Energy 156 (2018) 144–153

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Experimental investigation on oxygen diluted partially premixed and oxygen enriched supplemental combustion for low emission

Liang Tian, Liansheng Liu*, Runze Duan

School of Energy and Environment, Hebei University of Technology, Tianjin, China

ARTICLE INFO

Article history:
Received 1 November 2017
Received in revised form
6 April 2018
Accepted 4 May 2018
Available online 5 May 2018

Keywords:
Partially premixed combustion
NOx and CO emission
Oxygen diluted air
Oxygen enriched air
Response surface method

ABSTRACT

As one of the main sources of the air pollution, the NOx emission from combustion is difficult to avoid. In this research, a combustion method, named as Oxygen Diluted Partially Premixed and Oxygen Enriched Supplemental Combustion (ODPP/OESC) was proposed to reduce the NOx generation by adjusting the oxygen concentration. The relationships between the operating parameters were deduced. The effects of the ODPP/OESC on the NOx and CO emission were evaluated experimentally. Design of Experiments (DoE) was conducted to obtain the optimal operating parameters through the Response Surface Methodology (RSM). Further statistical analysis indicated that as the dominant operating parameter, the lower oxygen mole fraction of oxygen diluted air (Y_{od}) resulted in lower NOx but higher CO emission. The Y_{od} makes the most contribution to the NOx and CO emission, then the oxygen mole fraction of oxygen enriched air (Y_{oe}) does, and the equivalence ratio of premixed gas (ER_p) does the least. The regression analysis yielded two relationships between the NOx(CO), Y_{od}, Y_{oe}, and ER_p. The optimal operating parameters were obtained by the RSM and verified experimentally. NOx and CO emission were 22.6 mg/m^3 and 362 mg/m^3 under the optimal condition, respectively. So the ODPP/OESC was promising and feasible for the low emission of the CH_4/air combustion and the RSM can be used to control the combustion emissions.

1. Introduction

With development of the green economic, the consumption of natural gas increases rapidly in industrial and civil combustion equipment. Consequently, the NOx emission, which is the main pollution from the natural gas combustion, must be controlled at a low level to prevent harm to the atmosphere and human health. To accord with the strict restriction, the low-NOx combustion technology has been applied [1], and improved to acquire the higher combustion efficiency with low CO emission. As an effective method to inhibit NOx and CO emission, oxygen concentration adjustment had been widely investigated. In this paper, a new method was proposed and the effects of the operating parameters on NOx and CO emissions were tested through a statistical approach.

The oxygen diluted combustion is introduced to the Exhaust Gas Recirculation (EGR) and Moderate or Intense Low-oxygen Dilution (MILD) combustion. Yu et al. [2,3] introduced the EGR combustion into a small scale gas fired boiler. The numerical and experimental results showed that the NOx emission was lower than that under the normal condition. The results of the research on EGR [4–7] indicated that the NOx and PM mass emission decreased with the increase in the EGR rate, but too high of an EGR rate leads to the exorbitant PM mass. About the MILD method, Cavalierea and Joannon [8] provided an overview on the MILD combustion and introduced the mechanisms of the NOx suppression. The researches on the diluted species implied that the mechanisms of the N_2 dilution in reducing the NOx emission was to restrain the prompt-NOx, however, the high diluted level resulted in the high CO emission [9–12]. It can be seen that the oxygen diluted combustion indeed reduces the NOx emission, but accompanied by the increase in the CO or PM emission resulting in the combustion efficiency decreasing.

The oxygen enriched combustion has the advantages in wide extinction range and save of fuel [13,14]. Poirier [15] experimental results indicated that although having the disadvantage in NOx emission, the oxygen enriched combustion can provide high combustion temperature, low CO emission and high combustion efficiency. As the NOx generation was reduced with the oxygen

* Corresponding author.
E-mail address: liuliansheng@hebut.edu.cn (L. Liu).

https://doi.org/10.1016/j.energy.2018.05.033

concentration increasing when the oxygen mole fraction larger than about 60% [16], a lot of pure oxygen had to be supplied into the air to achieve such high oxygen concentration level resulting in the increased cost. Otherwise, lower oxygen enrichment level, such as 20%–30% [17–19], reduced the pure oxygen supply and also increased the combustion efficiency, but the NOx generation increased with the oxygen concentration increasing. To tradeoff the NOx emission and combustion efficiency, introducing the staged combustion and combining the oxygen diluted combustion with the low oxygen enrich level combustion were the effective methods which develop the advantage of oxygen diluted and oxygen enrichment combustion.

The Rich-Burn, Quick-Mix, Lean-Burn (RQL) concept was introduced as a strategy to reduce the NOx in gas turbine engines [20]. The fuel-rich combustion in RQL devices has been used to aid the conversion of fuel-bound nitrogen to N_2 rather than NOx [21]. Its fuel-rich zone not only limited NOx formation, but also increased flame stability. Its fuel-lean zone facilitated the burnout of CO. Lewis et al. [22] introduced the RQL into a duct combustor and accessed the NOx and CO emissions experimentally. In the practical design, a mass ratio was suggested to best control the NOx emission, and the other means were utilized to mitigate the CO emission for the fuel lean combustion. Actually, the high mass ratio brought the large quantity of oxygen mixed with the burned gas, which promoted the probability of the oxygen impacting with the unburned species, but the excessive N_2 supplying to the combustor subsequently. The excessive heated N_2 drove turbine to do work in the gas turbine, but it took a lot of heat away from the combustor through the exhaust gas in boiler or furnace. So the oxygen enriched air supplying to the fuel lean combustion not only promoted the unburned species reacting with the oxygen, but also reduced the heat loss from the exhaust gas. Consequently, the fuel rich and oxygen diluted combustion followed by the fuel lean and oxygen enriched combustion proposed in this paper to solve the problem of the tradeoff of the NOx and CO emission.

As the combustion process accompanied by the comprehensive chemical reactions, it was hard to predict the emissions. Although the numerical method simulated the whole combustion process, it relied on the flow model, combustion model and reaction mechanisms; especially it took a lot of time to calculate. The easy and effective method was to establish the prediction model by the regression analysis. It could provide the relationships between the results, such as emission, combustion efficiency and thermal efficiency, and the operation parameters, such as equivalence ratio, oxygen concentration and injection configuration [22,23]. However, the regression model obtained from the design of experiments (DoE) had a strong relationship with the combustion method. That meant the different organization of the combustion resulted in the different regression model. So it was necessary to establish an adaptive regression model to predict the NOx and CO emission for the application of the new combustion method. Meanwhile, the ANOVA and Response Surface Method based on the DoE provided the influence degree of each operation parameter and the optimal operation parameters respectively [22,24].

The present research focused on the effects of the oxygen concentration adjustment on the NOx and CO emission in a CH_4/air partially premixed combustion. For this purport, the air supplied to the combustion was divided into two streams. One steam with the oxygen mole fraction lower than 21% was named as Oxygen Diluted Air (ODA), and the other with the oxygen mole fraction higher than 21% was named as Oxygen Enriched Air (OEA). The ODA was mixed with CH_4 to form a rich premixed flame for reducing the NOx generation, while the OEA was supplied to form a lean diffusion flame for reducing the CO generation. This combustion method was named as the Oxygen Diluted Partially Premixed and Oxygen Enriched Supplemental Combustion (ODPP/OESC) which organized the fuel rich and oxygen diluted combustion followed by the fuel lean and oxygen enriched combustion with the total equivalence ratio near to 1.0. The air can be separated to ODA and OEA by an air separator, and all of them will be supplied to the combustion without waste. If ODPP/OESC reduces the NOx emission down to the limitation, there is no need of aftertratment devices and the cost of the air separator is lower than the aftertratment device. Besides, with the development of the membrane separation, the cost of the air pretreatment became lower. Consequently, the application prospect of ODPP/OESC can be expected.

In this paper, the emissions of ODPP/OESC were firstly tested experimentally. Subsequently, the DoE was conducted for further regression analysis to obtain the relationships between the emission and operating parameters, and then the influence degrees of the operation parameters on NOx and CO emission were evaluate by and ANOVA. Finally, the optimal operating parameters for both NOx and CO emissions were obtained by RSM and validated experimentally. This study aim to verify the feasibility of the ODPP/OESC in NOx emission reduction and provide the adjustment ranges of the operation parameters for the tradeoff between the NOx and CO emissions.

2. Experimental setup and method

2.1. Experimental setup

In the lab experiments, we mixed the O_2, N_2 and air to obtain the ODA and OEA respectively instead of air separator. The experiments were conducted through the combustion test system, as shown in Fig. 1. Four kinds of gas (air, CH_4, N_2 and O_2) were used and stored in the high pressure tanks. All of the gas was supplied from the tanks to the Mass Flow Controller (MFC) via pressure regulator which reduced the pressure to 0.15 MPa. The O_2 and N_2 were mixed in the Mixer I to simulate the OEA. The air, N_2 and CH_4 were mixed together to form the partially premixed gas in the Mixer II in which the air and N_2 were mixed to simulate the ODA.

The injectors were consisted of a 45-degree and eight spiral channels swirl nozzle at the center for the premixed gas injection and a direct nozzle injection outside of the swirl nozzle for the OEA. The outer lip of the swirl nozzle was 10 mm higher than the swirl-vane for the flame holding, and the outer lip of the direct nozzle was also 10 mm higher than that of the swirl nozzle for a better mixing of the OEA and burned gas. The injector was followed by a rectangular chamber operated at atmosphere pressure with an inner size of 300 mm × 100 mm × 100 mm (H × L × W). The

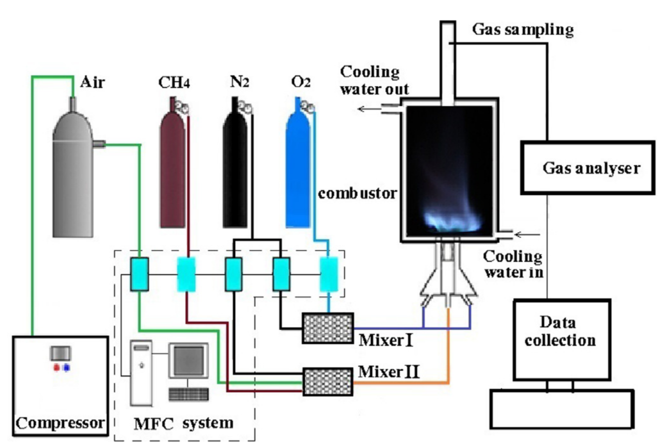

Fig. 1. Schematic diagram of experimental apparatus.