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L3-FLAME: Flame ball・対向流火炎・非伸長平面火炎の燃料希薄・過濃限界に関する数値的研究

L3-FLAME: Computational Study on Fuel-Lean and -Rich Limits of Flame Balls, Counterflow Flames, and Stretch-Free Planar Flames

角田陽[1,2], 秋葉貴輝[1,2], 中村寿[1], 手塚卓也[1], 菊池政雄[3], 丸田薫[1]
Akira TSUNODA[1,2], Takaki AKIBA[1,2], Hisashi NAKAMURA[1], Takuya TEZUKA[1], Masao KIKUCHI[3], and Kaoru MARUTA[1]
[1] 東北大学　流体科学研究所，Institute of Fluid Science, Tohoku University,
[2] 東北大学大学院　工学研究科，School of Engineering, Tohoku University,
[3] 宇宙航空開発機構　筑波宇宙センター，Tsukuba Space Center, Japan Aerospace Exploration Agency

1. Introduction

Flammability limit is one of the most important topics in the combustion science for the establishment of fire safety standards. However, it is difficult to define a specific flammability limit for a given premixture because extinction limits are strongly affected by heat loss, flame stretch, Lewis number: the ratio of mixture thermal diffusivity to molecular diffusivity of the deficient reactant $Le = \alpha/D$, and system configuration. Understandings on the near-limit flame behavior are needed.

Effects of flame stretch on near-limit flame dynamics and the flammability limit have been investigated by utilizing counterflow planar flames. It is one of the fundamental experimental platforms since it has no heat loss to burners and stretch rate can be controlled by the inlet velocity and burner distance. To investigate fundamental near-limit flame behavior, microgravity experiments are needed since buoyancy effect becomes no longer negligible near the limit. The C-shape extinction boundary curves on equivalence ratio - stretch rate plane have been observed in drop tower microgravity experiments[1)] and numerical studies[2)] in low-Lewis number mixtures. Besides, a peculiar combustion mode termed as "flame ball" has been studied separately from ordinary flame studies. It is a non-propagating spherical flame observed in quiescent and $Le \ll 1$ mixtures. Zel'dovich [3)] first mathematically predicted the existence of flame ball in 1940s. He also obtained that adiabatic flame balls have only unstable solutions. However, it was experimentally observed through 1980s to 90s in drop tower experiments[4)] and a Space Shuttle orbital experiment[5)]. In parallel to microgravity experiments, stability analysis revealed that the flame ball is stabilized by the heat loss[6)]. One of the notable characteristics of flame balls is that it was observed even lower fuel concentration mixtures than lean limits known before.

In this study, we overview the findings related to flammability limits and near-limit flame characteristics obtained from a series of experimental and numerical studies.

2. L3-FLAME: microgravity experiments and numerical simulations

Flame balls and conventional propagating flames have been separately studied because the former established in quiescent mixtures and the latter propagate relative to the mixture. A unified combustion limit theory that covers both flame ball and propagating flames are needed for the comprehensive understanding on the flammability limit. Our research group has been utilized counterflow field as a research platform realizing the intermediate condition where these two flames could coexist. By decreasing the flow velocity in counterflow field, quiescent mixtures and counterflow fields can be asymptotically connected. This research is selected as one of the experimental research projects in the Japanese experimental module "Kibo" in the International Space Station, and the space experiment is scheduled in FY 2023. The title of the research project is "Low-speed low-Lewis number counterflow flame experiment for unified combustion limit theory, L3-FLAME". Preliminary microgravity experiments for low inlet velocity conditions using airplane parabolic flight have been conducted for $CH_4/O_2/CO_2$, $CH_4/O_2/Kr$, and $CH_4/O_2/Xe$ mixtures[7–9] to investigate the effect of radiation heat loss and Lewis number on the near-limit flame characteristics. Fig. 1 shows the C-shape extinction boundary curve of the mixture obtained from one-dimensional computations and non-planar unsteady flames observed in microgravity experiments in the $CH_4/O_2/Xe$ mixture. Cellular and sporadic flames, the quasi-steady ball-shaped flames, have been observed in low inlet velocity conditions even outside of the C-shape extinction boundary curve. The three-dimensional numerical analysis for the counterflow configuration was also conducted to investigate the phenomena induced by diffusive-thermal instability in the experiments. The numerical analysis revealed that sporadic flames, are the intermediate combustion mode which segue flame balls and counterflow planar flames in terms of characteristic flame size and flame structure[9]. Furthermore, stable ball-like flames and splitting ball-like flames in extremely low inlet velocity conditions have also observed in a numerical analysis[10].

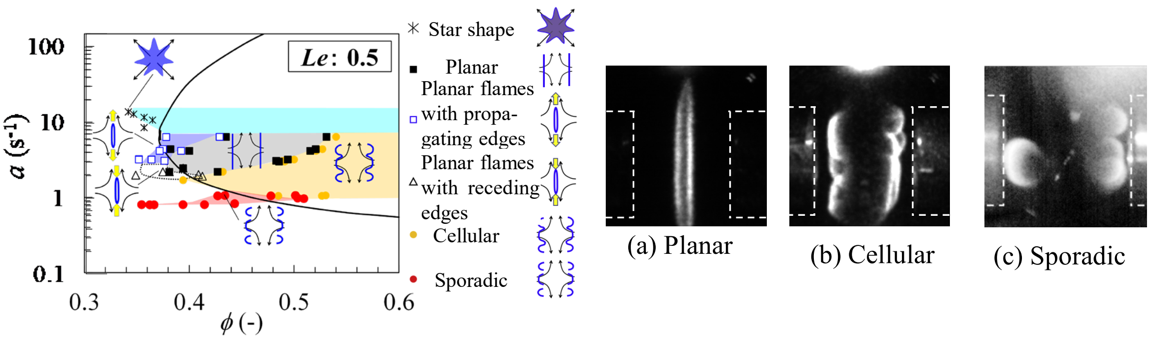

Figure. 1 The experimental flame regime of counterflow flames of the $CH_4/O_2/Xe$ mixture and C-shape extinction boundary obtained by one-dimensional steady computations. Representative flame picture of (a) planar flames, (b) cellular flames, and (c) sporadic flames are also shown.[9]

3. Computational study on near-limit flame characteristics for lean and rich conditions

For the next step of the study, we have overviewed the overall picture of near-limit flames through lean to rich conditions by numerical analysis. One-dimensional steady computations were conducted for flame balls, counterflow flames as a representative of stretched flames, and stretch-free planar flames for the $CH_4/O_2/Xe$ mixture. PREMIX-based spherical flame code[7], OPPDIF package , and PREMIX package in Chemkin-Pro v19.0[11] were used for the computations of flame balls, counterflow flames, and stretch-free planar flames, respectively. Optically thin radiation model [2] was used for computations of radiation heat loss.

Fig. 2 shows the flammable regime of flame balls, counterflow flames, and stretch-free planar flames. The vertical dash-dot lines are the lean and rich limits of each flame. The lean limit equivalence ratios were lower in the order of the flame balls, counterflow flames, and planar flames. Thus, the lean flammability limit of this mixture corresponded the lean limit of the flame balls. The rich limit equivalence ratios were higher in the order of the counterflow flames, planar flames, and flame balls. Thus, the rich flammability limit of the mixture corresponded the rich limit of the counterflow flames.

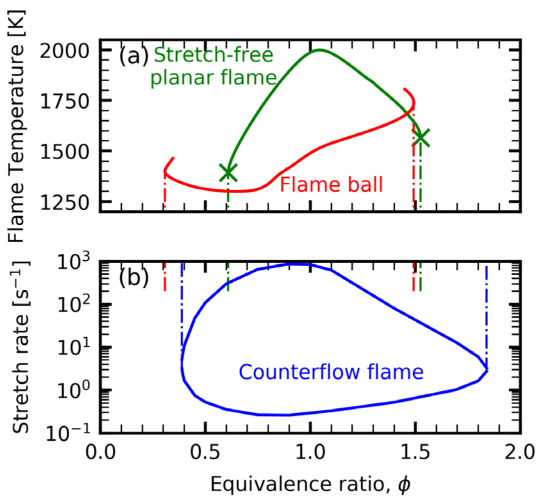

Figure. 2 (a) flame temperatures of the flame balls and stretch-free planar flames, the cross symbols are the lean and rich limits of the stretch-free planar flames. (b) flammable regime of counterflow flames bounded by stretch- and radiation-induced limits. The vertical dash-dot lines indicate the lean and rich limits of each flame.

It has been known that the border of the lean/rich combustions of flame ball is located at $\phi = \phi_c$. ϕ_c is a critical equivalence ratio defined as $\phi_c = Le_f/Le_o$ where Le_f and Le_o are Lewis numbers of fuel and oxidizer, respectively. This topic was theoretically suggested by Joulin[12)] and partially studied by numerical studies[13)]. To summarize the discussion about the border of the lean and rich combustions, we introduce a new parameter, essential stoichiometry: an equivalence ratio of the border of the lean and rich combustions. The mole fractions of CH_4, O_2, CO, and CO_2 were compared at the center of the flame ball, in the stagnation plane of the counterflow flame, and in the burned gas boundary of the planar flame. The vertical dash-dot lines indicate the critical equivalence ratio of $\phi = \phi_c \sim 0.87$ and the vertical dashed lines indicate the $\phi = 1$. Fig. 3(a) shows flame ball case, the mole fraction distributions were drastically changed at $\phi = \phi_c$. O_2 reached nearly 0, CO started remarkably increasing, and CO_2 attained its maximum. Therefore, essential stoichiometry of flame ball corresponded to $\phi = \phi_c$. Next, we discuss about Fig. 3(c) to confirm the conventional behavior of essential stoichiometry. The mole fractions distributions were drastically changed at $\phi = 1$, O_2 reached nearly 0, CO started remarkably increasing, and CO_2 attained its maximum. Therefore, essential stoichiometry of the stretch-free planar flames corresponded to $\phi = 1$. Fig. 3(b) shows counterflow flames case, the solid curves represented lower stretch rate case a = 0.347 1/s and the dashed curves represented higher stretch rate case a = 100 1/s. In higher stretch rate condition, the border of the lean and rich combustions closed to $\phi = 1$ despite it was ambiguous. O_2 reached nearly 0 and CO_2 attained its maximum. In lower stretch rate condition, the mole fraction distributions drastically changed at around $\phi \sim 0.92$ between $\phi = \phi_c$ and $\phi = 1$. O_2 attained its minimum, CO started remarkably increasing, and CO_2 attained its maximum. Therefore, the essential stoichiometry of the counterflow flames located between $\phi = \phi_c$ and $\phi = 1$ depending on its stretch rate.

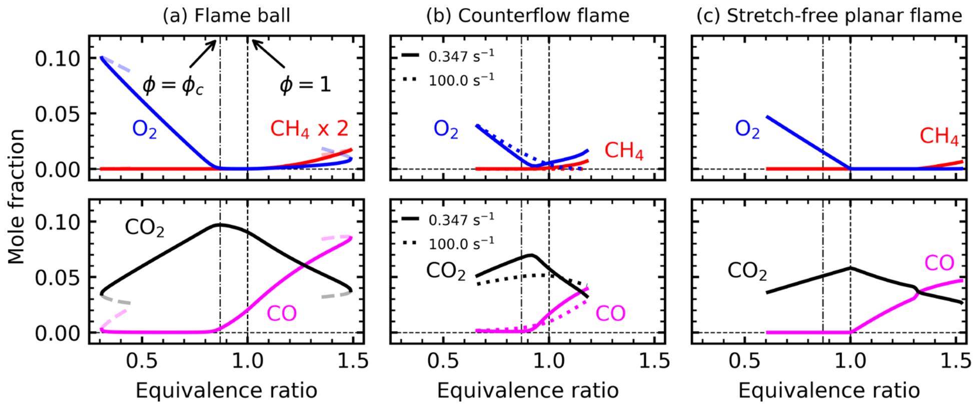

Figure 3 Mole fractions of CH_4, O_2, CO, and CO_2 (a) at the center of the flame balls, (b) in the stagnation plane of the counterflow flames, and (c) in the burnt gas boundary of the stretch-free planar flames.

4. Conclusions

The microgravity experiments and numerical studies toward the unified combustion limit theory that covers both the flame balls and propagating flames are summarized. The findings from the study with one-dimensional steady computations targeting near-limit flame characteristics in both lean and rich conditions are summarized as follows:

1) The lean flammability limit of the mixutre was represented by the lean limit of the flame balls. The rich flammability limit of the mixture was represented by the rich limit of the counterflow flames.

2) Essential stoichiometry: the border of lean and rich combusitons, of flame balls was $\phi = \phi_c$, of stretch-free planar flames was $\phi = 1$, and of counterflow flames changed between $\phi = \phi_c$ and $\phi = 1$ depending on its stretch rate.

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