レーザー誘起赤熱法によるプロパンガスと木粉拡散火炎中のすすおよび灰の測定*

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Measurement of Soot and Ash in Diffusion Flame of Propane Gas and Wood Powder by Laser-induced Incandescence Method

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炭化水素燃料と木粉の混合燃焼により発生するすすおよび灰は有害物質であり、燃焼設備の伝熱効率低下と腐食などの問題を引き起こす。このような燃焼過程におけるすすおよび灰の生成を抑えることが重要であり、そのためにすすおよび灰の生成特性を把握しなければならない。本研究では、プロパンガスと微細木粉混合燃料拡散火炎を形成して、火炎中のすすおよび灰の濃度を測定することを目的とし、レーザー誘起赤熱法を用いて、すすおよび灰の空間分布を調べた。プロパンガスと微細木粉混合燃料火炎とプロパンガス火炎のすす体積分率、火炎温度および微粒子質量濃度を比べた結果により、木粉の燃焼過程を解明した。

1. Introduction

Soot emitted from combustion process causes serious problems to the environment and human health. Ash is also a main component of the fine particles emitted from wood combustion. The deposition of ash on the surfaces of a heat exchanger can cause several problems such as fouling and corrosion, and decrease the efficiency of heat transfer^[1].

The diffusion flame of propane gas and wood powder of cedar was established to study the soot and ash behavior. Soot diameter was measured in the former research^[2]. This paper aims to measure the concentrations of soot and ash. The spatial distribution of the soot volume fraction, flame temperature and fine particle mass concentration are investigated. The flame of propane gas and wood powder is compared with the flame of propane gas to discuss the burning process of wood powder.

2. Properties of propane gas and wood powder

The term ‘propane gas’ refers to a mixture of hydrocarbon gases. The mole composition of the mixture is 96.8% propane, 1.6% isobutene, 0.8% normal butane, 0.8% ethane and ethylene. For clarity, this paper abbreviates ‘propane gas’ to ‘PG’, ‘wood powder’ to ‘WP’, ‘flame of propane

gas’ to ‘PG flame’, ‘flame of propane gas and wood powder’ to ‘PGWP flame’. The raw cedar lumber is dried, crushed, fine-milled and sieved to WP for experiment. Table 1 lists the properties of WP by TGA and reference^[3]. WP configuration analysis is carried out to understand the particle size and configuration. The samples of WP (3 images, 820 samples) are taken at the burner outlet under the

Table 1 Properties of WP and ash (Unit: wt.%)

Proximate analysis		Ash analysis	
Volatile	79.0	SiO ₂	28.05
Fixed carbon	15.7	CaO	24.31
Moisture	4.8	MgO	18.66
Ash	0.4	K ₂ O	11.05
Ultimate analysis		Al ₂ O ₃	8.35
Carbon	51.43	Fe ₂ O ₃	3.71
Oxygen	42.45	SO ₃	2.13
Hydrogen	6.10	Others	3.74

Fig.1 Distribution of heywood diameter

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Fig.2 Length and width of WP

same condition as experiment but the flame is not fired. Following reference [4], SEM image analysis is applied to measure the particle size. Fig.1 shows the Heywood distribution of WP. Fig.2 shows the length and width distribution of WP. Most of WP is in the shape of oblong or needle.

3. Experimental apparatus and method

The experiments are carried out in the laminar diffusion flames on a concentric burner at atmospheric pressure. Fig.3 shows the schematic of the burner. PG is supplied to the annular chamber between the inner and outer tube at 0.1l/min while the carrying air is supplied to the inner tube at 0.2l/min for both PG flame and PGWP flame. WP is supplied by the carrying air to the inner tube at 4.1mg/min for PGWP flame. The flame heights of both PG flame and PGWP flame are 45mm. The measurements are carried out from 10mm to 45mm *HAB* (Height Above Burner) at intervals of 5mm.

Fig.3 Schematic of burner

Fig.4 Experimental apparatus of LII

Laser-induced incandescence (LII) method [5][6][7] is employed to measure the soot volume fraction. Fig.4 shows the experimental apparatus of LII. The second harmonic (532nm) of a Nd:YAG laser (Spectron SL850) is used for exciting the soot. The pulse energy of laser beam is 1030mJ and the laser pulse duration is 6ns. The laser sheet ($0.2 \times 50 \text{ mm}^2$) formed by 3 cylindrical lenses is introduced to the axial center of flame. A flame stabilizer is used to keep the flame stable. Some windows are opened in the stabilizer wall for passing through laser beam and taking flame image. LII signals, after passing a 400nm (400BP10) or 500nm (500BP10) bandpass filter, are detected by an ICCD camera (Oriel, Instaspec V) which is perpendicular to the laser sheet plane. A delay/pulse generator (Stanford DG535) is used to control the timing of the laser pulse and the camera. The temporal peak of the LII signal (prompt-LII) is obtained by selecting the camera gate of 20ns width to describe the soot volume fraction.

The interpretation of *LII* (LII signal intensity) in terms of the soot volume fraction f_v is given as [8]:

$$LII = K f_v$$

in which the coefficient K depends on the excitation and detection wavelengths. Therefore *LII* of 400nm and 500nm are proportional to the soot volume fraction f_v .

The temperature of flame and surrounding air is measured by a JIS-R type thermocouple and recorded in a hybrid recorder (DR130). The temperature reading increases to peak values after the thermocouple is inserted into flame, then it decreases because of radiation loss by soot deposition on the thermocouple bead. The mean value of the peak temperatures is adopted as the local flame temperature. While the surrounding air temperature is obtained by directly averaging the temperature readings. The fine particle mass concentration is measured by filter sampling

method.

4. Experimental result

4.1 Soot volume fraction

Fig.5 shows the images of flame. The visual images of PG flame and PGWP flame are almost the same. There are two differences between the LII images of PG flame and PGWP flame. One is the intensity detected in the lower zone of PGWP flame and the other is that in the center zone. The intensities of both PG flame and PGWP flame at 500nm are higher than those at 400nm.

Fig.5 Image of flame

Fig.6 shows LII of flame. LII is obtained as Counts (Bg. Corrected)=Data-#Background, where 'Data' is the intensity of LII image, '#Background' is the intensity of visual image with filter.

LII of 500nm are detected in the flame edge ($r \approx \pm 4.5\text{mm}$), while LII of 400nm are too weak to be detected.

(1) $HAB=10\text{mm}$

LII of both 500nm and 400nm show peak values in the flame edge ($r \approx \pm 4\text{mm}$). LII of 500nm are also detected in the flame center zone ($r \approx \pm 2\text{mm}$).

(2) $HAB=15\text{mm}$

LII increase in the flame edge, but there is little variation in the flame center zone.

(3) $HAB=20\text{mm}$

LII continue increasing in the flame edge. LII of 500nm increase rapidly in the flame center zone.

(4) $HAB=25\text{mm}$

The peak values increase at center zone in the flame.
(5) $HAB=30mm$

LII continue decreasing at $HAB=45mm$.
(8) $HAB=45mm$

Fig.6 LII of flame

All the LII reach the maximum value at $HAB=35mm$.
(6) $HAB=35mm$

LII decreases at $HAB=40mm$.
(7) $HAB=40mm$

Fig.7 LII difference between PGWP flame and PG flame

On the proximate analysis in Table 1, TGA and DTA^[9] show that the burning process of WP is divided into 3 stages of water vaporization, volatile combustion and fixed carbon combustion. The main volatiles are light hydrocarbons. Ash is produced in the stage of fixed carbon combustion. The outflow of water vapor and volatiles prevents the PG reaction from consuming oxygen. The WP flow influences

the combustion process in the laminar diffusion flame. Soot and ash is produced in the high HAB zone. The total soot volume fraction is increased.

4.2 Flame temperature

Fig.8 shows the temperatures of the flame and the surrounding air. The peak temperature of flame is in the flame edge and increases along the HAB direction in the $HAB \leq 40\text{mm}$ zone. The temperature of PGWP flame is higher than that of PG flame at all measurement points.

Δt_{mean} and Δt_{max} , which are the arithmetic mean temperature difference and the maximum temperature difference between PGWP flame and PG flame, are shown in Fig.9. A Δt_{mean} of 5.5~6.8K exists in the $HAB \leq 25\text{mm}$ zone, then it increases to 15.3K at $HAB=30\text{mm}$ and reaches maximum value of 21.5K at $HAB=35\text{mm}$, finally it decreases to 11.0K at $HAB=45\text{mm}$. The Δt_{max} also shows the similar variation as Δt_{mean} . The heat released from the WP burning increases the temperature rapidly in the $HAB \leq$

(1) PG flame

(2) PGWP flame

Fig.8 Temperature of flame and surrounding air

Fig.9 Mean and maximum temperature difference

35mm zone. WP is burnt out till $HAB=35\text{mm}$ therefore the temperature difference decreases in the $HAB=35\sim 45\text{mm}$ zone.

4.3 Fine particle mass concentration

Fig.10 shows the fine particle mass concentration. The difference between PGWP flame and PG flame is 100~311 g/m^3 in the $HAB \leq 30\text{mm}$ zone. It is higher than that in the $HAB=35\sim 45\text{mm}$ zone (75g/m^3). This is because the fine particle consists of soot, ash and unburned WP in the $HAB \leq 30\text{mm}$ zone, while WP is burning out along the HAB direction, thereafter only soot and ash remain in the $HAB=35\sim 45\text{mm}$ zone. The difference of fine particle mass concentration of 75g/m^3 in the $HAB=35\sim 45\text{mm}$ zone is approximately equal to the theoretical ash mass concentration of 82g/m^3 , which makes it clear that WP is burnt out completely and ash is produced.

Fig.10 Fine particle mass concentration

5. Conclusion

The soot volume fraction, the flame temperature and the fine particle mass concentration in the diffusion flame of propane gas and wood powder are measured by Laser-induced incandescence method and other experimental measurements. The burning process of wood powder and the ash formation are deduced.

The dominant soot volume fraction exists along the flame edge in the $HAB \leq 25\text{mm}$ zone and at the flame center in the $HAB = 30 \sim 45\text{mm}$ zone, with the wood powder burning.

The flame of propane gas and wood powder produces higher soot volume fraction, higher flame temperature and higher fine particle mass concentration than the flame of propane gas.

Wood powder in the diffusion flame is burnt out in the $HAB \leq 35\text{mm}$ zone, while ash is produced and exists in the $HAB = 35 \sim 45\text{mm}$ zone.

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