Experimental Study on the Emission Performance of Lean Premixed Bunsen Flame with Piloted Rich Premixed Flame

Yongzhang Cui, Lili Zhang*, Chang Yu, Pengfei Yin, Yiming Liu

School of Thermal Engineering, Shandong Jianzhu University, Jinan 250101, China
*Email: cyz@sdjzu.edu.cn

Abstract. Lean premixed flame has lower nitrogen oxide emission for lower flame temperature. Whereas its poor flame stability, an annual rich pilot premixed flame was used to enhance flame stability and reduce emissions with lower ratio of pilot flame and main lean flame load. With the increasing of pilot flame load, air coefficient of main flame increases gradually. Increasing the main flame load, the air coefficient of stable main flame decreases, while the nitrogen oxide and carbon monoxide changes little. Under all main flame load, nitrogen oxide and carbon monoxide decrease sharply at first and then gets slowly. The ultralow Nitrogen Oxide of 18 mg/m³ and carbon monoxide of 50 mg/m³ can be reached, under the condition of main flame air coefficient from 1.3 to 1.5.

1. Introduction

As the emission standards for natural gas appliance become more and more strict, it is very important to develop an effective and environmentally friendly combustion technology for industrial and domestic appliance. Various types of burners [1,2], metal fibber burner and lean burner, have been studied and developed. Compared with the premixed flame, partially premixed flame produces relatively high nitrogen oxide emissions for higher residence time in the high-flame temperature zone. Lean premixed flames have shorter flame lengths and less nitrogen oxide emissions at lower flame temperature.

There are stabilization problems of lean premixed flames produced in burners such as quenching, flashback and blow off. For larger operating range, pilot flames were usually used to stabilize lean premixed flame [3-5]. It is expected that the pilot flame can affect the main flame through affecting the turbulent flow (resulting in the flame wrinkling and stretching), and through shielding the main flame from cold ambient air entrainment [6,7]. Pilot flames with equivalence ratio close to unity can support the main flame with not only hot gas but also radicals and fuels that are not completely oxidized, e.g., carbon monoxide. Furthermore, the pilot flame may improve the local equivalence ratio of the main flame [8].

This study aims at examining lean premixed Bunsen flame with pilot annual rich premixed flame. The effects of pilot flame load and main flame load and coefficient on emission of carbon monoxide and nitric oxide were investigated experimentally.

2. Experimental Setup and method

2.1. Burner configuration and operating conditions

As shown in figure 1, Test burner includes main lean premixed flame port and pilot rich premixed flame ports, with material of stainless steel. An axisymmetric Bunsen-type burner with a nozzle inner
diameter of 16.7 mm was utilized to produce main lean premixed flames. Air coefficients of main lean premixed flames varies from 0.9 to 1.6. To ensure that parabolic velocity profile was fully developed in the tube up to the maximum velocity tested in the present experiment, the length of the tube was set to 470 mm, satisfying the fully developed condition of ratio of tube length and tube inner diameter > 0.06Re. From figure 1(b), main flames were winkled with a broaden flame sheet.

An annual rich premixed flame was anchored to the rim of the burner and introduced as a pilot flame. Air coefficient of pilot flame are from 0.5 to 0.9. Pilot rich premixed flame can supply heat and plenty radicals to enlarge air coefficient and flame speed within interaction zone [8], which can enhance the main flame stability. However, higher pilot flame load could enhance interaction zone area, bringing higher CO concentration. Thus, optimum load should be controlled under experiments.

![Image 1](image1.png)

**Figure 1.** Lean premixed flame with piloted rich premixed flame.

2.2. **Experimental setup**

The experimental setup was illustrated in figure 2. Pure methane was supplied from high pressure gas container and its pressure was controlled by a regulator. The air is supplied through a compressor. Lean and rich mixtures were mixed into two tanks to assure a complete mixing. The flowrates for each gas were adjusted using flowmeter and pressure gauges. The calibrated mass flowmeters were used to control the flowrates of the filtered air and fuel. The accuracy for each of the flowmeter was ±0.80% on its reading, and ±0.20% on its full scale.

![Image 2](image2.png)

**Figure 2.** Schematic sketch of a single burner test rig.

The flame photographs were taken using a high-resolution Nikon camera. The flame lengths were measured from the flame photographs using the image processing software. The flame length was defined as the distance between the flame base and flame tip along the centreline of main flame.
An exhaust gas sampling system was employed in the present study. Combustion gases from the post flame zone was sampled using a water-cooled stainless steel probe mounted for the measurement of NOx, O2, CO, and CO2 concentration by OPTIMA 7 gas analyzer. Emission concentrations of NOx and CO were corrected on 3.5 Percent Oxygen.

3. Result and discussion

3.1. Pilot rich premixed flame load
The figure 3 shows the main flame air coefficient under different pilot flame load, on the condition that main lean premixed flame load is 2kW and air coefficient varies from 0.9 to 1.5, pilot rich premixed flame load changed from 0 to 0.2kW and constant air coefficient is 0.6. It can be seen that pilot flame can enhance main flame stability. Without pilot flame, main flame happens blow-off under 0.93 air coefficient and 2.0kW load. With 0.2kW pilot flame load, main flame happens blow-off under 1.51 air coefficient.

![Figure 3. Main flame air coefficient under pilot flame load.](image)

3.2. Main lean premixed flame load
The experiments of main lean premixed flame load various from 1.5 to 4kW and main flame air coefficient various from 0.95 to 1.6 are carried out at constant pilot rich premixed flame load of 0.5kW and air coefficient of 0.65.

3.2.1 Flame stability. Flame stability range is shown in figure 4. It can be seen that pilot flame can enhance main flame stability. Without pilot flame, main flame happens blow-off under 0.93 air coefficient and 2.0kW load. With 0.2kW pilot flame load, main flame happens blow-off under 1.51 air coefficient, so that the main flame stability enhanced greatly by pilot rich premixed flame, but higher main flame load resulting in lower flame stability range.

![Figure 4. Main flame load under main flame air coefficient.](image)
3.2.2 Nitrogen oxide and carbon monoxide. The emission of nitrogen oxide and carbon monoxide with different main flame air coefficient are showed in figure 5 and 6. From figure 5 and 6, nitrogen oxide and carbon monoxide all decreased rapidly and then relaxedly with main flame coefficient, not inversely increased and decreased in rich premixed flame. Within load from 1.5 to 3.0kW, air coefficient from 1.3 to 1.5, nitrogen oxide can be limited under 30mg/m³ and carbon monoxide can be limited under 20mg/m³. But effect of main flame load has an oblivious otherness.

From figure 5, the nitrogen oxide of low main flame load is lower than that of higher main flame load under lower air coefficient, but higher than that of higher main flame load under higher air coefficient. Under lower air coefficient, the higher main flame load makes the flame temperature of main flame higher, resulting in more nitrogen oxide generation. Under higher air coefficient, lean premixed combusted with lower flame temperature and lower nitrogen oxide, attributing to the interaction between lean and rich flame zone for max flame temperature. Higher main flame air coefficient and higher air coefficient within interaction zone result in lower flame temperature.

![Figure 5. Emission of Nitrogen Oxide.](image)

At the same air coefficient in all stability operating range, the higher the main flame load gets, the more the carbon monoxide concentration reaches. The concentration of carbon monoxide changes a lot with the air coefficient increasing from 0.95 to 1.2. While, the concentration of carbon monoxide decreases slowly when the air coefficient larger than 1.2. that is to say carbon monoxide did not effected by pilot rich flame, so carbon monoxide within low air coefficient must be effected by partial combustion of pilot rich flame. Thus, a complete combustion with very low carbon monoxide content can be obtained under a higher lean flame with pilot flame.

![Figure 6. Emission of Carbon Monoxide.](image)

3.2.3 Flame color and height. The figure 7 shows flame imagines under different air coefficient. The flame thickened firstly for higher corrugation by turbulent fluctuation and then thinned for lower
consumption speed and higher mixture flow velocity. Flame colour is deep violet radiation and reddish glow due to excited CH radicals under lower air coefficient, and blue colour under higher air coefficient for lower flame temperature.

Figure 8 shows the relationship between flame height and main flame air coefficient. It can be seen that flame height increases with air coefficient and main flame load under air coefficient from 0.95 to 1.6, and the flame height also increases with main flame load. Flame height can be controlled by turbulent consumption speed and mixture flow velocity. The laminar flame speed and turbulent flame surface density are higher under lower air coefficient, which contributes to a lower flame height. Whereas, the laminar flame speed is lower and main mixture flow velocity is higher under higher air coefficient, resulting in lower flame height.

Figure 7. Flame imagines under different air coefficient.

Figure 8. Flame heights under air coefficient and main flame load.

4. Conclusions
The main findings of the study are: (1) As pilot flame load increasing, flame height increases and flame stability gets stronger. When the ratios of pilot and main flame load various from 5 to 15 percent, the flames can be stabilized under air coefficient from 1.2 to 1.4. (2) As main flame load increasing, heating effect of main flame base heated by pilot flame decreases and flame speed under main flame base decreases, until that the main flame blow-off happens, stabilization range of main flame narrowed. (3) As air coefficient of main flame increasing, Nitrogen Oxide and carbon monoxide decreases fast firstly and then gets slowly. When the main flame air coefficient changed from 1.3 to 1.5, the ultralow Nitrogen Oxide of 18 mg/m³ and carbon monoxide of 50 mg/m³ can be reached.

Reference
[1] Jörn H, Daniel F, Stefan S B, Heinz-Jörg T, Heinz P 2018 Numerical and experimental investigation of pollutant formation and emissions in a full-scale cylindrical heating unit of a condensing gas boiler Apply Energy 229 977
[2] Dongfang Z, Fengguo L, Xueyi Y, Rui Z, Binlong Z, Guilong H 2015 Optimization of a premixed cylindrical burner for low pollutant emission Energy Conversion and Management
[3] Dong H, Aman S, Jay P. G, Robert P. L 2018 Experimental study of CO2 diluted, piloted, turbulent CH4/air premixed flames using high-repetition-rate OH PLIF Combustion and Flame 193 145

[4] Zhi X C, Ivan L, Robert S. B, Nedunchezian S 2020 Prediction of local extinctions in piloted jet flames with inhomogeneous inlets using unstrained flamelets Combustion and Flame 212 415

[5] Ivan A Z, Nikita I G, Sergey G. M 2017 Lean Blowout Limit Prediction in a Combustor with the Pilot Flame Energy Procedia 141 273

[6] Tomás M Lúcio & Edgar C. Fernandes 2016 Effects of CO 2, H 2 O, and Exhaust Gas Recirculation Dilution on Laminar Burning Velocities and Markstein Lengths of Iso-Octane/Air Mixtures Combustion Science and Technology 188 415

[7] Sahu K B,Kundu A, Ganguly R,Datta A 2009 Effects of fuel type and equivalence ratios on the flickering of triple flames, Combustion and Flame 156 484

[8] Pires J M, Fernandes E C 2018 Combined effect of equivalence ratio and velocity gradients on flame stability and emission formation, Energy 222 800