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包括的燃焼限界理論の構築に向けた低ルイス数予混合気による極低流速対向流火炎の軌道上実験
―装置開発のこれまでとこれから―

Space Experiment Project of Low-speed Counterflow Flame with Low Lewis Number Mixture toward Establishing Comprehensive Combustion Limit Theory

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1. Introduction

As solutions of global warming have been attaining attention, fuel-lean combustion is expected as one of the potential solutions. Lean combustion of SI engines leads to less emission of CO_2, and improve thermal efficiency by increasing heat capacity ratio and decreasing heat loss due to low flame temperature. However, unstable behaviors near combustion limit emerge due to essential flame instability under certain conditions. In order to control such instability and understand combustion limit theory, our research group has been investigating flame behaviors with counterflow configuration. In addition, this research topic was selected as a research theme in Japanese experiment module “Kibo” in International Space Station (ISS) in 2010 and experimental apparatus is planned to be launched in FY 2022. In this study, we overview knowledge on combustion limit and recent works related to the construction of the comprehensive combustion limit theory.

2. Research of Combustion Limit and Flame Ball

An investigation for combustion limit originated in explosion at coal mine in 19th centuries. While various attempts to evaluate the flammability have been carried out, several factors, such as conductive heat loss to wall and buoyancy prevent from evaluating the exact flammability limit with such factors eliminated. The counterflow flame approach under microgravity environment is one of the promising approaches to evaluate combustion limit. In counterflow configuration, twin steady flat flames are stabilized near the stagnation plane for a premixed mixture, which means that such flames are not suffering from any conductive heat losses to the burners should be considered. Buoyancy effect can be eliminated under microgravity environment. An important parameter in counterflow configuration is stretch rate, which is defined as the ratio of mixture flow velocity at burner outlet to burner distance. Stretch rate is difficult to evaluate in actual combustors in general but play an important role in determining the flammability limit. From these characteristics, counterflow configuration under microgravity environment has been widely used for determining the flammability limit.

Flammability limit of flame ball has been considered as a different topic from that of counterflow flames. Flame ball is a steady ball-shaped flame in a quiescent fuel/oxidizer mixture. Propagation of a reaction front to unburned gas is an essential characteristic for a flame in a quiescent premixture in general. However, flame ball does not show propagation, which is unique characteristics of flame ball. The history of flame ball and the related topics were summarized in Fig. 1. Flame ball was firstly predicted analytically by a Russian mathematician Zeldovich in 1940's, but he also claimed that it might be an unstable solution which could not be stabilized in a realistic system 1). In 1980's, however, an American researcher Ronney accidentally found the seemingly steady ball-shaped flame in a low Lewis number mixture under microgravity 2). The experiments to confirm the stability of flame ball in JAMIC, a drop tower in Hokkaido 3), and on a space shuttle finally concluded that flame ball can be realized 4). Through the studies, flame ball was found to survive under extremely low equivalence ratio conditions. This fact raised a new question on flammability limit of a premixture.

The analytical study also progressed in the same period. Buckmaster conducted an analysis on stability of flame ball with heat loss 5). He revealed that by considering adequate amount of heat loss, flame ball has two analytical solutions in terms of radius. Smaller-radius solution corresponded to unstable solution while larger-radius one stable. With the decrease of heat loss, the smaller-radius solution was connected to the solution predicted by Zeldovich under the adiabatic condition. This result demonstrated existence of flame ball and implied that radiation heat loss plays an important role in stabilizing flame ball since radiation is essentially inevitable for flame close to the limits. In the same period, some studies on flame ball have been conducted, leading to deep understandings the nature of flame ball 6–11).

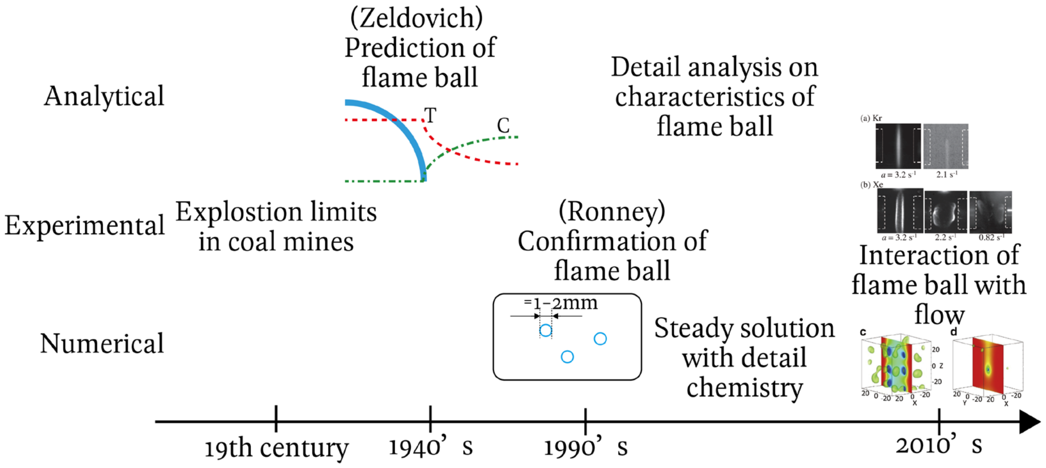


Fig. 1 History of flame ball study and related topics.

3 Experiments at ISS Toward Comprehensive Combustion Limit Theory

The analysis of combustion limit using counterflow and the discovery of flame ball are overviewed in this section. Counterflow flame and flame ball were investigated separately and the relations between these two were unclear. The main reason for the lack of information connecting them is the requirement of microgravity environment to obtain flame ball. In addition, two flames of counterflow and flame ball were not believed to be handled under the same approach in terms of the nature with and without flame propagation. In order to reveal the relation between the two flames, we have suggested low-speed counterflow approach to explore the intermediate condition of two flames. The diffusion and convection are dominant in transport of mass and energy in counterflow flame while only diffusion takes part in transport in flame ball. Based on these facts, we thought that by decreasing flow velocity as competing with mass diffusion transport, the condition where two flames realized should be close. By extremely decreasing the flow velocity, the characteristic time scale of the system becomes long since diffusion transport is dominant, which requires long duration of microgravity environment. We believe that the relations of the two flames should be addressed not only in terms of basic knowledge for understanding comprehensive combustion limit, but also for society to utilize knowledge of lean combustion. This research was selected as a research theme on Japanese experiment module "Kibo" on the ISS and experimental apparatus is planned to be launched in FY 2022. In advance, some experimental and numerical attempts have been conducted. Recent trials are summarized.

One of the important parameters that characterizes counterflow flame is a stretch rate, thus appropriate target approach can be classified with stretch rate. The relation of stretch rate and required approach are summarized in Fig. 2. Under high

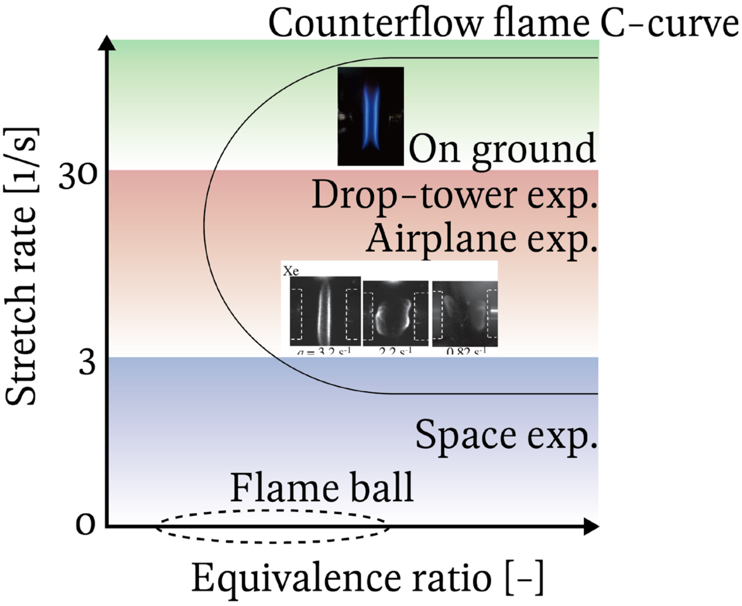
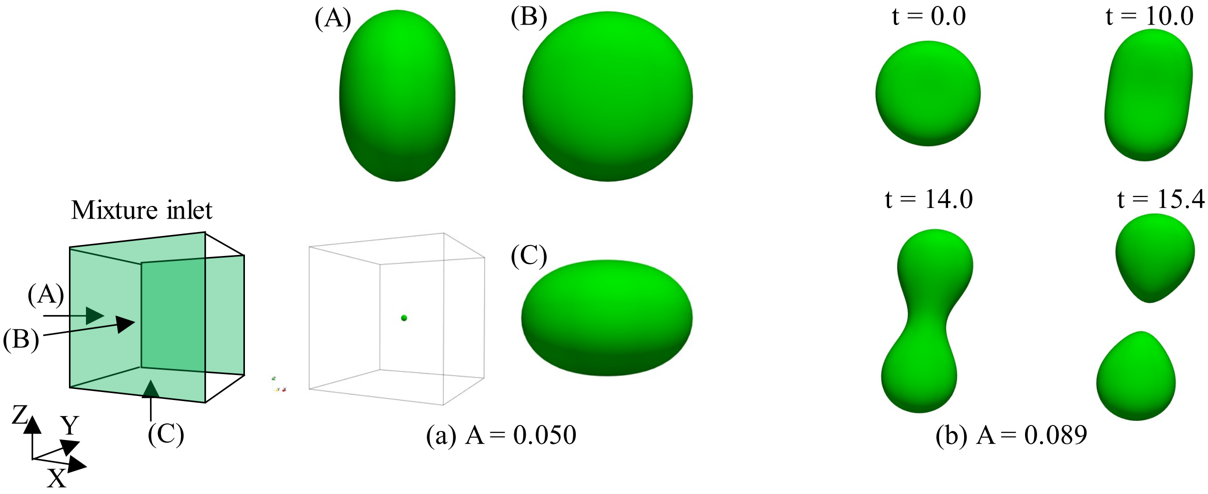


Fig. 2 Target stretch rate condition and required approach

stretch rate conditions (higher than typically 30 s^{-1}), effect of the buoyancy can be neglected because the contribution of natural convection to disturbing flame behavior is much smaller than that of flow convection. Thus, flames can be stabilized and analyzed precisely on ground. Generally flat double flames can be obtained near the stagnation plane of counterflow field. Buoyancy effect needs to be considered at stretch rate lower than around 30 s^{-1}, so microgravity environment is essential. Most of experiments with drop tower and airplane parabolic flight have been conducted targeting this stretch rate conditions [2–4,12,13)]. Stretch rate lower than 3 s^{-1}, characteristic time scale of phenomena gets longer, which require long duration of microgravity. As the durations of microgravity with airplane parabolic flight and drop tower are 20 and 10 seconds respectively, experiments on space shuttle or on orbit are needed.

As preliminary experiment for space experiments, we have been conducting counterflow experiments with airplane parabolic flights with low Lewis number mixtures [12,13)]. The counterflow apparatus were loaded on an airplane, and during around 20 seconds microgravity by a parabolic flight, a mixture was ignited and equivalence ratio and/or stretch rate were changed with a quasi-steady state manner. Representative flame images are shown in Fig. 2 [13)]. Under stretch rate around 2-3 s^{-1}, ball-like flames were confirmed and was considered as an intermediate combustion mode between normal counterflow flat flame and flame ball. In space experiments with longer duration of microgravity and lower stretch rate, we expect to explore more various condition or even find totally new flame behavior.

In addition to experiments, some feasibility studies with numerical approach have been conducted [13–17)]. By extremely decreasing stretch rate, ball-like flames which repeat formation and extinction, named sporadic flames, were found with



(a) A = 0.050

(b) A = 0.089

Fig. 3 New flame behavior (a) stable non-spherical ball-like flame and (b) split of ball-like flame [17)].

a three-dimensional Diffusive Thermal model 13). This flame behavior was also observed in experiments. In addition, numerical experiments showed two new flame behaviors; stable non-spherical ball-like flame under extremely low stretch rate and the split of ball-like flame under relatively high stretch rate condition 17). These flame dynamics are shown in Fig 3. The non-spherical steady solution in the low velocity counterflow field was totally new combustion mode which should be a bridge between flame ball and the counterflow planar flame. In the analysis of the splitting mechanism of ball-like flame, it was found that some amount of fuel remained unburned at the center of the ball-shaped flame. The amount of the unburned fuel increase with the increase of stretch rates, and the diffusion of the unburned fuel from the center of flame acted as a splitting force under the splitting condition. Validation of these new flame behavior predicted by numerical experiments needs microgravity experiments for long characteristic times, and so the validity of these results and stability of flame ball will be clarified in the future space experiments.

4 Conclusions

The progress of studies on the combustion limit was summarized. The history of combustion limit research and that of flame ball were reviewed. Recent studies including some preliminary experiments and numerical experiments were introduced. The existence of intermediate combustion mode between counterflow planar flame and flame ball has been suggested through these studies. Space experiment is expected to provide further information for validating these new findings and predictions.

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