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Combustion Characteristics of Solid Waste Fuels Burning in High Temperature and Low Oxygen Atmosphere

Akiko OKAJIMA*, Yasuhiro TAKAYAMA*, Masashi WATANABE *and Satoshi OKAJIMA**

Experiments have been performed to elucidate the combustion stability and flame development of waste fuel combustion in high temperature and low oxygen concentration under both conditions of normal and microgravity. In order to extract the fundamental characteristics of solid-waste fuels which are often obscured by buoyancy forces, microgravity atmosphere is employed. The range of ambient temperature and oxygen concentration in the electric furnace are 350℃ to 1100℃ and 3% to 21% by volume, respectively.

The stable and unstable combustion region on burning process of solid waste fuels can be deduced from the variation of flaming duration and surface combustion period with ambient temperature at a given oxygen concentration. These regions of stable and unstable combustion may be mapped as an inverse relationship between ambient temperature and oxygen concentration.

Key Words: Solid Waste Fuel, Combustion Stability, High Temperature, Microgravity

1. Introduction

From the viewpoint of environmental problem caused by solid waste fuels produced by domestic and industrial sector, it is important to develop techniques to use them as a source of energy. In practical, this stable combustion of solid waste fuel in incinerators requires very high temperature environment, which is usually achieved by recirculation of combustion products. But the precise temperature conditions and more importantly, the basic combustion characteristics remain somewhat uncertain.

Solid waste fuels are necessarily multicomponent system and therefore one can anticipate unusual features such as cracking, microexplosion, and evolution of vapor pockets and so on. However, all such features get submerged in the buoyancy driven field when it comes to experimental observability. Complete understanding and theoretical modeling of such combustion process would nevertheless require knowledge of these subtle details. The present experiment have therefore been carried out both in normal and microgravity conditions to unravel these features as well as the gross characteristics such as ignition delay, combustion stability and flame development. Critical control parameters are temperature and oxygen concentration in the environment for a given type of solid waste fuel. Both from the point of view of experimental and analytical case and the available past experience, spherical geometries chosen for the present study whence the diameter of the particle becomes another important variable especially since the whole process is inevitably unsteady.

In this study, experimental apparatus and procedure are mostly the same as our previous study.[1] The range of ambient temperature and oxygen concentration in the electric furnace are 350℃ to 1100℃ and 3% to 21% by volume, respectively. The food of Nishiki-Koi(Japanese color carp) is used as representating solid waste fuels because its physical and chemical properties are very similar to those of solid waste fuels. The size of fuel sphere investigated is 3 mm to 5 mm in diameter and, ignition and combustion behavior of solid waste fuels are observed by taking the direct photographs with 8 mm-video camera.

The microgravity duration in the study is about 10 seconds and gravity level inside the drop capsule is 10^{-5} g which is realized in 490 m drop shaft located in Kamisunagawa, Hokkaido, Japan (Japan microgravity center, JAMIC).[2]

* Mechanical Engineering, Graduate school of Engineering
**Department of Mechanical Engineering, Faculty of Engineering

2. Combustion Behavior of Solid Waste Fuels

2.1 Combustion Event

Figure 1 (a, b) shows the direct photographs on combustion behavior of solid waste fuels under both conditions of micro- and normal gravity at 750℃ of ambient temperature T_0 and 15% of oxygen concentration c. After introducing the solid waste fuel supported by fine quartz fiber into the electric furnace, ignition occurs after a time delay and brightness on the surface of solid waste fuels. The combustion process of solid waste fuels can thus be divided into three sequential periods, that is, ignition, luminous diffusion flame and surface combustion (Fig.2) . In addition to the near-spherical nature of the flame structure at microgravity in relation to the elongated flame under normal gravity (Fig.1), one can observe blobs of luminous zone of microgravity flame. They appear to contribute to the flame development and stabilization around the solid waste fuel, though the flame shape is markedly disturbed from a perfect sphere by these particles.[3,4,5]

Figure 3 shows the direct photographs on the behavior of surface combustion at 500℃ of ambient temperature and 15 % of oxygen concentration under normal gravity. During the surface combustion there is very strong luminosity on the surface of solid waste fuels.

2.2 Combustion Characteristics

Ignition Delay

For the ignition delay, an important result on combustion of solid waste fuels has been obtained from our previous study,[1] where an empirical equation for ignition delay τ with ambient temperature T has been derived as $\tau \sim T^{-4}$ (Fig.4). This indicates that the ignition delay mostly depends on the radiant heat transfer from the hot environment to the fuel sphere. In Fig.5 is shown the ratio of ignition delays versus ambient temperature at 3 mm in fuel diameter $\mathbf{D_0}$ obtained under both conditions of normal(1g) and microgravity(μ g). From this figure it is recognized that there is not much difference between ignition delays obtained under normal and microgravity. This once again confirm that the radiant heat transfer is the dominant process in causing ignition and that the natural convection present under normal gravity plays a very insignificant role.

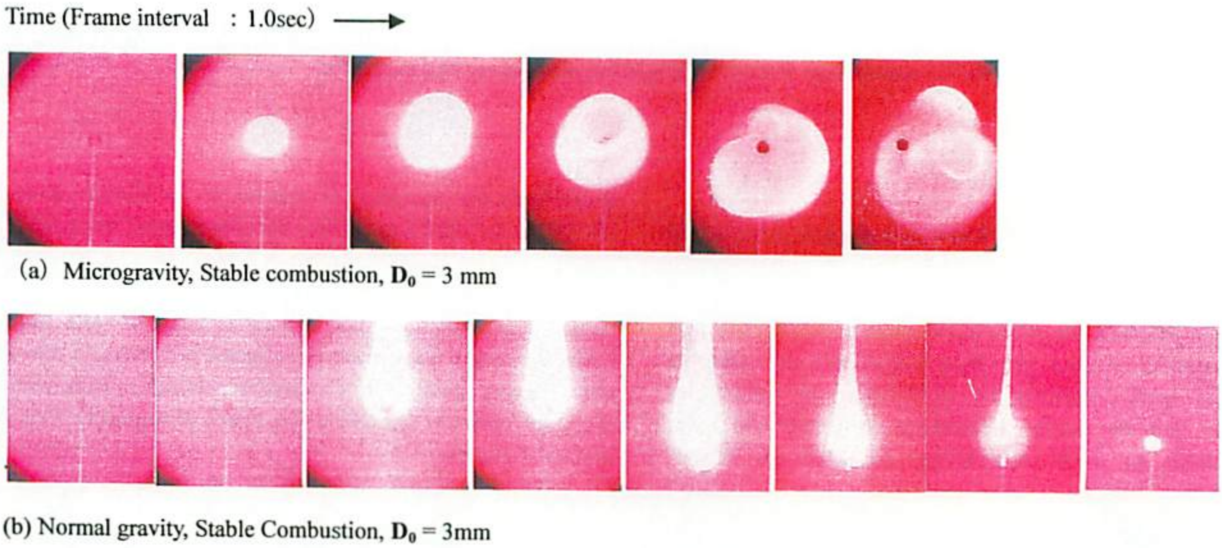

Fig.1 Direct photographs of combustion behavior of solid waste fuels at 750 ℃ of ambient temperature and 15% of oxygen concentration by volume.

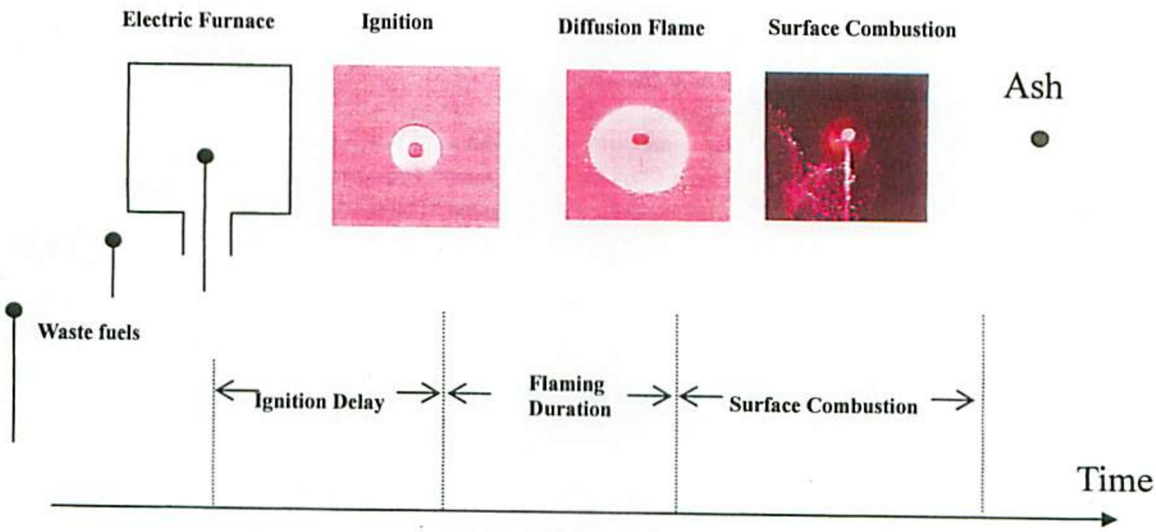

Fig.2 Combustion phases

Time → (Frame interval: 5 seconds)

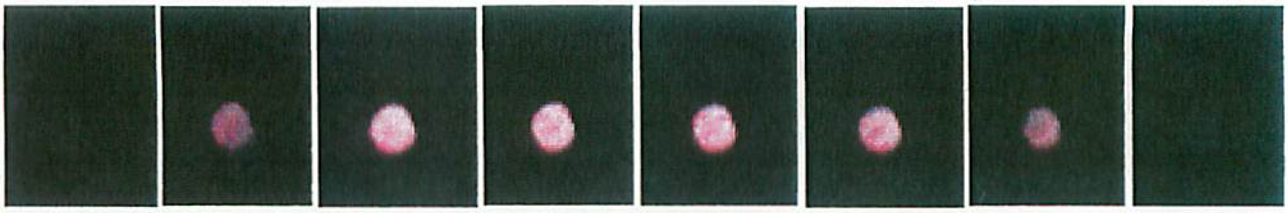

Fig. 3 Direct photographs on behavior of surface combustion at 500℃ of ambient temperature and 15% of oxygen concentration by volume under normal gravit

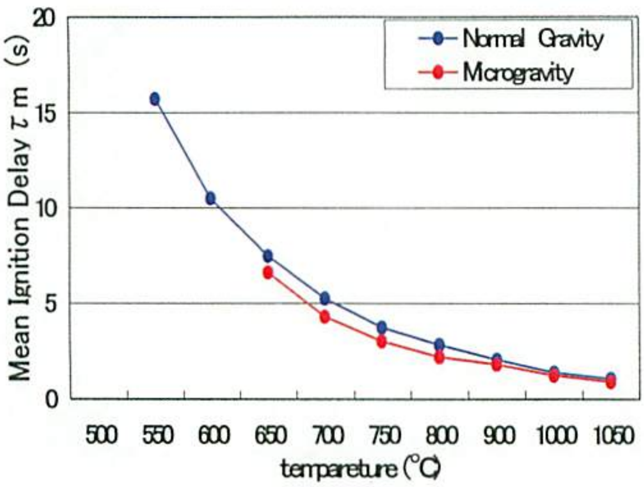

Fig. 4 Ignition delay

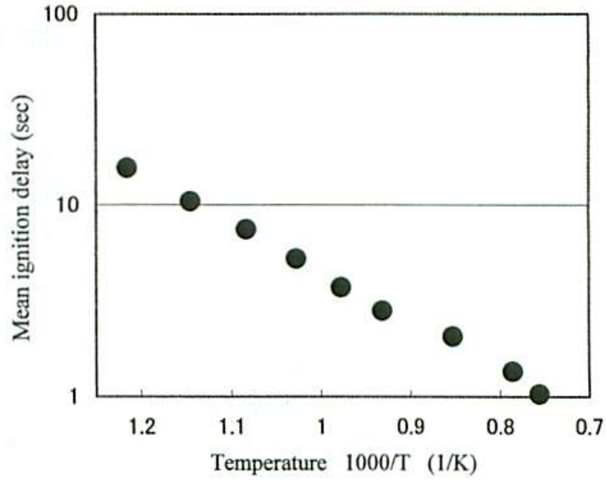

Fig.6 Arrhenius plot of ignition delay

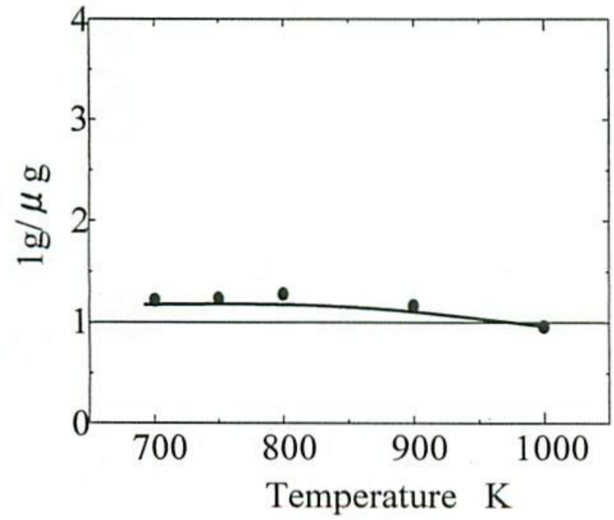

Fig.5 Ratio of ignition delays

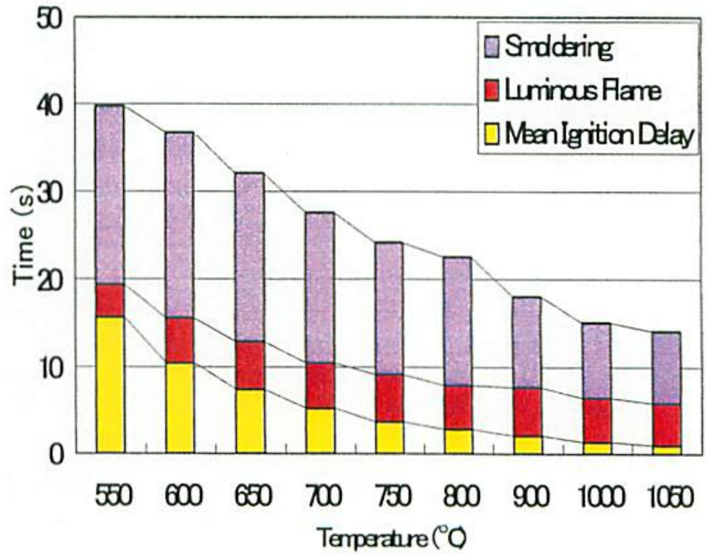

Fig.7 Total burning time

Figure 6 shows the Arrhenius plot of ignition delay to evaluate the overall activation energy of the solid waste fuels. The value of overall activation energy obtained from the inclination of line is approximately 50 kJ/mol and it is the same order to that of polymer such as polypropylene.[6] This fact indicates that the heating period of solid waste fuel is very significant factor to determine the combustion behavior.

Flaming Duration and Surface Combustion

Figure 7 shows the total burning time of 3 mm in fuel sphere against ambient temperature at 21 % of oxygen concentration by volume. The total burning time here includes all the three combustion phases of ignition delay, flaming duration and surface combustion period. Figure 8 shows the variation of flaming duration versus ambient temperature at 3 mm to 5 mm sphere at 21% of oxygen concentration by volume obtained under normal gravity. Here where the flaming duration is defined as the time interval in which the luminous flame is continuously maintained. From this figure it is seen that, above 600℃ of ambient temperature the flaming duration gradually decreases with increasing ambient temperature for any size of sphere diameter. Below 550℃ of ambient temperature it decreases steeply with increasing ambient temperature. This fact probably denotes that, above 600℃ of ambient temperature the increment of ambient temperature may be lead to increase the chemical reaction in the flame zone so that the flaming duration decreases. On the contrary below 550℃ of ambient temperature the ignition delay is relatively longer so that much of combustible volatiles would have escaped before a flame is established.

Figure 9 shows the variation of surface combustion period versus ambient temperature at the same condition of Fig.8. The surface combustion period linearly decreases with increasing ambient temperature for any diameter of solid waste fuel and its reduction rate becomes larger as the sphere diameter increases.

Mass Burning Rate

Figure 10 shows the mass burning rate Δm/Δt versus ambient temperature for 3 mm to 5 mm in sphere diameter of solid waste fuels and Fig.11 shows a replot of the mass burning rate with initial diameter of fuel sphere ranging from 500 ℃ to 1100℃. These results are obtained under normal gravity at 21% of oxygen concentration by volume. In the mass burning rate, m is between the initial mass and mass after surface combustion and time Δt includes flaming duration and surface combustion period. As may be expected, the mass burning rate increases with increasing ambient temperature and the rate appears to vary linealy with the sphere diameter of solid waste fuels. The values of mass burning rate at 600℃and 800℃of ambient temperature and at 5 mm of fuel sphere are approximately 0.8 mg/s and 1.0 mg/s, respectively.

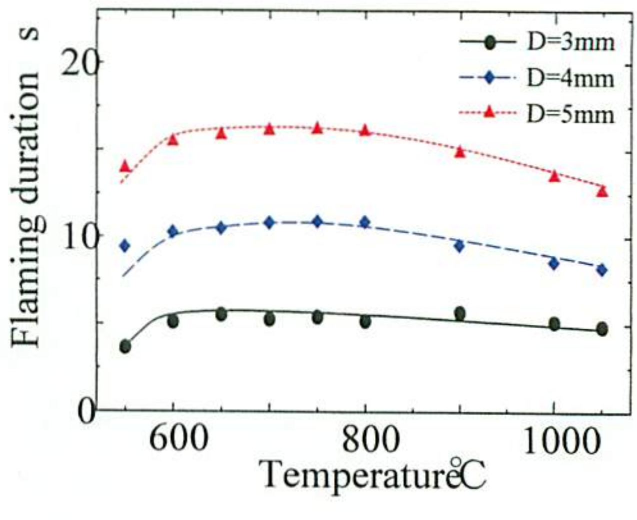

Fig.8 Flaming duration

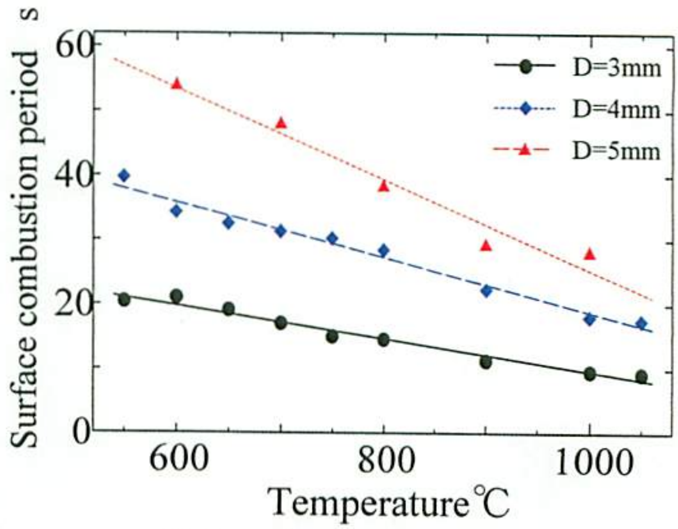

Fig.9 Surface combustion period

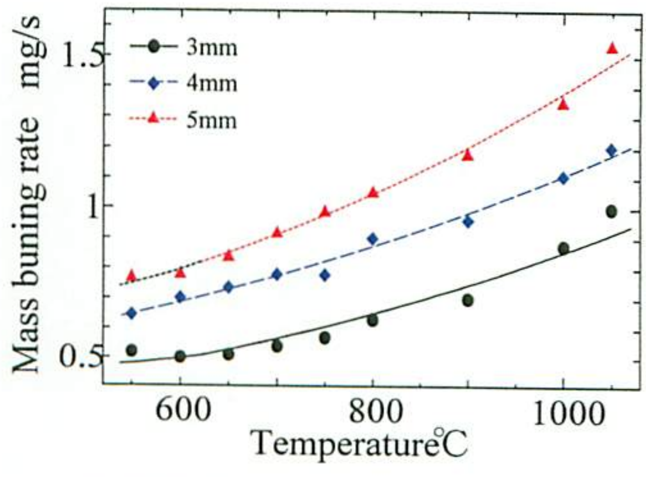

Fig.10 Mass burning rate with ambient temperature

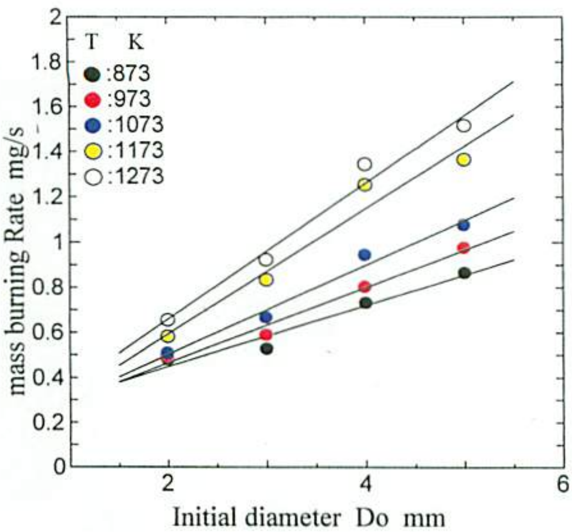

Fig.11 Mass burning rate with initial diameter

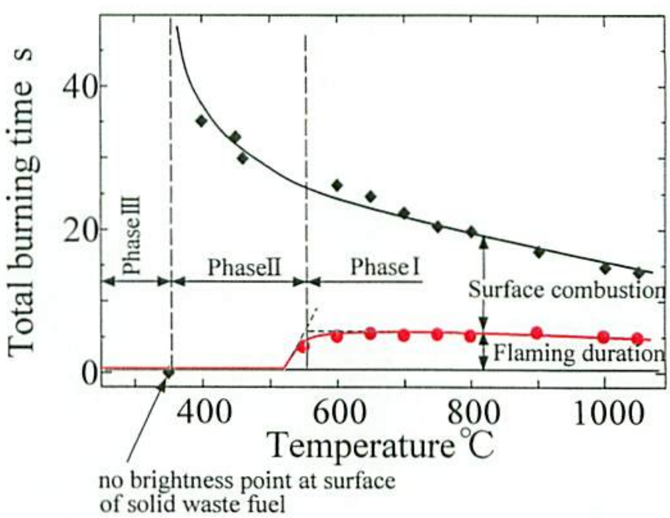

Fig.12 Determination of combustion phase

2.3 Combustion Stability

Figure 12 shows the variation of flaming duration and surface combustion period versus ambient temperature for 3 mm sphere at 21% in oxygen concentration by volume. From this figure we can infer that there are three distinct temperature regimes in burning process of solid waste fuels. First phase (Phase I) perfectly includes all the three processes of ignition, luminous flame and surface combustion. Second phase (Phase II) is mostly occupied by surface combustion, though there are some cases of very short flaming duration shown in Fig.12 and third phase (Phase III) is non-combustion process, that is, combustion does not occur at any ambient temperature of less than approximately 370℃ and at any oxygen concentration employed in the study. So, these combustion phases (I, II, III) correspond to regions of stable and unstable combustion and non-combustion, respectively.

In Fig.13 is shown the outline of three combustion phases in relation to ambient temperature and oxygen concentration obtained under normal gravity. From this figure it is observed that the combustion behavior of solid waste fuels strongly depends on ambient temperature and also depends on oxygen concentration, and the phase boundary demarking (phase I, II and III) shows an inverse relationship between ambient temperature and oxygen concentration.

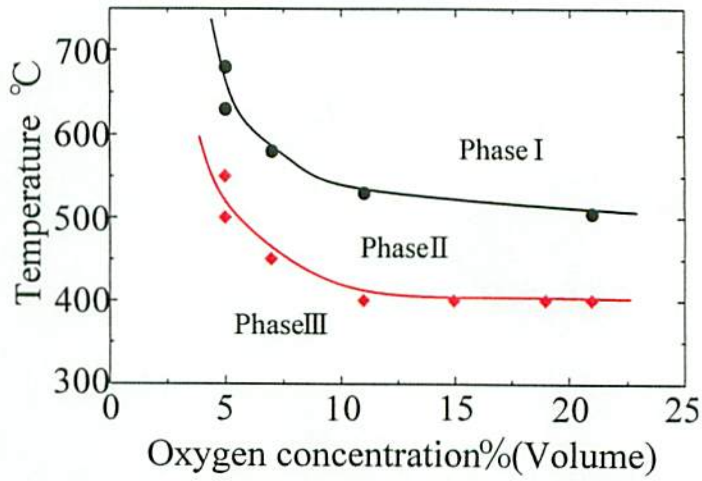

Fig.13 Combustion stability

2.4 Combustion Model

Figures 14 and 15 show schematic combustion models of the solid waste fuels burning in quiescent air. The flame is the reaction zone into which oxygen from the ambience and fuel vapor from the parent sphere of solid waste fuel diffuse as shown in Fig.14. But occasionally, the tiny satellite particles emerge from the parent sphere and move towards the flame, at the same time evaporating/pyrolysing enroute. This excess fuel vapor supply contributes to the development of small blobs of flame (as were seen in Figure 1) superposed on the main flame and tends to support the main flame even when the vaporization from the parent sphere becomes weak. This also alters the fuel vapor profile albeit locally between the particle surface and the flame zone as shown in Figure 15. On the contrary, in the case of conditions of ambient temperature and oxygen concentration in which the smaller fuel particles do not appear to come out from fuel sphere, so the flame does not develop and extinguish gradually with the progress of combustion process.

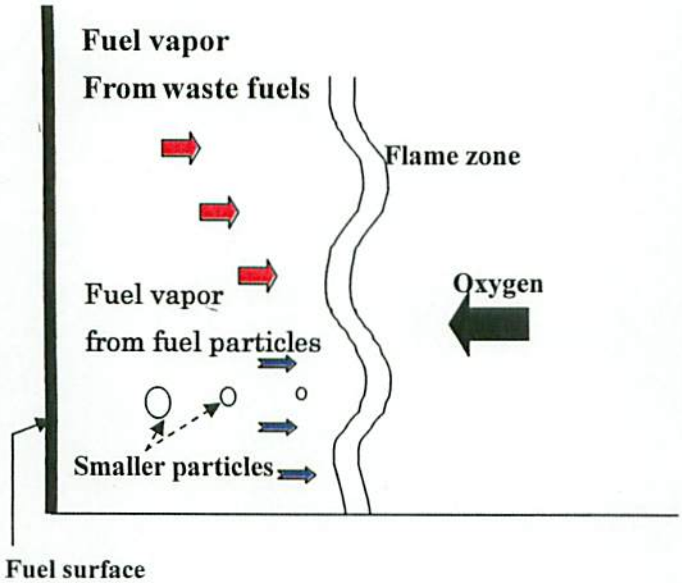

Fig.14 Behavior of smaller fuel particles

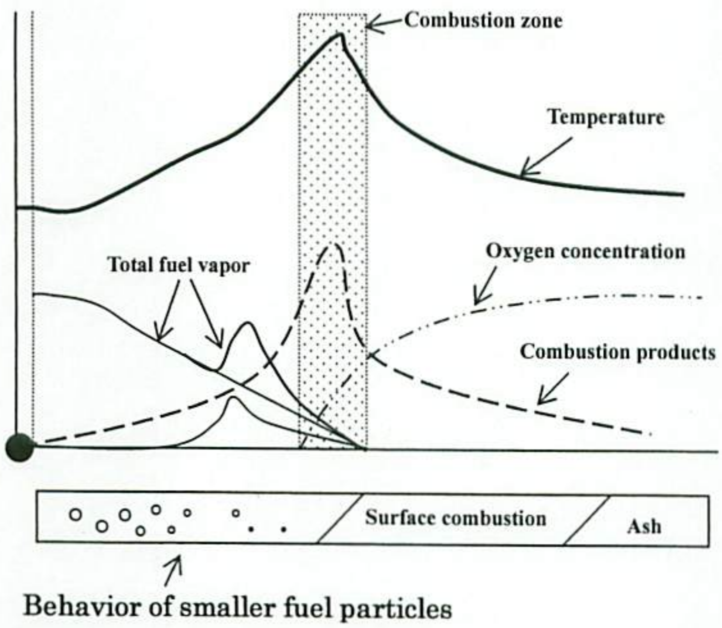

Fig.15 Comprehensive combustion model

3. Conclusions

Experiments have been conducted to elucidate the combustion stability and flame development of solid waste fuels in high temperature and low oxygen atmosphere. The main conclusion of the present study are as follows: (1) the combustion behavior of solid waste fuels can be classified into three sequential regimes of ignition, luminous flame and surface combustion, (2) the stable and unstable combustion region on burning process of solid waste fuels can be related to the variation of flaming duration and surface combustion period and (3) the boundaries separating these regimes show a well defined inverse relationship between ambient temperature and oxygen concentration. Though many of these can be observed by experiments under normal gravity, the microgravity experiment enable one to uncover finer aspects that aid modeling of the combustion process of solid waste fuels.

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