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Microgravity Observation on Combustion Behavior of Solid Waste Fuels in High Temperature and Low Oxygen Atmosphere

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From the viewpoint of effective use in the incinerators of solid waste fuels produced from town and industrial fields, it is considered important to examine the combustion behavior of solid waste fuels in high temperature and low oxygen atmosphere.

Experiments have been performed to throw light on some basic features of solid waste fuels in an atmosphere of high temperature and low oxygen concentration under microgravity. The microgravity condition makes it possible to examine these properties of combustion phenomena by realizing spherical symmetry and distinguishing radiation dominated processes from convection dominated ones.

From these experiments the authors have elucidated the fundamental combustion characteristics of solid waste fuels such as ignition delay, flame development, mass burning rate and the influence of oxygen concentration on their combustion behavior. Especially, it is found that, there are three categories for the combustion of solid waste fuels at high temperature atmosphere, that is, gas phase ignition, luminous flame and smoldering. The volatile compositions produced from the surface in the form of small fuel particles appear to play a very important role in the flame development.

Key Words: Micrograsvity, Combustion, Solid waste fuels, Smoldering

1. INTRODUCTION

In recent years the energy and environmental concerns have prompted studies on efficiency and mechanism of combustion of solid waste fuel produced from domestic and industrial wastes. The design and modeling efforts in this area of combustion are hampered by the lack of accurate experimental data. While fairly detailed experimental studies under normal-gravity condition can provide useful data for designers of combustion devices, at a more fundamental level dealing with the mechanism underlying the phenomena of combustion of solid waste fuel, accurate data that can be generated under microgravity conditions are thought to be very valuable. In this direction, the present study encompasses experimental investigation of solid waste combustion under both microgravity and normal gravity in high temperature and low oxygen concentration environment.

The food and kitchen waste of Nishiki-Koi (Japanese color carp) is used in the present study as representating solid waste fuel because its chemical composition is very similar to that of solid waste fuels produced from town and industrial fields. These are characterized by substantial contents of water and ash intimately bonded with the combustible compounds.

Study of combustion of solid waste fuels under normal gravity may not call for any unusual design of experimental set-up. However, when it comes to microgravity study, with which the authors are associated[1,2], it calls for some innovative arrangements especially when very high ambient temperature and low oxygen concentration environment has to be imposed. The intrinsically low burn rate and the necessity of high ambient temperature imply a strong role for buoyancy under normal gravity which would limit the information that can be obtained on fundamental aspects.

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2. EXPERIMENTAL APPARATUS

Figure 1 shows the schematic of drop-test set up employed for the study. It is 800×300×800 mm in size and weighs is about 100 kg. It contains the cylindrical closed bomb equipped with an electric furnace, a 8-mm video camera, an air cylinder, a temperature control equipment of electric furnace, a relay device and a back-light system. Further details of electric furnace are shown in Fig.2. It is rectangular shape of dimensions 110 × 110 mm and length 150 mm. Also shown in Fig.2, is the temperature profile inside the furnace indicating nearly uniform temperature around the axis and minor deviations near top and bottom surfaces.

As mentioned earlier, the solid waste fuel whose composition is shown in Fig.3 is made up of food and kitchen-waste of an industry. It may be observed that both the chemical composition and elemental composition are very much similar to those produced from town and industrial wastes. The outcome of this study may therefore be considered as a good representative of the waste-fuels whose utilization is of great concern at present.

The experiments have been conducted in high temperature environment of 550 ℃ to 1100℃ and an ambient oxygen concentration ranging from 21 % to 7 % by volume. Solid fuel in the form of 3 mm diameter sphere supported by a silica filament of 0.2 mm diameter is moved to the center of the electric furnace with the aid of pneumatic actuator. The subsequent processes of ignition, combustion and smoldering are recorded with the video camera.

Both normal gravity and microgravity environment are made use of for the study. The microgravity environment of 10 seconds is realized in free fall facility of 490 m drop shaft in JAMIC located in Kamisunagawa, Hokkaido, Japan[3]. As will be seen in the following sections, the microgravity experiments reveal several elemental processes underlying the global combustion behavior of solid fuels which are obscured under normal gravity.

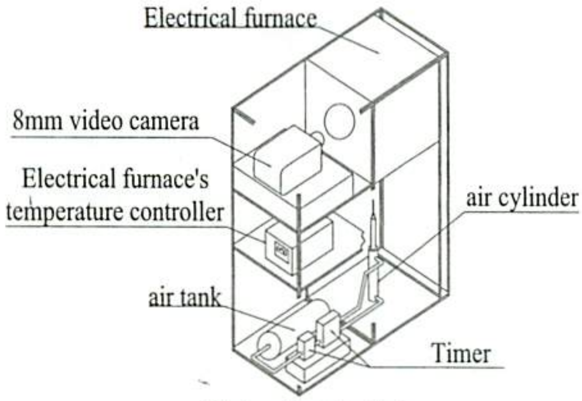


Fig.1 Test Facilities

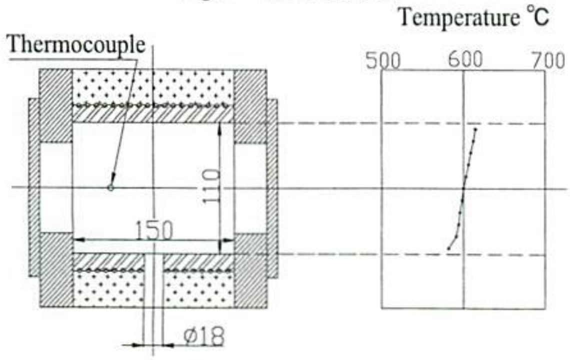


Fig.2 Electric Furnace

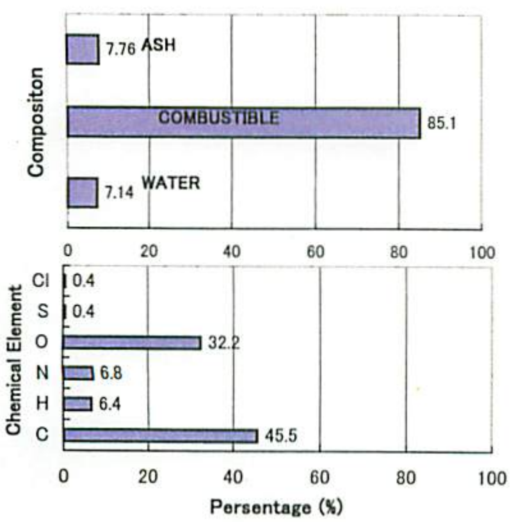


Fig.3 Composition of solid waste fuels

3. EXPERIMETAL RESULTS

General Observation on Combustion Behavior of Solid Waste Fuels under Microgravity

The sequences of processes that proceed following the introduction of fuel particle into the furnace are (i) gradual heating of the particle leading to ignition, (ii) combustion with a luminous envelop flame and (iii) smoldering. In the first phase, partially evaporated water and volatile contents tend to escape from the particle eventually leading to build-up an ignitable mixture at the surface. This phase is used to identify ignition delay times which can be used to estimate an overall activation energy as will be discussed later.

Figure 4 shows direct photographs of the combustion phase of a 3 mm solid waste fuel particle in a sequence of 1.0 second interval at two different furnace temperature of 750 ℃ and 1050℃ under microgravity. The ambient oxygen concentration is 21% for both the cases. The effect of oxygen concentration itself is demonstrated by the two other sequences in Fig.5 corresponding to lower oxygen concentration of 15 % and 7%.

The resemblance of the picture to those on combustion of multicomponent fuels is evident. It is seen that the volatile compositions generated by thermal decomposition of solid waste in high temperature environment produce a spherically symmetric diffusion flame[4]. An important observation from Figs.4 and 5 is that during the flame phase, there are a lot of tiny fuel particles emitted from the surface. This may be due to superheating of air in the pores and the water contained initially in the solid waste fuel as well as the localized ejection of volatile components. However, at 7% oxygen concentration, these particles do not appear inside the flame zone and the flame extinction occurs gradually. By comparing Figs.4 and 5 one can also notice the increase in luminous flame diameter as the oxygen percentage is reduced.

Figure 6 shows a similar sequence of photographs taken under normal gravity. The example refers to a 3 mm particles burning under ambient conditions of 750℃ temperature and 21% oxygen concentration and hence can be directly compared with its counterpart in Fig. 4 under microgravity. In addition to loss of symmetry under buoyancy effect, the flame luminosity is more intense. This obscures the presence of microparticles coming out of the surface which one would expected as the physical processes inside a 3 mm particle leading to such ejection are unlikely to be affected by gravity.

Ignition Delay

Figure 7 is a plot of mean ignition delay of 3mm solid waste fuels against ambient temperature under normal and microgravity conditions. Monotonic decrease of ignition delay with temperature holds good in both cases and the absolute values of ignition delay at any temperature also differ little from each other. This indicates that the radiant heat transfer from the hot environment to the fuel sphere is the dominant factor rather than convective heat transfer. It is also indicative of the fact that the gaseous mass emanating from the fuel sphere during the ignition phase either under spherical symmetric manner or otherwise does not seriously alter the ignition delay, especially when the ambient temperature is high.

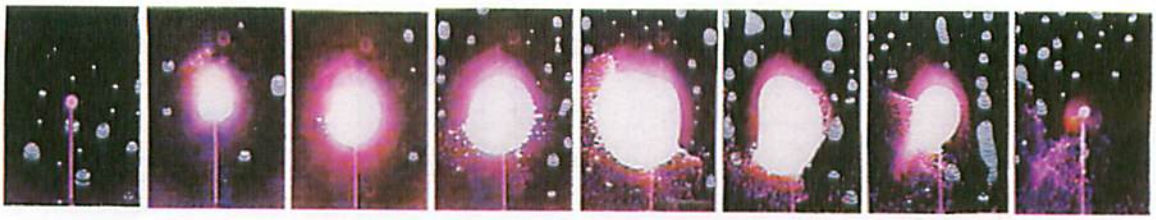
Figure 8 shows Arrhenius plot of ignition delay to obtain the overall activation energy of the solid waste fuels[5,6]. The values of overall activation energy given by the slope of the line is about 50 KJ/mole and it is of the same order as that of polymers such as polypropylene[6].

The variation of ignition delay of the solid waste fuel with oxygen concentration at 750℃ of ambient temperature under microgravity conditions is shown in Fig.9. It may be observed that the ignition delay is nearly constant over a range of 21% to 10% oxygen concentration and below 10% concentration it increases to some extent. Ambient temperature seems to be the factor dictating the ignition delay and oxygen concentration plays a relatively weaker role in the range of the present experimental study.

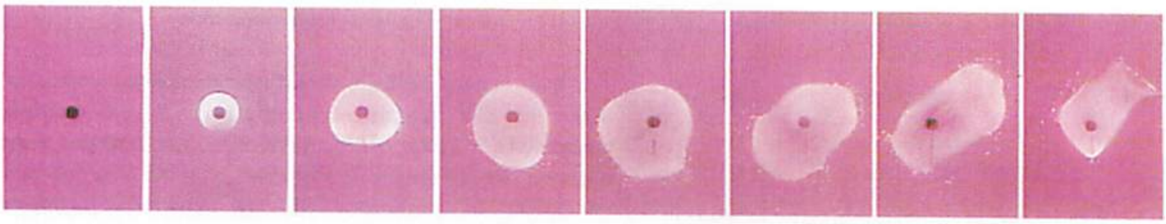
Total Burning Time

In the facility of JAMIC where only 10 seconds of microgravity can be realized, one could not study the entire burning of the fuel particle. However, under normal gravity this restriction is not present and the third phase of smoldering could also be followed. In Fig.10, the total burning time of 3 mm particle of solid waste fuel is plotted against ambient temperature. The total burning time here includes all the three phases of ignition, flaming and smoldering each of which is identified in the figure. It is seen that the duration of combustion with luminous flame is nearly same at all ambient temperature except 550℃, though the total burning time decreases with increasing ambient temperature. At 550℃, the duration of luminous flame is less than half of that at 750℃. This shows that at low ambient temperature which are associated with long ignition delays, much of combustible volatiles escape before a flame is established.

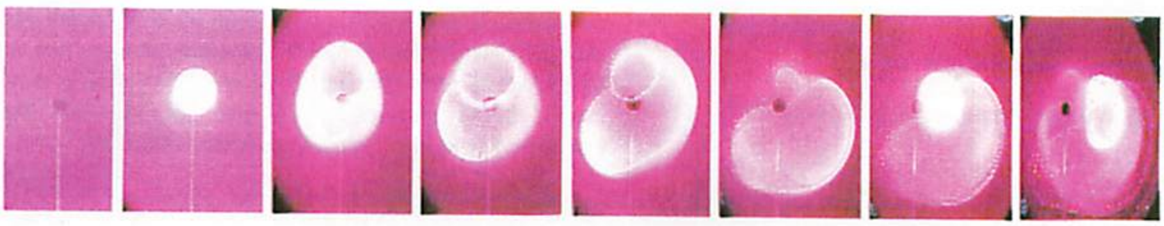
time ⟶ (frame interval:1.0second)



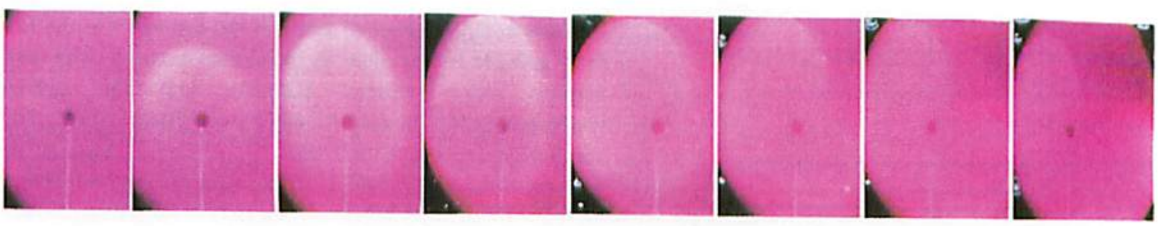
(a) Ambient temperature: 750℃, Sphere diameter: 3 mm, Oxygen concentration: 21% (volume)



(b) Ambient temperature: 1050℃, Sphere diameter: 3mm, Oxygen concentration: 21%(volume)
Fig.4 Direct photographs on combustion behavior of solid waste fuels under microgravity



(a) Ambient temperature: 750℃, Sphere diameter: 3mm, Oxygen concentration: 15%(volume)



(b) Ambient temperature: 750℃, Sphere diameter: 3mm, Oxygen concentration: 7%(volume)
Fig.5 Direct photographs on combustion behavior of solid waste fuels under microgravity

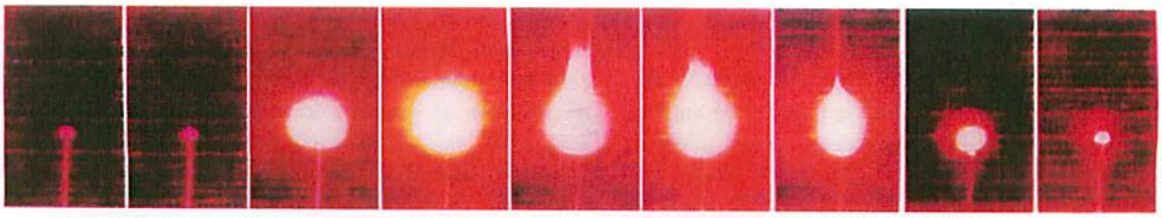


Fig.6 Direct photographs on combustion behavior of solid waste fuels under normal gravity (Ambient temperature: 750℃, Oxygen concentration :21%(volume), Sphere diameter: 3mm)

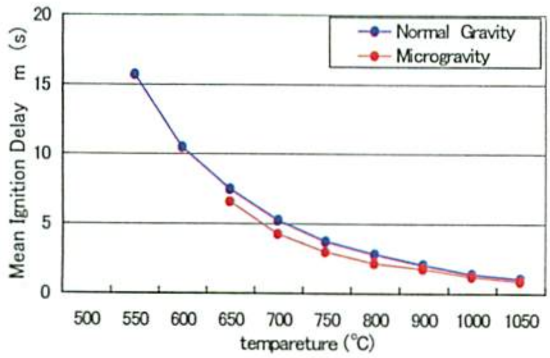


Fig.7 Mean ignition delay

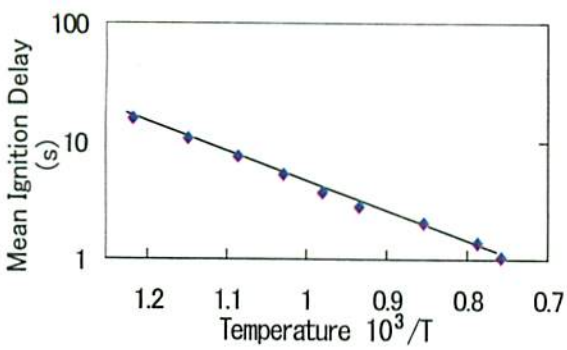


Fig.8 Arrhenius plots of ignition delay

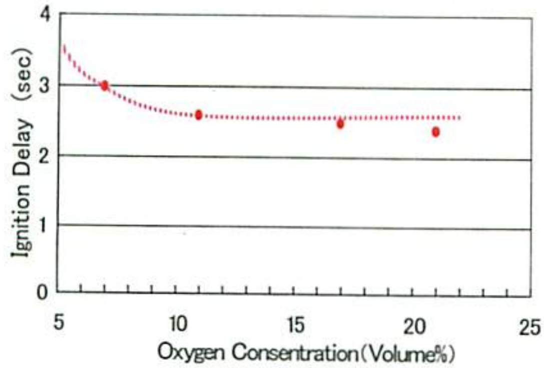


Fig.9 Influence of oxygen concentration on ignition delay

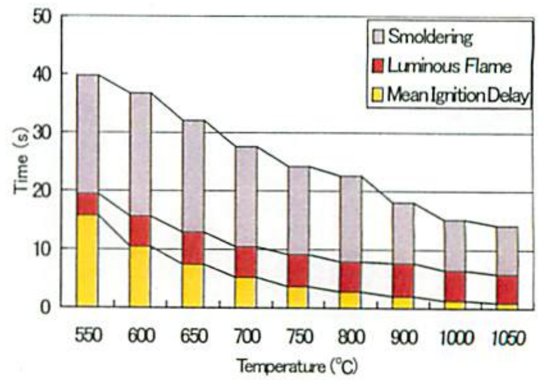


Fig.10 Total burning time

It is indeed difficult to achieve complete combustion even at 21% oxygen concentration, if the ambient temperature is below 550℃. Very often, the luminous flame regime is totally absent at these low temperatures and only smoldering is observed. On the contrary, complete combustion is always achieved above 600℃and 21% oxygen concentration.

The constancy of flaming duration over a wide range of ambient temperature indicates that (i) once the flame is established, it is the heat transfer form the flame rather than the surroundings that dictate the pyrolysis of waste fuel and (ii) the volatile fuel content of the waste fuel particle is not much altered during low ignition periods (<5 sec) corresponding to high temperature ranges(>600℃).

Mass Burning Rate

In Fig. 11 is shown the mass burning rate which is defined as Δ m/t, where Δ m is the difference of mass between initial solid waste fuel and the ash and t is the time from ignition to the end of smoldering process. The mass burning rate increases gradually with the ambient temperature. For instance between 600℃and 1050℃, the burning rate rises from 0.5 mg/s to 1.0 mg/s. However, the mass burning rate at 550℃ is not much smaller than that at 600 ℃ because the time 't' excludes the long ignition delays at such low temperatures during which substantial mass is also lost without contributing to combustion process.

From the results presented above, namely the constancy of flaming period and increasing mass burning rate in the high temperature region, it is clear that the terminal phase of smoldering is governed by the ambient temperature (also seen on Fig.10) as can be expected intuitively.

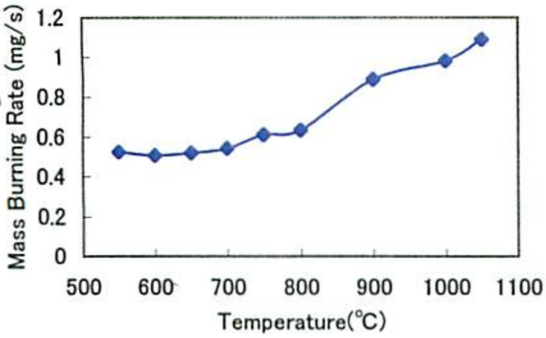


Fig.11 Mass burning rate

4. CONCLUSIONS

The main conclusions from the experimental study of combustion of waste fuels in high temperature and low oxygen environment are as follows:

1) Solid waste fuel under these conditions experiences three phases: ignition, luminous flame and smoldering.
2) The ignition at high temperature environment is accompanied by intense luminous flame.
3) The ambient temperature has to be fairly high (>600℃) to achieve complete combustion.
4) In the cases where complete combustion occurs, many smaller fuel particles are emitted by the solid waste fuel and these may have a role in flame development and stabilization.
5) The value of overall activation energy of the reaction of solid waste fuels with air seems to be around 50 KJ/mole.

REFERENCES

1. Okajima S., Iimuma K. and Kumagai S., Twentieth Symposium (International) on Combustion, The Combustion Institute, pp. 1951-1956 (1984)
2. Okajima S., J.Jpn. Microgravity Appl.Vol.15, pp.254-259(1999)
3. Okajima S., and Kawakami T. and Sakuraya T., Space Forum, Vol. 6, pp. 355-365(2000)
4. Kato J. and Okajima S., Proceedings of The Third Asia-Pacific Conference on Combustion, pp. 347-350(2001)
5. Murty Kanury, A: Introduction to Combustion Phenomena, Grdon & Breach Science Publication, 1975
6. Okajima S., Bulletin of Facility of Engineering, Hosei University, Vol. 17, pp.87-95(1981)