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JAPAN'S RESEARCH ON DROPLET AND DROPLET ARRAY COMBUSTION

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Introduction

In Japan, the ignition and combustion of the droplet and droplet array have been investigated by using microgravity condition. This is the short introduction of those studies; interactive combustion of two droplets (ref. 1), ignition experiment on droplet array (ref. 2), and microexplosion behavior of an emulsified fuel droplet (ref. 3).

Interactive Combustion of Two Droplets

In spray combustion, droplets burn interactively and the combustion mechanism is different from that of the single droplet due to interaction between the droplets. Droplet array combustion has been studied experimentally and theoretically to understand the interaction from a microscopic viewpoint. It is important to use the basic and the simplest configuration, that is two droplets, in order to improve understanding of multiple droplet combustion mechanisms. In the present study, experiments in microgravity have been performed on the burning of two suspended droplets for a wide range of the initial separation distance.

Two droplets (n–heptane) of the equal size were dispensed in air at atmospheric pressure and initially 295±1 K at the same time. Then they were ignited by two hot wires at the same time. Microgravity conditions were attained by dropping the apparatus with a drag shield in the drop tower at University of Tokyo, which provides about 1.4 s microgravity conditions. Experiments in normal gravity were also performed. Two orthogonal views of the combustion process were taken by two CCD cameras. The suspending fiber diameter was 0.125 mm. The initial droplet diameter (d_0) was 0.81±0.03 mm. The droplet was nearly elliptical in shape due to the existence of the fiber inside, and thus, an equivalent spherical droplet diameter was used as the droplet diameter.

The flame shapes are classified roughly into two modes; individual flames surrounding each droplet (Mode 1) and one merged flame surrounding two droplets (Mode 2). The flame

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shapes in microgravity are qualitatively in good agreement with the theoretical predictions by quasi-steady analysis. Within a certain range of the initial separation distance (l/d_0), the transition occurs from Mode 1 to Mode 2 firstly, and then the contrary transition occurs from Mode 2 to Mode 1.

The dependence of the burning lifetime (t_{b0}) on the initial separation distance (l/d_0) is shown in Fig. 1. Here, t_{b0} is the burning lifetime of the droplet with d_0=1 mm, to which all the burning times (t_b) were corrected by assuming t_b is proportional to d_0^2. l and d_0 are the distance between the droplet centers and the initial droplet diameter, respectively. The infinite l/d_0 denotes the single droplet combustion. In normal gravity, t_{b0} has a minimum at a certain l/d_0. As l/d_0 decreases, natural convection around each droplet is enhanced. This increases oxygen supply to the flame. Further decrease in l/d_0 causes oxygen starvation between two flames.

As seen in Fig. 1, t_{b0} in microgravity decreases slightly with decreasing l/d_0 until it reaches the minimum around $l/d_0=10$ and then increases sharply. The prediction by the quasi-steady theory shows that the instantaneous burning rate decreases monotonically with decreasing instantaneous separation distance (l/d) and therefore, t_{b0} increases monotonically with decreasing the initial separation distance (l/d_0). Contrary to the prediction, t_{b0} has a minimum for a certain l/d_0 and is larger than the theoretical value for any l/d_0. The difference between the experimental results and the theoretical prediction is mainly caused by the difference of the droplet heating, which is neglected in the theory.

The rate of the decrease in the squared droplet diameter ($d(t)^2$) is defined as the instantaneous burning rate ($K(t)$). $K(t)$ for different l/d_0 are plotted every 0.05 t/t_b versus instantaneous separation distance ($l/d(t)$) in Fig. 2. According to the quasi-steady theory, $K(t)$ is only a function of $l/d(t)$. Experimental results show that $K(t)$ is a function of $l/d(t)$ and l/d_0. $K(t)$ for different l/d_0 increase and approach an asymptote with increasing $l/d(t)$. The deviation of $K(t)$ from the asymptote is due to the slow evaporation during heating period.

In order to investigate unsteady interaction effects, the instantaneous burning rate of two droplets was compared with that of the single droplet for the same normalized diameter (d/d_0). We introduce an instantaneous burning rate correction parameter ($\in$) which is expressed as,

$$\in(d/d_0) = K(d/d_0)/K_S(d/d_0) - 1.$$

When $\in(d/d_0)$ is positive, $K(d/d_0)$ is larger than $K_S(d/d_0)$ for the same d/d_0. We call this "positive interaction". When $\in(d/d_0)$ is negative, "negative interaction" occurs.

The instantaneous burning rate correction parameters ($\in(d/d_0)$) were derived and are plotted versus $l/d(t)$ every 0.05 $(d/d_0)^2$ in Fig. 3. For $l/d_0>5.4$, the positive interaction occurs in the earlier stage. $\in(d/d_0)$ decreases with increasing $l/d(t)$ (or with time), and then the positive interaction transfers to the negative one. As $l/d(t)$ increases, $\in(d/d_0)$ approaches an asymptote. The existence of this positive interaction causes the minimum in the burning lifetime (t_{b0}) (Fig. 1). For $l/d_0<5.4$, $\in(d/d_0)$ is negative for the entire period of combustion and to be smaller for smaller l/d_0 when $l/d(t)$ is the same. The radiative heat transferred from the other flame promotes droplet heating. On the other hand, the oxygen starvation between the flames suppresses combustion. These effects changes with l/d_0 and $l/d(t)$ (or time).

Ignition Experiment on Droplet Array

Many experimental works have been carried out on ignition of a single droplet in a high temperature ambience. The most interesting phenomena is the effect of initial droplet diameter. Another interesting point is the characteristic ignition time of a droplet consisting of blended liquid fuels with different boiling points. In ignition of an actual spray, however, there should be a strong interaction effect between droplets; experiments on droplet arrays are thus warranted to determine the fundamental aspects of spray ignition. In the present work, ignition times of droplet arrays which were quickly immersed in an electric furnace were measured by changing the diameter of the droplets and the interval between droplets.

The experimental capsule is dropped about 6 m and the test duration is about 1.1 s. The cylindrical electric furnace in the capsule with an inner diameter of 88 mm and a length of 150 mm is heated in advance. When the capsule begins to drop, the furnace is pulled by the two springs, so that the droplet array is quickly immersed in the furnace from a thin window at the bottom of the furnace. The droplet array is heated by radiation from the furnace wall and heat conduction through hot air. Ignition time is defined as the period from the entry of the droplet array into the furnace until light emission caused by ignition. In order to obtain droplets with the same diameter, an array of droplets made of porous ceramics and soaked with liquid fuel was employed. Both ends of the array of five droplets arranged horizontally were soaked with water instead of liquid fuel, because droplets there are known ton ignite faster than the other three intervening droplets. As liquid fuels, n–heptane (boiling point: 371.6K) and n–hexadecane (560.0K) were mainly used.

Hexadecane has a relatively high boiling point and therefore the greatest part of ignition time is required to rise droplet temperature. If ignition time is affected mostly by heat conduction, a rough similarity should be easily available. Figure 4 is the plot of the nondimensional ignition time normalized by ignition time of a single droplet (t_{single}) versus the nondimensional span, which is the distance between droplets (S), normalized by the droplet diameter (d_0). It is shown that all data are combined into one curve. It was also found that there exits no difference in the results under normal gravity and microgravity conditions. For a heptane droplet array, ignition time obtained shows a relatively complicated change as shown in Fig. 5. The ignition time in microgravity were about 30% shorter than those in normal gravity, because vaporized fuel gas descends and is cooled by silica fibers below droplets in normal gravity.

Microexplosion behavior of an emulsified fuel droplet under microgravity

The combustion of emulsified fuel involves vaporization of water within the combustion fields. There is the frequent occurrence of explosive vaporization of water in emulsified fuel by means of supper heating above its boiling points by convective and radiative heat supply from surrounding combustion gases and flame. The explosive vaporization causes the secondary atomization which improves the mixing of fuel and air. Three process are included in the secondary atomization which are called as 'disruption', 'puffing' and microexplosion'.

It has been recognized that the formation and growth of the vapor bubble in the emulsion plays an important role in the microexplosion behavior. Especially, the bubble nucleation is one of key factors which has a dominant effect on the occurrence of microexplosion.
The objectives of the present study is to obtain the statistical information about the onset of microexplosion for a burning emulsion droplet. We consider that the information of this type is essential to an understanding of the mechanism of microexplosion. The falling assembly was made of steel frames and contained a combustion chamber and a 8 mm videocamera. An emulsion droplet was suspended at the tip of a quarts fiber of 0.25 mm diameter. An electrically heated wire was passed just below the droplet for ignition. The behavior of burning droplet was observed and recorded by using the 8 mm videocamera. The droplet temperature was measured by using the Pt–PtPh(13%) thermocouple of 0.05 mm in diameter.The fuel employed in the experiment was n–dodecane (boiling point; 489.5 K). The surfactant as emulsifier was polyoxyethylene nonylphenyle ether. The emulsion of oil–in–water type (O/W) composed of 79% (in volume) fuel and 20% (in volume) water was prepared with 1% surfactant. From the microphotographs of the emulsion, the microdroplets of fuel were surrounded by the water thin film of the thickness of less than 5 μm. The size of the largest microdroplet is about 15 μm. The emulsion was degassed keeping it at about 5 KPa for two hours.

Figure 6 shows the Weibull plots of distribution function of the waiting time t_{wi} which is defined as the period of time between the instant of microexplosion and the time of the first microexplosion. The distribution is approximately plotted on the two straight line. This indicates the waiting time is correlated with the Weibull distribution expressed as the next equation.

$$f(t) = \frac{m}{\alpha}\left(\frac{t}{\alpha}\right)^{m-1}\exp\left[-\left(\frac{t}{\alpha}\right)^{m}\right]$$

where t is the time, m is the shape parameter and α is the scale parameter. For the microgravity, the shape parameter is about 2 in the early stage of the waiting time ($t_{wi} \leq 0.43$), and it is unity in the long waiting time region ($t_{wi} \geq 0.43$). Thus, the onset of microexplosion is classified to the wear failure type in the early stage, and it is classified to the chance failure type in the last stage of the burning.

References

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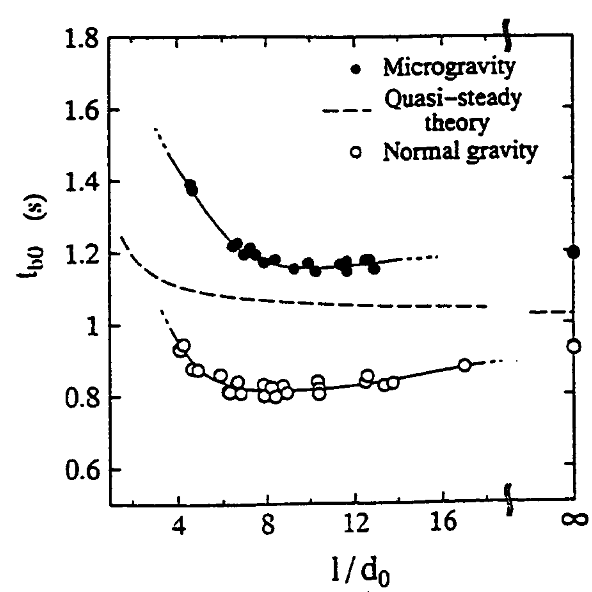

Figure 1. Dependence of the burning lifetime (t_{b0}) on the initial separation distance (l/d_0).

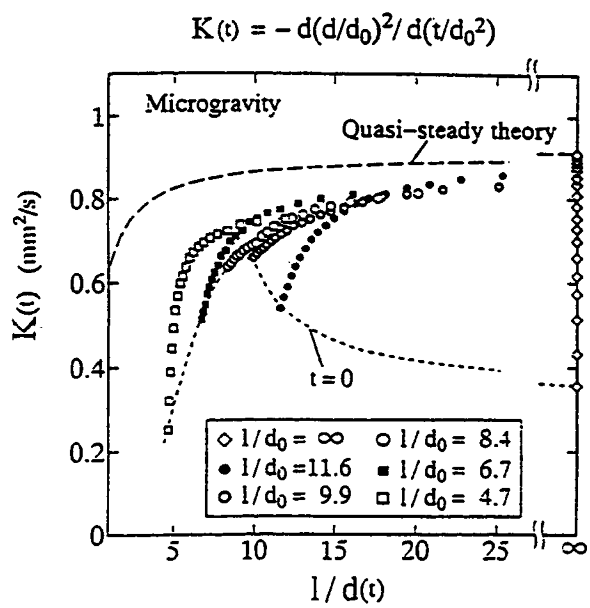

Figure 2. Dependence of the instantaneous burning rate (K(t)) in microgravity on the instantaneous separation distance (l/d(t)) for different initial separation distance (l/d_0).

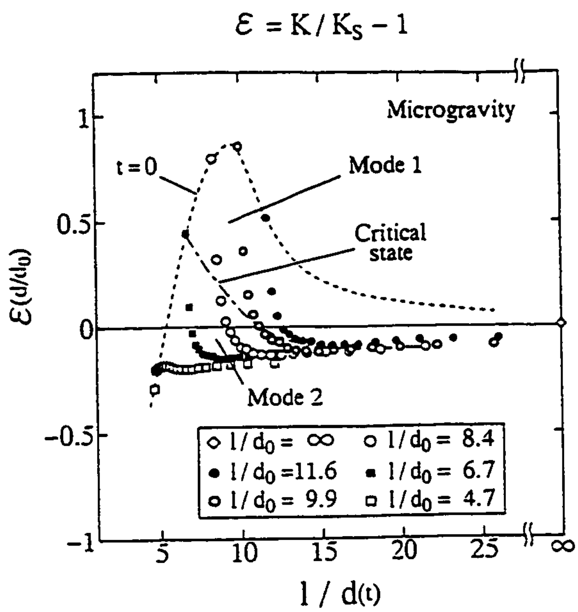

Figure 3. Dependence of the instantaneous burning rate correction parameter ($\in(d/d_0)$) on the instantaneous separation distance ($l/d(t)$) for different initial separation distance (l/d_0).

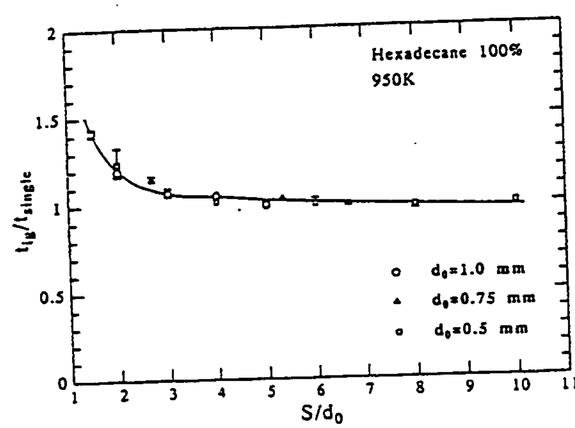

Figure 4. Nondimensionalized plot of ignition time in normal gravity.

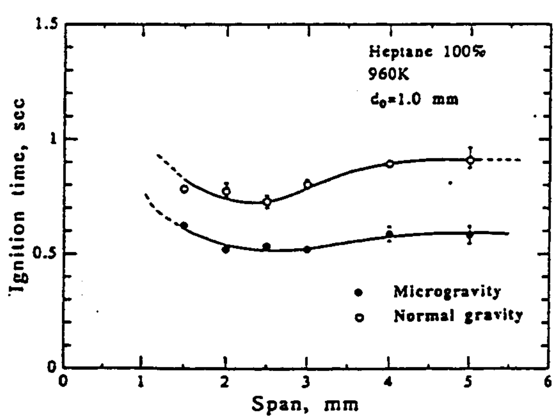

Figure 5. Comparison of ignition time in normal gravity and microgravity.

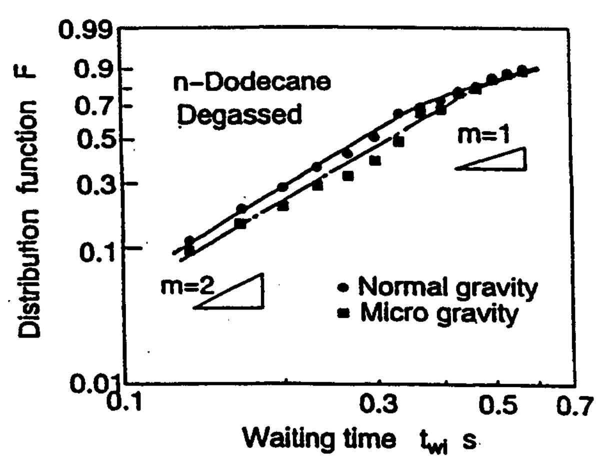

Figure 6. Weibull plots of distribution function of waiting time.