# Characterization of laminar premixed flame firing biomass derived syngas with oxygen enriched air

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# Abstract

Ceramic industries are highly energy intensive, with more than 50% of total cost from liquefied petroleum gas (LPG) used for firing process. Biomass derived syngas may be deployed to substitute LPG in this process. In this work, characterization of laminar premixed flame (laminar flame speed and flame stability) firing biomass derived syngas was carried out with varying oxygen contents in air (21-50%). From the experimental work, it was found that laminar flame speed increased with increasing oxygen concentration in enriched air. This was mainly because reduction in nitrogen dilution resulted in higher burning temperature and faster reaction rate. Increasing oxygen content in air also improved the flame stability to be available in a wider range of combustible mixture and higher blowoff limit. This way, applications with more power and higher flame temperature can be achieved from utilization of biomass derived gaseous fuels.

Keywords: biomass, combustion, flame propagation, gasification, renewable energy

# 1. Introduction

Ceramic industry is an important industrial group, producing a wide range of products such as tableware, giftware, sanitary wares, wall and floor tiles, refractories, technical sensors, prosthetics, etc. Ceramic industries are highly energy intensive. Major production cost is from firing or kilning process [1]. The industry normally uses premixed burners with liquefied petroleum gas (LPG) as fuel to generate heat at over 1,200 °C in the process. Recent increase in LPG price has adversely affected the production cost. Alternative energy development for substituting LPG in the firing process is extremely crucial. For the substitute fuel in the firing process, it must be clean and have sufficiently high energetic content to achieve high firing temperature.

Biomass derived gas is one of alternative fuels that may be able to replace LPG in ceramic firing process [2]. It is typically derived from gasification process of biomass or charcoal using air as gasifying medium. However, this product gas usually has a large amount of nitrogen dilution, hence, low calorific value (4-6 MJ/m<sup>3</sup>). To achieve higher calorific value, oxygen or steam as gasifying medium may be used. With low nitrogen content, hydrogen and carbon monoxide are the main components of this biomass derived syngas, with heating value around 9.3-20.5 MJ/m<sup>3</sup>. It has been proven to be adequate in combustion system [3]. This gas has been studied as a gaseous fuel in gas turbine [4], an intermediate substance for methanol production [5], liquid fuels via Fischer-Tropsch [6], and H<sub>2</sub> production [7]. So far, relatively little works has been reported on applications for process heat in ceramic industry.

Burner is important for heating application. There are two types of gas burner designs; premixed and non-premixed burner types. Ceramic firing process uses premixed burners to form flame in generating heat. For this burner type, fuel and oxidizer are mixed before approaching the combustion. The basic functions when using gas burners are to prepare a combustible mixture with a proper oxidizer to fuel ratio,

doi: 10.12720/sgce.8.6.702-709

<sup>\*</sup> Manuscript received August 15, 2018; revised July 30, 2019.

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ensure complete combustion, stabilize the flame, and provide desired thermal power of flame. An important key parameter controlling the premixed combustion behavior of gas fuel is laminar flame speed. A flame will be stable when the reactant velocity balances with the laminar flame speed. When an imbalance between them occurs, instability phenomena such as blowoff and flashback happen. The laminar flame speed can be measured experimentally by many techniques such as spherical closed vessels, counter flow burner, flat flame, and cone flame. Conical flame technique is commonly performed [8-10]. Flame speed of the mixture gas varies, depending on the proportion of individual gas. Dong et al. [8] and Bouvet et al. [11] studied the laminar flame speed of syngas mixtures in various  $H_2/CO$  ratios. They found that the laminar flame speed increases as more  $H_2$  is added to the fuel mixture. The laminar flame speed is reduced by the dilution of  $CO_2$  and  $N_2$  inert gas [12-15]. Oxygen enriched air combustion is a good technique to improve the combustion process. It increases the laminar flame speed and flammability limits of producer gas significantly [16]. It can be seen that combustion study of biomass derived syngas with oxygen enriched air is somewhat lacking. Therefore, the objective of this work is to investigate and characterize laminar flame speed and flame stability of biomass derived syngas with oxygen-enriched air.

#### 2. Materials and Method

### 2.1 Syngas generation

In this study, biomass derived syngas was generated from oxygen gasification of charcoal in a laboratory fixed bed gasifier [17, 18], shown in Fig. 1. It was equipped with a 5 kW electrical heater and insulated covering. Typically, a 100 g of charcoal was loaded into the heating section. The  $O_2$  feed rate of 400 ml/min was used. The product gas was subsequently cleaned and collected in an aluminum multi-layer foil bag. The mean composition analyzed using gas chromatography is shown in Table 1.



Fig. 1. Schematic of biomass derived syngas generator.

## 2.2 Experimental setup and procedure

The experimental setup for laminar flame measurement is shown in Fig. 2. Air (21%  $O_2$  content) and oxygen enriched air (30, 40, and 50%  $O_2$  content) based on membrane technology [19] were used as oxidizers. They were made to order with a certification in their composition. Stoichiometric air-fuel ratio of any oxidizers depends on enrichment level, as shown in Table 2. Amount of oxygen is the same for all cases at stoichiometric condition. A lesser nitrogen dilution in higher oxygen content results in lower air-fuel ratio. The mixture equivalence ratio is calculated as,

$$\phi = \frac{AF_{stoichiomatic}}{AF_{actual}} \tag{1}$$

Table 1. Composition of the biomass derived syngas

Properties	Value
H <sub>2</sub> (%)	35.84
O <sub>2</sub> (%)	1.17
N <sub>2</sub> (%)	5.57
CO (%)	29.83
CH <sub>4</sub> (%)	11.12
CO <sub>2</sub> (%)	16.47
LHV (MJ/m <sup>3</sup> )	11.61
density (kg/m <sup>3</sup> )	0.838
dynamic viscosity (kg/m.s)	1.33E-05

Table 2. Air-fuel ratio at stoichiometric combustion

Oxidizer	Stoichometric air to fuel ratio
Air (21%O <sub>2</sub> , 79%N <sub>2</sub> )	3.69
30%O <sub>2</sub> , 70%N <sub>2</sub>	2.62
40%O <sub>2</sub> , 60%N <sub>2</sub>	1.99
50%O <sub>2</sub> , 50%O <sub>2</sub>	1.61



Fig. 2. Schematic of premixed laminar flame experimental setup.

The fuel gas was pumped to mix with oxidizers in a mixer. The fuel and oxidizer flow rates were controlled by calibrated rotameters. The mixer was made of a PVC pipe inserted with twisted aluminum sheet for better mixing. There was a flashback arrestor (made from rolled stainless steel wire mesh) placed before the entrance of the burners to prevent possible explosion in the mixer when flashback occurs. Atmospheric straight burners made from copper tubes with diameter (D) of 2.4, 4.2, and 6.7 mm were used. The edges of the burners were sharpened to avoid any irregularity that could affect the flame stabilization. The pipe length was more than 50D to ensure that the flows were fully developed. The burner diameters were chosen to ensure that the flows remained laminar ( $Re_D < 2300$ ) and to prevent flashback and blowoff. Schlieren technique consisting of a light source, a slit, concave mirrors, knife edge,

and a CCD camera was used for photo capture. The Schlieren edge gave higher accuracy of the cone angle than visible edge. The concave mirrors used had focus length of 250 mm, and diameter of 75 mm. The burners were set between the alignment of concave mirrors. When a flow rate at a desired air-fuel mixture ratio produced steady flame, at least three photos were taken by the camera with frame rate of 60 fps, 1280 x 720 pixels. The conical images from Schlieren technique were analyzed for the cone angles (Fig. 3) using ImageJ program. At least three pictures were employed and the angles were averaged. The mixture velocities and the angles were used to calculate laminar flame speed as

$$S_L = u \sin \alpha \tag{2}$$

where *u* is mixture velocity.

For the flame stability experiment, the setup was similar to the flame speed experiment but there was no Schlieren technique applied. Burner diameter of 2.4 mm was fixed for all runs to eliminate sizing effect. At any mixture ratio, mixture flow rate was gradually increased and decreased until the flame blowoff and flashback occurred. The highest and lowest velocities that occurred blowoff and flashblack were recorded. At least three replications were performed for each flow rate.



Fig. 3. Illustration of Schlieren edge to determine conical flame.

# 3. Results & Discussion

## 3.1. Laminar flame speed

Combustion characteristics of biomass derived syngas were observed in different levels of oxygen concentrations in air as oxidizer. The blue cone flame was captured to calculate laminar flame speed. Variations of laminar flame speeds with equivalence ratio are shown in Fig. 4. The flame speed was observed to increase with equivalence ratio in lean mixture, and then decrease in rich mixture. For the air combustion, the maximum flame speed was at equivalence ratio around 1.1, 64 cm/s. Similar trend was observed in air combustion of biomass derived syngas from steam gasification, around 50 cm/s at equivalence ratio of 1.14 [3]. Higher flame speed in this work was expected due to higher  $H_2$  content. Using higher oxygen concentrations in enriched air, the laminar flame speed increased with increasing oxygen concentrations. The maximum moved to lower equivalence ratio. This behavior agreed well with the numerical results by Cardona and Amell [20] and the experimental results by Dirrenberger et al. [21]. Comparing against the air combustion at the stoichiometric condition, oxygen concentrations of 30, 40, and 50% increased the laminar flame speeds to 67, 80, and 96 cm/s or by approximately 5, 26, and 51%, respectively. The increase in laminar flame speed was contributed to the fact that reduction of nitrogen inert gas in higher oxygen content oxidizer produced higher flame temperature. The high temperature favored higher reaction rate [22]. Yepes and Amell [16] and Zhou et al. [23] also described that laminar flame speed was relative to adiabatic flame temperature. The adiabatic flame temperature of this gas combustion in lean and rich mixtures is shown in Fig. 5.



Fig. 4. Laminar flame speed results.



Fig. 5. Adiabatic flame temperature for different enrichment levels.

## 3.2 Flame stability

Laminar flame speed relates directly to flame stability. A stable flame is achieved when the laminar flame speed is equal to the perpendicular component of the reactant velocity. At any equivalence ratio, the regions of reliable flame, flashback, and blowoff can be observed. Fig. 6 shows the stability diagrams of the biomass derived syngas combustion with different oxygen enriched air oxidizers. Above the solid lines are the boundaries of blowoff, and below the dashed lines are the boundaries of flashback. Stable flames were achieved between these two lines. For the air combustion, it was observed that stable flame was in the equivalence ratio ranged from 0.4 to 1.6. Blowoff velocity increased with increasing equivalence ratio. Flashback occurred during equivalence ratio of 0.4-1.2, with gas-air mixture velocity lower than 1.2 m/s.

It can be seen that changing an oxidizer to oxygen-enriched air improved the flame stability to higher blowoff limit and wider range of equivalence ratio. Blowoff velocity moved up with the increment of oxygen concentration. At stoichiometric conditions, the blowoff velocity increased from 8.5 to 14, 19, and 30 m/s when changing from air to oxygen enriched air with 30, 40, and 50% oxygen content, respectively. Flashback regions were extended to lean mixture and flashback velocities also increased with increasing oxygen enrichment. The maximum flashback velocity was 1.2 m/s for air, and 4.6 m/s for 50% enrichment. These extensions of each region were due to the increase in laminar flame speed in higher oxygen content oxidizer. The higher blowoff velocity means that higher flow rate, hence higher

power can be achieved in industrial heating process, which was an advantage in practical operation. However, extra cares should be taken when using low flow rates in a high oxygen content oxidizer.



Fig. 6. Flame stability diagram of biomass derived syngas combustion with (a) air (b) 30% oxygen content (c) 40%

oxygen content (d) 50% oxygen content.

### 4. Conclusion

Characterization of biomass derived syngas combustion in terms of laminar flame speed and flame stability was undertaken for different levels of oxygen content in air. The laminar flame speed was found to vary with equivalence ratio and type of oxidizer. Maximum flame speed from air combustion was 64 cm/s at equivalence ratio of around 1.1. At the stoichiometric ratio, the use of 30, 40, and 50% oxygen in enriched air increased the laminar flame speed by approximately 5, 26, and 51%. This was because the reduction in nitrogen dilution increased the burning temperature and the reaction rate. Increasing oxygen content resulted in wider flame stability region, allowing for a wider range of equivalence ratios and higher reactant velocities. The blowoff velocity increased, and more power can be achieved. Moreover, the increase in oxygen concentration also provided higher flame temperature. For future works, applications of oxygen enriched air and biomass fuel gas will be introduced to and tested with an industrial ceramic burner.

## Acknowledgements

The authors wish to acknowledge the supports from Thailand Research Fund (RSA5680011), the Energy Policy and Planning Office, Ministry of Energy, and Chiang Mai University.

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