JASMAC
Conference of the Japan Society of Microgravity Appllication

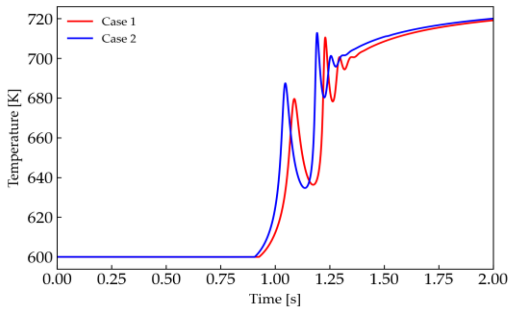
OS3-6

単一燃料液滴の冷炎振動に及ぼす蒸発速度の影響

Influence of Evaporation Rate on Cool Flame Oscillation of Isolated Fuel Droplet

江端滉世[1], 柳原結衣[1], 菅沼祐介[2], 野村浩司[2], 田辺光昭[3], 齊藤允教[3]
Kosei EBASHI[1], Yui YANAGIHARA[1], Yusuke SUGANUMA[1], Hiroshi NOMURA[1], Mitsuaki TANABE[1] and Masanori SAITO[1],
[1] 日本大学大学院理工学研究科航空宇宙工学専攻，Graduate School of Science and Technology, Nihon University
[2] 日本大学生産工学部，College of Industrial Technology, Nihon University
[3] 日本大学理工学部，College of Science and Technology, Nihon University
* Correspondence：csko24008@g.nihon-u.ac.jp

Abstract: The influence of the evaporation rate of isolated fuel droplet on cool flame oscillation was investigated. The ambient gas was air with the temperature 600 K, and the pressure of 0.1 MPa of two diffrent fuel were employed: one was *n*-decane and the other is an imaginary fuel based on *n*-decane, whose transport properties were modified so that its evaporation rate was equivalent to that of *n*-heptane. Cool flame oscillation was observed in both cases, with no significant difference in the oscillation mode. Prior to the onset of the cool flame, no difference was observed in the variations of evaporation amount or surface temperature due to the evaporation rate. After the onset of the cool flame, a phase shift of approximately the ignition delay time was confirmed. However, the influence of the evaporation rate on the rates of change was minor, suggesting that it exerts little influence on the oscillation mode.



Keywords: Cool flame oscillation, Droplet combustion, Spontaneous ignition

1. Introduction

In recent years, Sustainable Aviation Fuel (SAF) has attracted attention as part of efforts toward carbon neutrality. SAF produced via Fischer–Tropsch synthesis contain normal-chain higher alkanes. Rocket and jet engines, where such SAF is utilized, commonly employ spray combustion. In spray combustion, fuel is injected and undergoes a complex sequence of processes including evaporation of countless droplets, spontaneous ignition, and flame spread. The smallest constituent unit of a spray is a droplet, and studies on droplet combustion serve as a fundamental approach to understanding spray combustion. Tanabe et al. 1) reported the existence of a cool flame during the spontaneous ignition process of droplets composed of higher alkane fuels. Cool flames are known to exhibit oscillatory behavior. Griffiths et al. 2) conducted simulations including heat loss and clarified the influence of thermal losses on cool flame oscillation. Iemura et al. 3) investigated the influence of Lewis and Damköhler numbers, which are important parameters governing heat dissipation, on cool flame oscillation, and clarified their influence on oscillation modes. Although the relationship between these parameters and oscillation modes is important, the influence of mass and heat feedback due to fuel evaporation has not been considered. Therefore, it is necessary to investigate the influence of the evaporation rate on cool flame oscillation.

In this study, numerical simulations are conducted using hypothetical fuels with modified physical properties to investigate the influence of evaporation rate on cool flame oscillation.

2. Simulation Conditions and Method

Figure 1 and **Table 1** show the simulation computational domain and conditions. The simulation was carried out by using ANSYS Fluent with two-dimensional (2D) unsteady scheme of axisymmetric numerical domain. The vaporization process was directly calculated by the following equations. For further details, refer to reference [4].

$$\dot{m} = \frac{\Delta q A_c}{\Delta H_v} \tag{1}$$

Where $\dot{m}$ is the mass flow rate, A_c is a cell area, ΔH_v is the enthalpy of vaporization, and Δq is the difference in the heat flux of gas and liquid phase side across the droplet surface. The enthalpy of the vaporization is calculated by the following equation,

$$\Delta H_v = \frac{\alpha}{M}(1 - T_r)^{\beta}\exp(-\beta T_r) \tag{2}$$

$$T_r = \frac{T_s}{T_c} \tag{3}$$

where M is the molecular weight of the fuel, α and β are the constants depending on the species. Reduced temperature T_r is calculated by the surface temperature T_s and critical temperature T_c of fuel. Two conditions with different evaporation rates are employed for fuel by change in the constants related to the enthalpy of vaporization. The constants for enthalpy of vaporization are listed in Table 2. Case 1 represents the constants corresponding to *n*-decane, while case 2 corresponds to those of *n*-heptane.

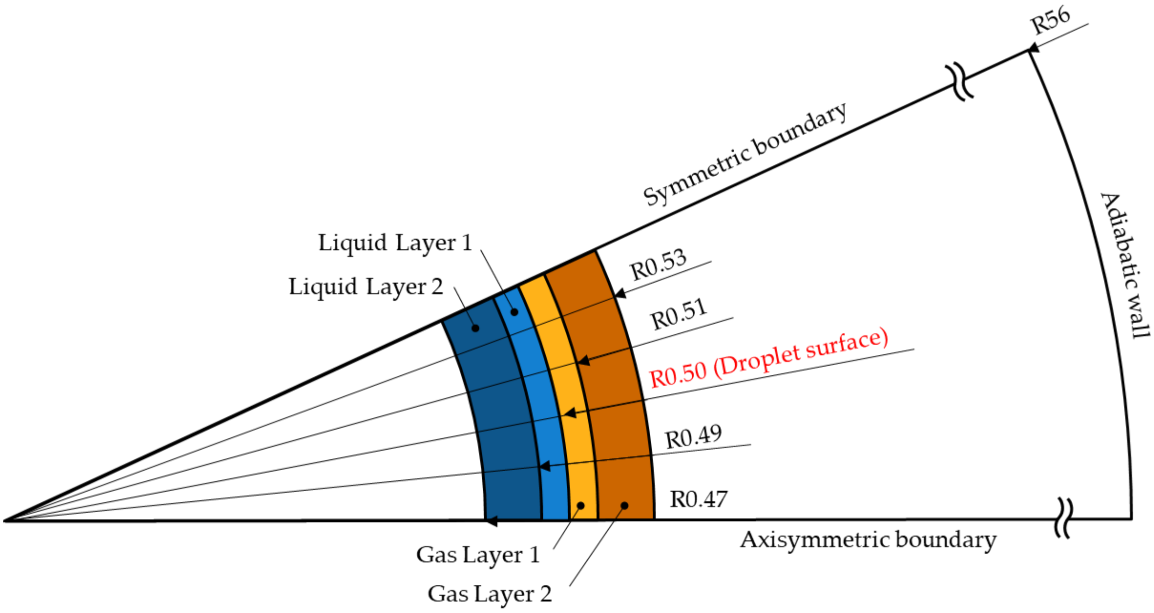


Figure 1. Numerical simulation domain for an isolated droplet.

Table 1. Simulation initial conditions.

Chemical-kinetic model	77 species, 287 reactions [5]
Ambient temperature T_a [K]	600
Ambient pressure [MPa]	0.1
Ambient gas composition [%mol]	O_2: 21, N_2: 79
Droplet diameter d_0 [mm]	1
Droplet temperature [K]	300

Table 2. Constants for each equation 6).

case	1	2
Molecular weight M [g/mol]	142.2817	100.2056
α [-]	74.38	53.66
β [-]	0.3238	0.2831
T_c [K]	617.4	540.2

3. Results and Discussion

Figure 2 shows the nondimensional droplet diameter history. From **Fig. 2**, evaporation rate was faster in case 2 than in case 1, but the difference was small. In the PHOENIX-2 project 7), combustion experiments of single n-decane droplet with a diameter of approximately 1 mm were conducted, and it was reported that the evaporation rate constant was $K = 0.35\ \mathrm{mm}^2/\mathrm{s}$ at an ambient temperature of 564 K.

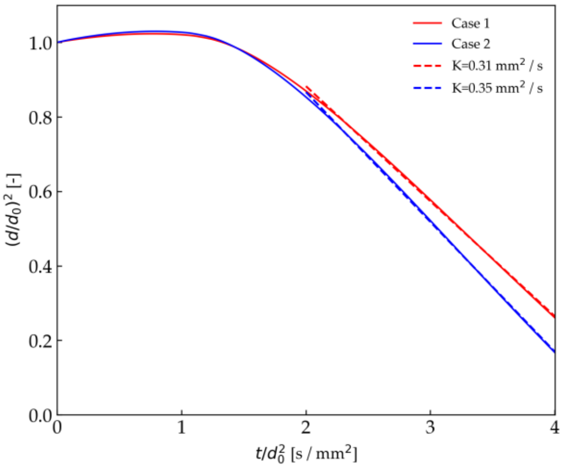
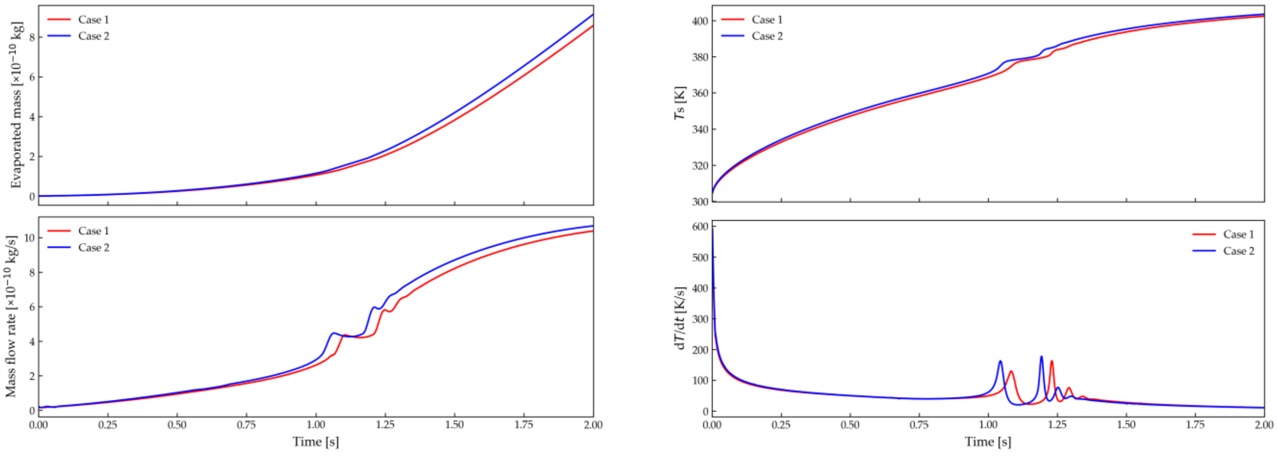


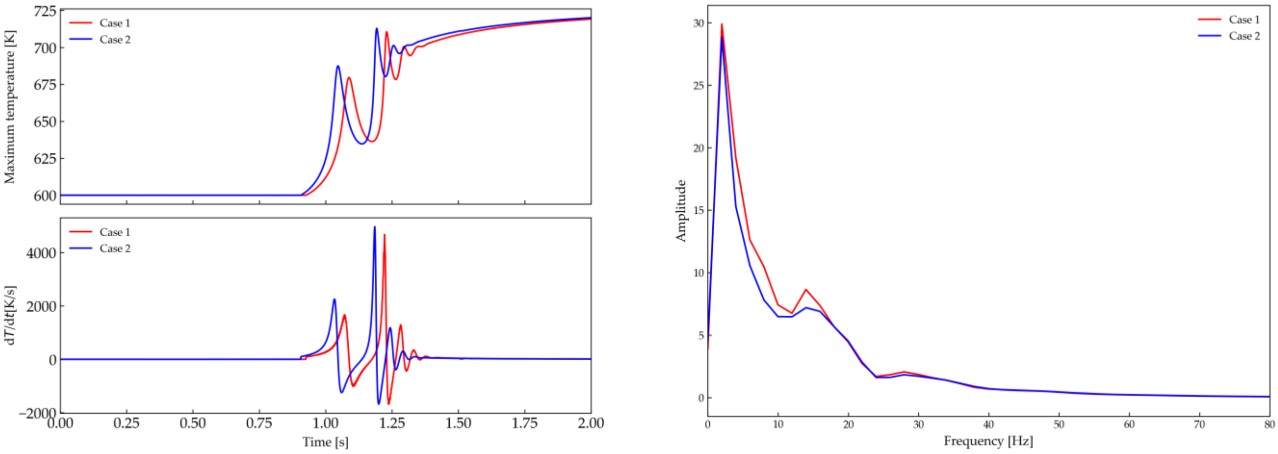
Figure 2. Histories of squared nondimensional droplet diameter.

Figure 3 (a) shows the time histories of the evaporation amount and the mass flow rate, while **Fig. 3(b)** presents the time histories of the droplet surface temperature and its rate of increase. A comparison before and after the ignition delay time reveals that, prior to ignition, there is little difference between the two cases in both **(a)** and **(b)**. After ignition, although a temporal shift is observed between the two cases in both **(a)** and **(b)**, the same behavior is exhibited, and no significant difference in magnitude can be identified.



(a) (b)

Figure 3. (a) Evaporated mass (upper) and mass flow rate (lower) history;
(b) Droplet surface temperature (upper) and the temperature rise rate (lower) history.



(a) (b)

Figure 4. (a) Maximum temperature (upper) and temperature rise rate (lower) history;
(b) FFT spectrum of maximum temperature history.

Figure 4(a) shows the maximum temperature and its rate of increase, and **Fig. 4(b)** presents the FFT spectrum of the maximum temperature history. From **Fig. 4(a)**, it is evident that both cases exhibit oscillatory behavior, and the time intervals between successive local maxima of $\mathrm{d}T/\mathrm{d}t$ are comparable. From **Fig. 4(b)**, the frequency and period exhibit the same trend in both cases, indicating that no significant difference in the oscillation mode can be identified.

4. Summary

To investigate the influence of the evaporation rate on cool flame oscillation, two different fuel were employed: one was *n*-decane and the other is an imaginary fuel based on *n*-decane, whose transport properties were modified so that its evaporation rate was equivalent to that of *n*-heptane. The following results were obtained from numerical simulations.

・It was suggested that the evaporation rate affects the timing of the temporal variations in temperature and evaporation amount, but its influence on their behavior is minor, and it has little influence on the oscillation mode.

Acknowledgments

This study was supported by ISAS-JAXA as *The Front-Loading Project* and *Small-Scale Project*, by JSPS KAKENHI Grant Number JP19K04843 and JP21K14347 and JP24K07887, and by Nihon University President Grant Initiative.

References

1) M. Tanabe, T. Bolik, C. Eigenbrod, H. J. Rath, J. Sato and M. Kono: Spontaneous ignition of liquid droplets from a view of non-homogeneous mixture formation and transient chemical reactions, Proc. Combust. Inst., 26 (1996) 1637
2) J. F. Griffiths and S. K. Scott: Thermokinetic interactions: fundamentals of spontaneous ignition and cool flames, Prog. Energy Combust. Sci., 13 (1987) 161
3) K. Iemura, R. Saito, Y. Takahata, M. Saito and M. Tanabe: Influence of dimensionless number in a dynamics model a droplet pair on the cool flame oscillation, JASMAC-35 (2023)
4) M. Saito, Y. Ohno and M. Tanabe: Numerical study on the cool flame dynamics of n-decane fuel droplets by 2D simulation with gas-liquid equilibrium, JASMAC-32 (2020)
5) L. Qiu, X. Cheng, X. Wang, Z. Li, Z. Wang and H. Wu: Development of a reduced n-decane/ α -methylnaphthalene/polycyclic aromatic hydrocarbon mechanism and its application for combustion and soot prediction, Energy Fuels 30 (2016) 10875
6) C. B. Willingham, W. J. Taylor, J. M. Pignocco and F. D. Rossini: J. of Res. Of the NBS, 35 (1945) 219

7) K. Iemura, M. Saito, Y. Suganuma, N. M. Figueira, F. Meyer, C. Eigenbrod, H. Nomura and M. Tanabe: Cool flame diameter of single *n*-decane droplet spontaneous ignition experiment under microgravity using a texus rocket, ISTS 35 (2025)