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# EXPERIMENTAL INVESTIGATION OF WASTE FUEL COMBUSTION IN HIGH TEMPERATURE AND LOW OXYGEN EXHAUST GAS

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Abstract

In practical, the stable combustion of solid waste fuels in incinerators requires very high temperature environments, which is usually achieved by recirculation of combustion exhaust gas. Experiments have been conducted to extract the fundamental combustion characteristics of solid waste fuels in flowing combustion gas generated from flat flame burner. The essential burning behavior of solid waste fuels such as ignition delay, flaming duration and surface combustion are observed by taking the direct photographs with 8-mm video camera. It is concluded that there are three combustion processes of solid waste fuels burning in high temperature environments such as gas phase ignition, luminous diffusion flame and surface combustion and its flame behavior can be classified three types depending on gas flow velocity, temperature and oxygen concentration, that is, envelope flame, wake flame and lifted flame. The boundary gas flow velocity between the stable and unstable combustion is determined by the variation of flame configuration from envelope to wake or lifted flames.

Key Words: Solid waste combustion, High temperature and low oxygen environments, Ignition delay, Flaming duration, Stable combustion region

## 1. INTRODUCTION

In recent years, though the progress of science and technology has been brought us a convenient and comfortable life style, the environment problem in the terrestrial scale of the lack of energy and resources, the acid rain, the ozone layer depletion, the global warming and desertification is aggravating. Especially a large quantity of wastes produced by mass production and consumption are disposed by the incineration, although the reuse, the reducing and the recycling are practiced. Therefore the useful technique on the waste fuel combustion should be developed immediately and it is required to achieve the effective use as a source of energy and it is also required to realize the suitable combustion of solid waste fuels such as high thermal efficiency and low air pollution.

In practical, the stable combustion of solid waste fuels in incinerators such as stoker type and fluidized bed type requires very high temperature environments, which is usually achieved by recirculation of combustion products. Moreover 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.[1]

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Thus, the experimental technique for establishing the solid waste fuel combustion under high temperature and low oxygen environments has been developed by flowing combustion gas produced from the flat flame burner capable to control the gas temperature and oxygen concentration of combustion gas and their fundamental combustion characteristics such as ignition delay, flame development involving stable combustion, total burning time and mass burning rate have been elucidated.

## 2. EXPERIMENTAL APPARATUS AND PROCEDURE

Experimental apparatus shown in Fig.1 consists of combustion chamber equipped with a flat flame burner, a power controller for sirocco fan to supply air into the flat flame burner, a high-pressure air tank to operate the air cylinder which is attached the fine quartz fiber and a 8-mm video camera to observe the combustion behavior of solid waste fuels. In Fig.2 is shown the outline of the flat flame burner investigated in the study. The air enters from the burner and is rectified by 64 fine tubes of 3 mm in diameter. The fuel gas entered from the burner-side throughout 64 fine tubes is mixed with air at the top of the burner and the semi-flat flame is established.

Experiments have been carried out by achieving the combustion behavior of solid waste fuels in high temperature and low oxygen environments in flowing combustion gas generated from the flat flame burner. The gas velocity, gas temperature and oxygen concentration of flowing combustion gas are adjusted by changing the flow rate of air and propane (99.9% purity). The gas temperature, oxygen concentration and gas velocity are the ranges of 600°C to 1000°C, 2% to 18% by volume and 1.0 m/s to 4.0 m/s, respectively.

The food of Nishiki-koi is used as representating fuel of solid waste fuels because its chemical and physical properties are very similar to those of solid waste fuels produced from domestic and industrial sector.[2, 3] The Solid fuel in the spherical form of 5 mm in diameter supported by a quartz fiber of 0.4 mm in diameter is moved to the upper position of flat flame burner by the aid of pneumatic actuator. The subsequent processes of ignition and combustion are recorded with 8-mm video camera and are analyzed to examine the fundamental characteristics of solid waste fuels burning in high temperature and low oxygen environments.

## 3. EXPERIMENTAL RESULTS AND DISCUSSION

Figure 3(a, b, c) shows the direct photographs on combustion behavior of solid waste fuels burning in the flowing combustion gas at 800°C of gas temperature and 10 % of oxygen concentration by volume. From these photographs it can be seen that the combustion behavior of solid waste fuels in flowing combustion gas are divided three phases, that is, gas phase ignition, luminous flame and surface combustion, and there are three types of flames depending on the combustion gas velocity, that is, an envelope flame at approximately 2.0 m/s of gas velocity, a wake flame at approximately 2.7 m/s and a lifted flame at approximately 3.7 m/s. Where the envelope flame is a pure diffusion flame established around the fuel sphere, and wake and lifted flames are semi-premixed flame in which air is slightly introduced into the flame zone from the top surface of fuel sphere.

Figure 4 shows the total burning time of 5 mm diameter in fuel sphere against gas flow velocity (V) at 800°C of gas temperature (T) and 10 % of oxygen concentration by volume (c), and in Fig.5 is shown the total burning time of 5 mm diameter ($D_0$) in fuel sphere against oxygen concentration at 900°C of gas temperature and 2.0 m/s of gas flow velocity. The total burning time here includes all three combustion phases of ignition delay, duration of luminous flame (flaming duration) and surface combustion period. For the case of envelope flame region, the increase of gas flow velocity leads to decrease the ignition delay,

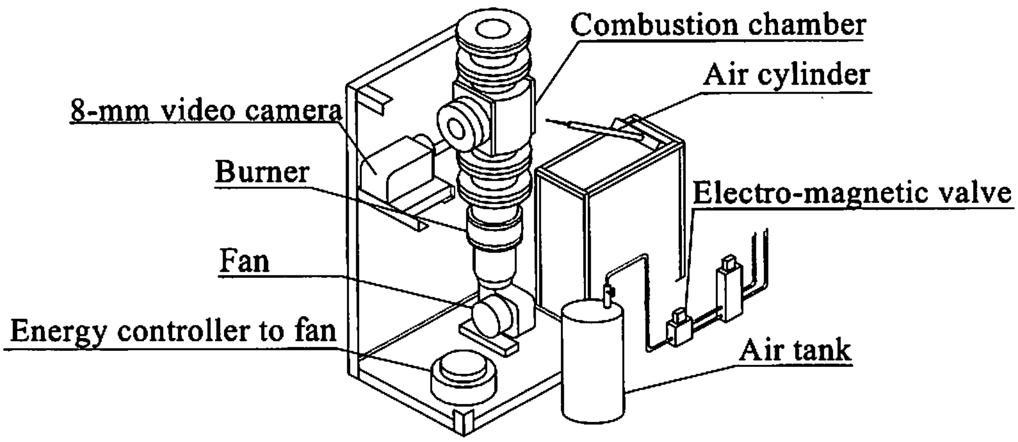



Fig.1 Experimental apparatus

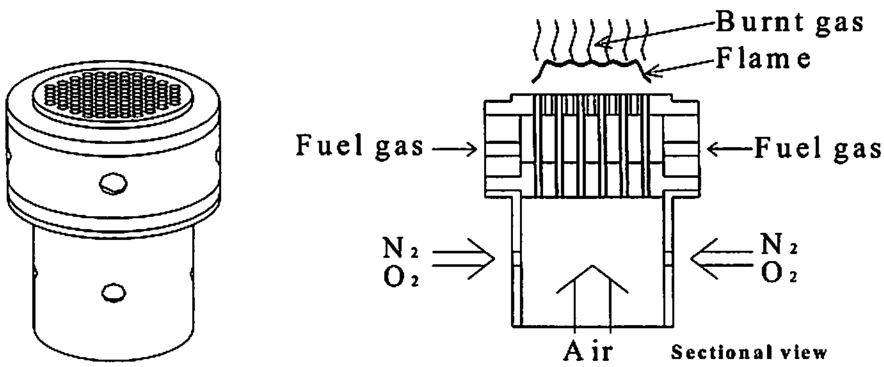
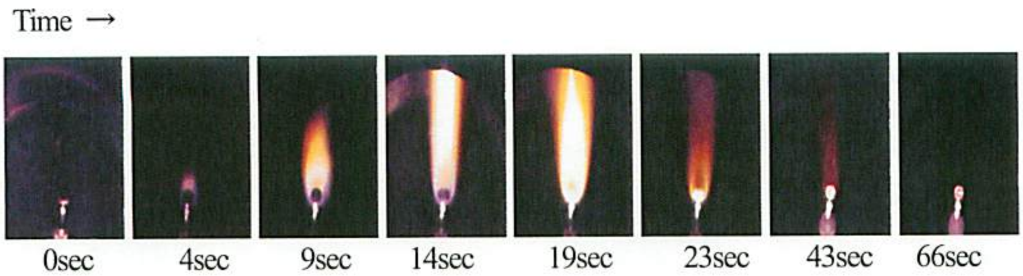


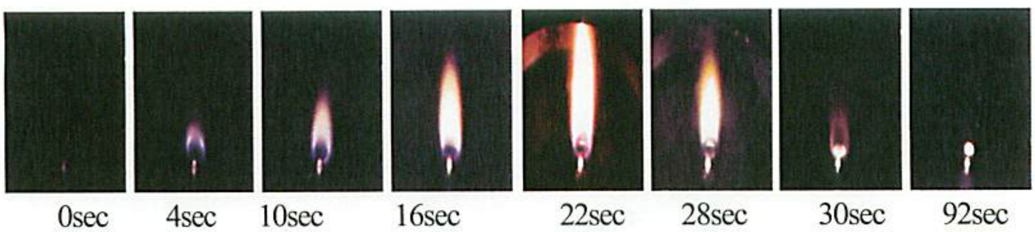

Fig. 2 Flat flame burner

flaming duration and surface combustion period at any oxygen concentration. On the contrary, for the case of wake and lifted flame regions, the flaming duration increases with increasing gas flow velocity corresponding to the change of flame configuration from envelope to wake or lifted flames, and the surface combustion period decreases with increasing gas flow velocity due to the introducing much of the oxygen content into the surface of fuel sphere.

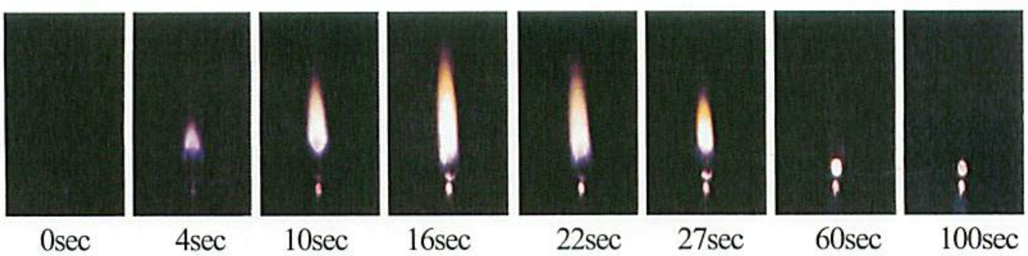
Figure 6 shows the ignition delay against gas flow velocity at 900°C of gas temperature as a parameter of oxygen concentration and Fig.7 also shows the ignition delay against oxygen concentration at 900°C of gas temperature and 2.0 m/s of gas flow velocity. The ignition delay is defined as a time from exposure of solid waste fuel in combustion gas to the instant of appearance of luminous flame. From Fig.6 it is found that the ignition delay decreases as the gas flow velocity increases, and then increases at higher gas flow velocity. It may be explained that, for the region of relatively low gas flow velocity, the ignition delay is mainly determined by vaporization time because the Damkoler number is large and chemical reaction time between vaporized fuel gas and oxygen is very short so that the ignition delay decreases as the gas flow velocity increases. On the other hand, when the gas flow velocity becomes high, Damkoler number becomes small value and exothermic reaction in the gas phase becomes




(a) T=800°C, c=10%(vol.), V= 2.0m/s, $D_0$=5mm




(b) T=800°C, c=10%(vol.), V= 2. 7 m/s, $D_0$=5mm




(c) T=800°C, c=10%(vol.), V= 3.7m/s, $D_0$=5mm

Fig.3 Direct photographs on combustion behavior of solid waste fuels at various gas flow velocities

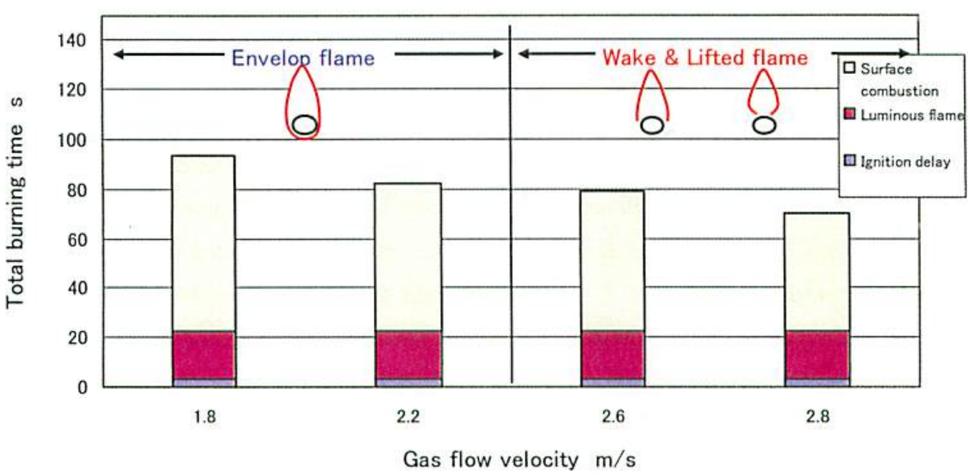



Fig.4 Total burning time against gas flow velocity ($D_0$=5mm, T=800°C, c=10%)

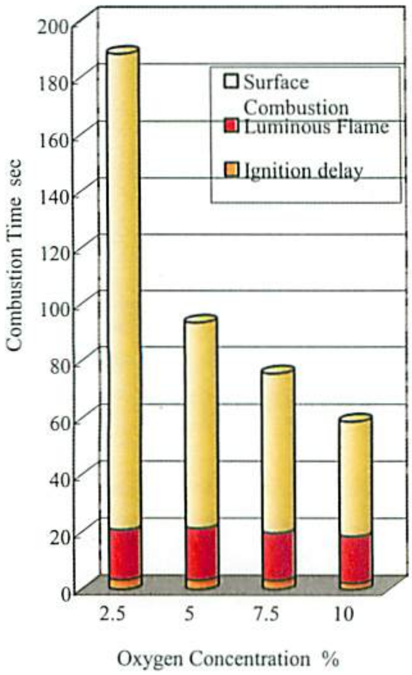



Fig.5 Total burning time against oxygen concentration ($D_0$=5mm,T=900 °C, V=2.0m/s)

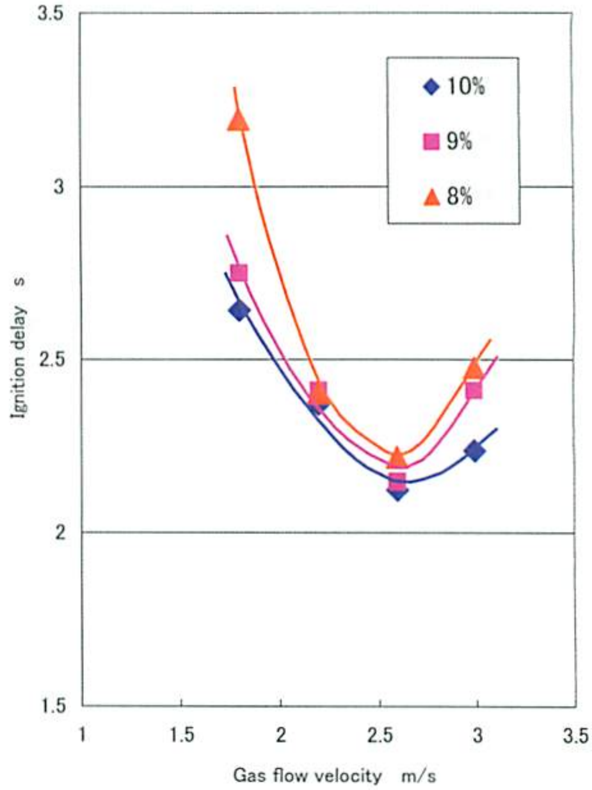



Fig.6 Ignition delay against gas flow velocity ($D_0$=5mm,T=900°C)

relatively weak, and consequently the temperature rise in the gas-phase is very slowly, although the gasification is completed within the short time at higher velocities. Consequently the ignition delay increases in this velocity fields due to the increase of induction time.[4,5]

Moreover it can be recognized from Fig.7 that the effect of oxygen concentration on ignition delay is not so large, though the increase of oxygen concentration makes it possible to promote the burning rate of solid waste fuels. This fact indicates that for such high temperature environment the ignition of solid waste fuels is governed mainly by physical process such as heating period of fuel sphere.

Figure 8 shows the flaming duration against gas flow velocity at 800°C of gas temperature as a parameter of oxygen concentration and Fig.9 also indicates the flaming duration against oxygen concentration at 900°C of gas temperature and 2.0 m/s of gas flow velocity. The dotted line in Fig.8 denotes the boundary of appearance between the envelope and wake or lifted flames of solid waste fuels obtained in the flowing gas velocity under high temperature environments. From Fig.9 it can be seen that there is not so large differences on the burning time of luminous flame (flaming duration) except below 2.5 % of oxygen concentration. However, below 2.5 % of oxygen concentration the luminous flame can not be observed and it is almost occupied by surface combustion.

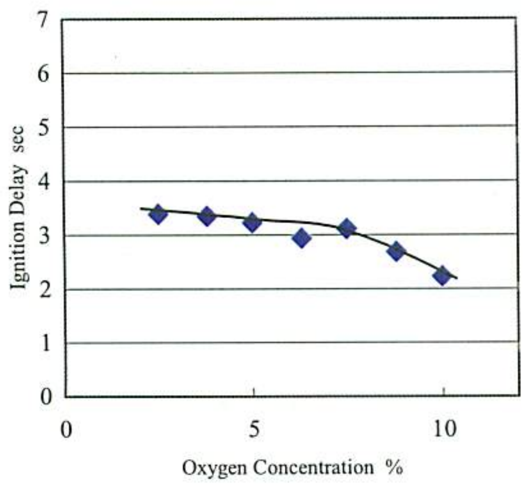



Fig.7 Ignition delay against oxygen concentration ($D_0$=5mm, T=900℃, V=2.0m/s)

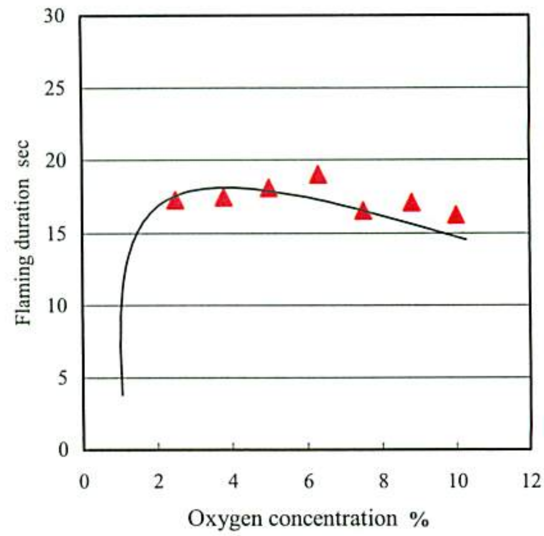



Fig. 9 Flaming duration against oxygen concentration ($D_0$=5mm, T=900°C, V=2.0m/s)

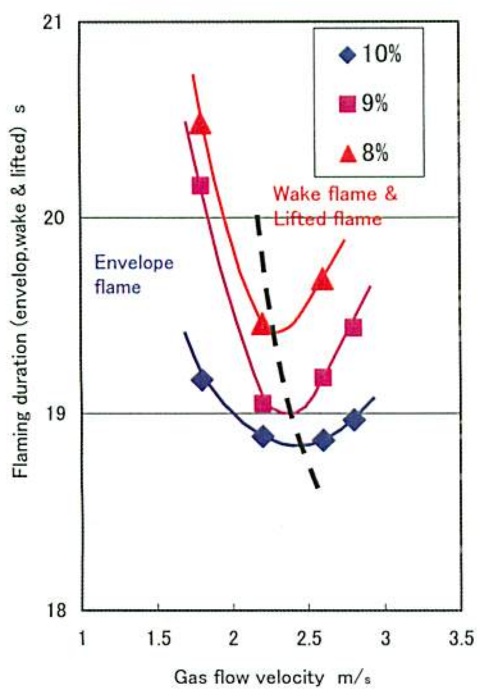



Fig.8 Fig8 Flaming duration against gas flow velocity ($D_0$=5mm,T=800℃)

Figure 10 shows the surface combustion period against gas flow velocity at 800°C of gas temperature as a parameter of oxygen concentration. The surface combustion period monotonically increases with increasing gas flow velocity regardless the change of flame configuration from envelope to wake or lifted flames. This means that the surface combustion is promoted as the increase of gas flow velocity makes it possible to supply much of oxygen content into the surface of fuel sphere.

Figure 11 shows the mass burning rate against gas flow velocity at 800 °C of gas temperature and 10% of oxygen concentration by volume and Fig.12 also denotes the mass burning rate ($\Delta m / \Delta t$) against oxygen concentration at 900 °C of gas temperature and 2.0 m/s of gas flow velocity. In the mass burning rate, $\Delta m$ is difference between the initial mass and mass after surface combustion and $\Delta t$ includes the flaming duration and surface combustion period. From these figures it can be recognized that for all the regions of envelope and wake or lifted flames the increase of gas flow velocity monotonically leads to increase the mass burning rate due to the promotion of surface combustion with increasing oxygen content and the increase of oxygen concentration in flowing gas also leads to increase the mass burning rate.

Figures 13 shows the boundary gas flow velocity between the stable and unstable combustion against oxygen concentration at 800°C of gas temperature, where the stable combustion means that the envelope flame is maintained during the combustion process and unstable combustion is mainly occupied by wake or lifted flames. Figure 14 also shows the boundary gas flow velocity between the stable and unstable combustion against gas temperature at 14% of oxygen concentration by volume. From these figures it is recognized that, though the increases of gas temperature and/or the oxygen concentration bring about to elongate the region of stable combustion, its effect on the rise of gas temperature is more sensitive compared with that of oxygen concentration. .

## 4. CONCLUSION

Experiments have been carried out to elucidate the fundamental combustion characteristics of solid waste fuels in high temperature and low oxygen exhaust gas. The main results obtained in the study are as follows: (1) the combustion behavior of solid waste fuels in flowing gas fields can be classified by three processes of gas phase ignition, luminous flame and surface combustion and there are three flame types with combustion gas velocities, that is, envelope flame, wake flame and lifted flame, (2) the ignition delay is relatively insensitive for the increase of oxygen concentration, though it is very sensitive for the increase of ambient temperature, (3) the ignition delay decreases with increasing gas flow velocity, but it increases at higher gas flow velocity, (4) flaming duration decreases with increasing gas flow velocity for the case of envelope flame region, but increases with increasing gas flow velocity for the case of wake and lifted flames. The stable and unstable combustion region on burning process of solid waste fuels can be determined from the variation of flame type with the gas flow velocity, and (5) the mass burning rate monotonically increases with increasing gas flow velocity.

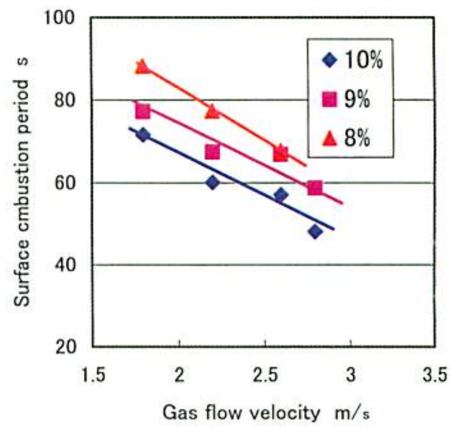



Fig.10 Surface combustion period against gas flow velocity($D_0$=5mm,T=800°C)

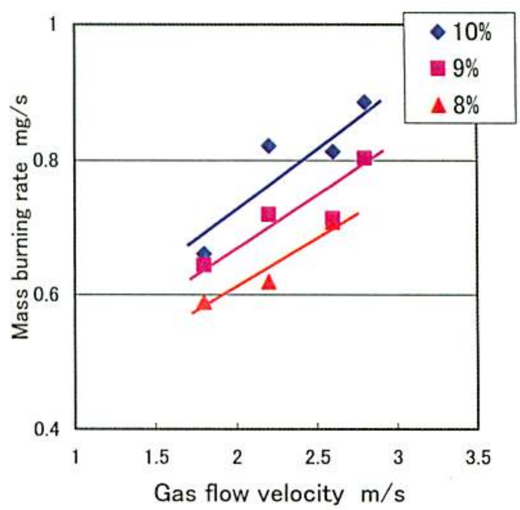



Fig.11 Mass burning rate against gas flow velocity ($D_0$=5mm,T=800°C)

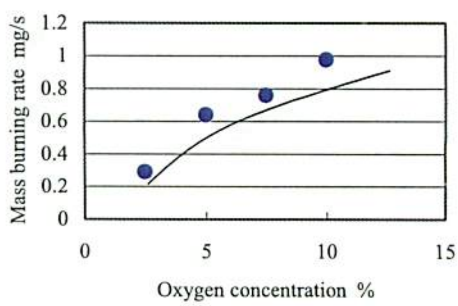
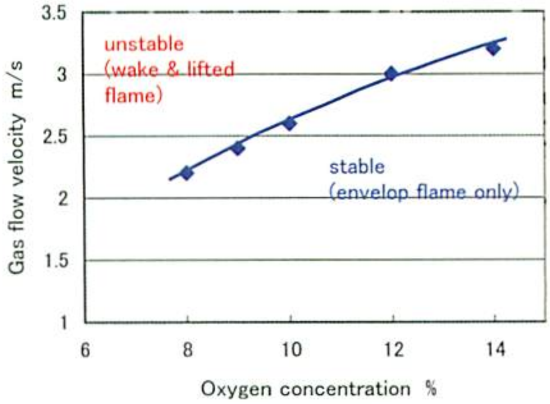



Fig.12 Mass burning rate against oxygen concentration($D_0$=5mm.T=90°C, V=2.0m/s)



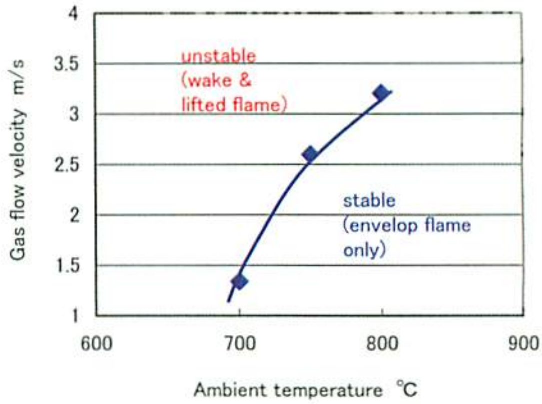




Fig.14 Stable combustion region against ambient temperature at 14% of oxygen concentration by volume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