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二液滴の力学系モデルにおける無次元数が冷炎振動に及ぼす影響

Influence of Dimensionless Numbers in a Dynamics Model of a Droplet Pair on the Cool Flame Oscillation

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1. Introduction

Combustion engines such as jet engines and liquid rocket engines use spray combustion. The operational range of these engines involves a two-stage ignition process, occurring both cool flame and hot flame. The smallest element of the spray is a droplet. Tanabe et al.[1-3] conducted droplet combustion studies using a drop tower and numerical simulations, clarifying the occurrence of cool flame during the spontaneous ignition process of droplets. One interesting behavior of cool flames is their oscillation[4-5]. Griffiths et al.[5] studied a 0-dimensional dynamics system of low-temperature reactions with diffusion in detail. Tanabe et al.[6-7] simulated cool flame oscillation with the simplest dynamical system that covers the characteristics of cool flame based on reactions. In his study, the amount of the chain agent and temperature influenced the dissipation term. This enables the simulation of the cool flame in the droplet system. It was reported that cool flame oscillation in the droplet system depends on the rate of reaction and dissipation. Saito et al.[8] used Tanabe's dynamical system model to simulate differences in the relative dissipation of substance and heat. They reported that as the value of the heat dissipation term is increased, the chain branching reaction is reactivated with decreasing temperature, resulting in a limit cycle. These studies considered diffusion to the ambient but did not consider the interaction phenomena that occur around the droplet pair system or diffusion to the other droplet.

In practical spray combustion, numerous droplets exist. Moriue et al.[9] clarified two interaction effects during the spontaneous ignition process of droplet pairs, before and after the occurrence of cool flame. In the “FLEX” project in the United States, they discovered the cool flame occurrence during the extinction process of the hot flame in the droplets[10]. Mikami et al.[11] conducted the first combustion experiment at the International Space Station's Kibo module titled “Group Combustion” as a bridge to fill the gap between droplets and sprays. Recent research has shown the occurrence of cool flame even in the flame spread

process[12]. In the spontaneous ignition process, "PHOENIX-2"[6] is an underway collaborative project between Japan and Germany. This project aims to clarify the cool flame dynamics including cool flame oscillation[13], cool flame spread, and so on near the spontaneous ignition limit.

In this paper, we describe cool flame oscillations that occurred around droplet pair using the simplest dynamics model. The model is based on Tanabe's system. We introduce dimensionless numbers resembling Damköhler and Lewis numbers and discuss their influence on cool flame oscillations.

2. Modeling of cool flame oscillation occurred around droplet pair

Equations (1) to (4) define the rates of concentration and temperature rise with time at droplets 1 and 2. Subscripts of T and C denote droplets 1 and 2. Subscripts of 0 indicate initial conditions. Equations (5) to (9) express Arrhenius-type reaction rate constants. The "k*" is the reaction rate constant when the production and consumption terms are equal where the temperature is defined as "T*" at that moment. The "Da" and "Le" represent dimensionless numbers that imitate the Da and Le. The Da and Le are defined in equations (10) and (11). The "hs" corresponds to the coefficient indicating the diffusion of the substance. Also, the "hh" corresponds to the coefficient indicating the diffusion of the heat. The "C_a" and "T_a" denote concentration and temperature in the ambient conditions. The C_a was determined based on the cool flame oscillation that occurs around the droplet in 2D simulation. The T_a was determined based on the cool flame temperature at 1 (750 K). The "a" is defined as the interaction coefficient and larger values influence the other droplet. The "T_e" corresponds to the activation temperature. The "T_{e1}" was determined from the slope of an Arrhenius plot consisting of cool flame delay time and temperature. The "q" is the energy value. The q was determined from the dT/dC which consists of the gas phase maximum temperature and the maximum molar concentration of OH in the cool flame oscillation that occurs around the droplet in 2D simulation.

$$\frac{dC_1}{dt} = k_1 C_1 - k_2 C_1 - \frac{k^*}{Da}(1-a)(C_1 - C_{a1}) - \frac{k^*}{Da}a(C_1 - C_2), \tag{1}$$

$$\frac{dC_2}{dt} = k_3 C_2 - k_4 C_2 - \frac{k^*}{Da}(1-a)(C_2 - C_{a2}) - \frac{k^*}{Da}a(C_2 - C_1), \tag{2}$$

$$\frac{dT_1}{dt} = k_2 C_1 q - Le\frac{k^*}{Da}(1-a)(T_1 - T_{a1}) - Le\frac{k^*}{Da}a(T_1 - T_2), \tag{3}$$

$$\frac{dT_2}{dt} = k_4 C_2 q - Le\frac{k^*}{Da}(1-a)(T_2 - T_{a2}) - Le\frac{k^*}{Da}a(T_2 - T_1), \tag{4}$$

$$k_1 = A_1 \exp\left(-\frac{T_{e1}}{T_1}\right), \tag{5}$$

$$k_2 = A_2 \exp\left(-\frac{T_{e2}}{T_1}\right), \tag{6}$$

$$k_3 = A_1 \exp\left(-\frac{T_{e1}}{T_2}\right), \tag{7}$$

$$k_4 = A_2 \exp\left(-\frac{T_{e2}}{T_2}\right), \tag{8}$$

$$k^* = A_1 \exp\left(-\frac{T_{e1}}{T^*}\right), \tag{9}$$

$$Da = \frac{k^*}{hs}, \tag{10}$$

$$Le = \frac{hh}{hs}, \tag{11}$$

Table 1 shows the values used in the dynamics model.

Table 1. The values in the system equations (1) through (9).

A_1	1	T_{a1}, T_{a2}	0.8	T_{01}	1.15	a	0.3, 0.7
A_2	148	C_{a1}, C_{a2}	2.0×10^{-9}	T_{02}	1.14		
Da	1~10	T_{e1}	13	C_{01}	0	q	10^7
Le	0.1~5	T_{e2}	18	C_{02}	0		

3. Result

Figure. 1 is spanned by the *Da* and *Le*. Red represents no oscillation, green represents damping, and blue represents the limit cycle. The left hand of the figure shows the interaction coefficient "*a*" at 0.3, and the other hand shows it at 0.7. The combination of the *Da* and the *Le* indicates whether the oscillation phenomenon occurs or not. When the *Da* is greater than 3 and the *Le* is greater than 0.3, there are regions of oscillation in both cases. Limit cycle oscillations also occur as the *Da* and *Le* increases. In this system, an equilibrium point reaches as increasing the *Le*, and the oscillation phenomenon does not occur. Increasing the *a* expands the oscillation region. An increase in the *a* from 0.3 to 0.7 also leads to an expansion of the limit cycle region.

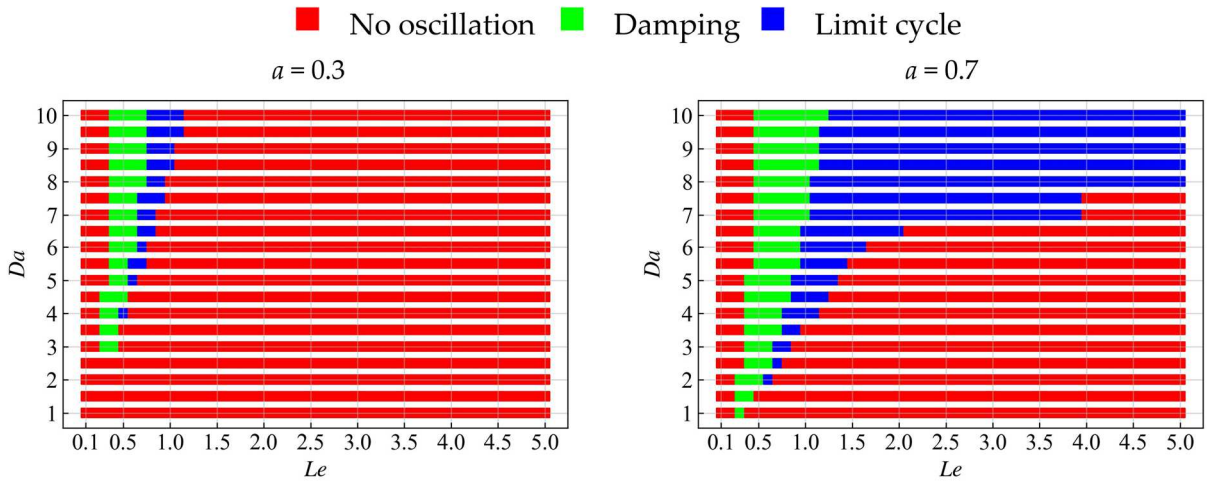

Figure 1. Mapping of the occurrence of oscillation phenomena by dimensionless numbers.

4. Summary

The combination of the Damköhler number *Da* and the Lewis number *Le* determines whether cool flame oscillation phenomena will occur. Considering the diffusion into the other droplet, an interaction coefficient *a* is introduced. When the *a* is 0.3 and 0.7, there is an oscillating region if the *Da* is greater than 3 and the *Le* is greater than 0.3. As the *Le* increases, an equilibrium point is reached, and the oscillation does not occur. Increasing the *a* expands the damping and the limit cycle region.

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