、福本 康秀（九州大学 マス・フォア・インダストリ研究所）
平面および円筒状予混合火炎の拡散・熱不安定性再訪

- 16:10-16:50

松江 要（九州大学 マス・フォア・インダストリ研究所）
着火・火炎対応の分岐理論による新描像