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Experimental and numerical study of MILD combustion in a bench-scale natural gas partial oxidation gasifier

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HIGHLIGHTS

- MILD combustion is studied in a natural gas partial oxidation gasifier.
- MILD combustion is achieved in an inverse diffusion configuration.
- MILD combustion is established due to the dilution of oxygen before ignition.
- A barrier stream between oxygen and syngas is necessary for realizing MILD combustion in gasifiers.

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ABSTRACT

Moderate and intense low-oxygen dilution (MILD) is a promising combustion technology for the non-catalytic partial oxidation (POX) process of natural gas. This study investigates the establishment of MILD combustion in a bench-scale non-catalytic partial oxidation gasifier. Experiments under both inverse diffusion configuration (IDC) and normal diffusion configuration (NDC) are carried out using methane and pure oxygen as reactants. The flame appearances and temperature profiles are recorded using an imaging system and thermocouples, respectively. Results show that no visible flame can be observed in IDC case while a flame can be observed near the burner exit in NDC case. The effects of jet velocity and O_2/CH_4 ratio on the IDC flame are further studied. Numerical simulations of the experimental cases are also performed and the results agree well with the experimental results. It is found that the recirculation rate inside the furnace is sufficiently high to fully dilute the reactants. Combustion regime classification on grid scale shows that MILD combustion is established in the gasifier in IDC case. Analysis on the flame structure in IDC case shows that dilution of oxygen before ignition is the reason for the establishment of MILD combustion and the barrier effect of fuel between oxygen and hot syngas in the necessary condition for this process.

1. Introduction

Moderate and intense low-oxygen dilution (MILD) combustion is one of the most promising combustion technologies due to its high combustion efficiency, low pollutant emissions and good stability. In combustion chambers, MILD combustion is usually achieved by intense burnt gas recirculation which dilutes the reactants to a low-oxygen level and meanwhile heats the reactants to a temperature above their self-ignition temperature. Due to the good mixing condition and low oxygen level, MILD combustion has some features different from conventional combustion, such as no visible flame front, uniform temperature distribution, large volume of reaction zone, low pollutant emissions, low noise and etc. These advantages have attracted much focus on such kind of new combustion technologies. Some similar concepts based on preheating and dilution have also been proposed and studied, such as: Flameless Oxidation (FLOX) [1], High Temperature Air Combustion (HiTAC) [2], Colorless Distributed Combustion [3,4]. These technologies are not exactly identical. According to the definition given by Antonio Cavaliere et al. [5], a combustion process in a perfect stirred reactor (PSR) can be classified as MILD combustion when the inlet temperature is higher than the self-ignition temperature

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Abbreviations: MILD, moderate and intense low-oxygen dilution; POX, partial oxidation; IDC, inverse diffusion configuration; NDC, normal diffusion configuration; FLOX, flameless oxidation; HiTAC, high temperature air combustion; PSR, perfect stirred reactor; OMB, opposed multi-burner; EDC, eddy dissipation concept; ISAT, in situ adaptive tabulation.

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of the mixture and meanwhile the temperature increase is lower than the self-ignition temperature.

MILD combustion has been achieved and studied in various furnace systems, including gaseous fuel furnaces [6–8], liquid fuel furnaces [9,10], pulverized coal furnaces [11] and gas turbines [12]. Many early studies focused on MILD combustion with preheated high temperature air [13,14]. While some recent studies showed that preheating is not necessary for the establishment of MILD combustion, MILD combustion without preheated high temperature air had been achieved [8]. Flame characteristics, scalar fields and NO_x formation in MILD combustion had been investigated under the condition of different fuel types [7,15], mixing patterns [6] and burner configurations [8,15,16]. To gain a fundamental understanding of the MILD combustion, turbulent jet flames in diluted hot coflow were proposed [17]. High temperature and low oxygen coflows were used to simulate the recirculating hot gases in combustion chambers. Such jet flames were extensively studied through both experimental [17,18] and numerical methods [19–22]. Results of these flames were widely used for the assessment of combustion models for MILD combustion.

MILD combustion had also been achieved in oxy-combustion systems and this technology was named as "MILD oxy-combustion". Narayanan Krishnamurthy et al. [23] found that MILD mode can be established with high velocity oxygen in an asymmetric burner system and little soot and acetylene formation were found in MILD mode. Li et al. [24] studied MILD oxy-combustion in a laboratory-scale furnace and also found that MILD combustion can be established even with pure oxygen. MILD combustion under enhanced oxygen concentration was also achieved in a regenerative furnace [25], low NO_x emission and higher efficiency were observed under MILD combustion mode.

MILD combustion also seems to be a promising technology for natural gas non-catalytic partial oxidation (POX) process. The POX process is an important technology used in the production of syngas ($CO + H_2$) [26]. In a typical POX gasifier, fuel and pure oxygen are usually injected into the furnace through a coaxial burner mounted at top of the furnace. A combustion zone is formed in the upper section of the furnace and a reforming zone is formed in the downstream due to the insufficient amount of oxygen [27]. In the combustion section, the peak flame temperature can be above 3000 K due to the use of pure oxygen as oxidizer [28,29]. Such high temperature flame causes serious problems in POX gasifiers, such as burner ablation, flame stability and soot formation [30,31]. These are the main problems restricting the long period operation of commercial POX gasifiers. However, these problems do not exist in MILD combustion systems. If the partial oxidation process can be combined with MILD combustion technology, the above problems may be solved due to the advantages of MILD combustion. Several researches [31–34] were conducted to study the combustion process in POX gasifiers, but few work focused on the realizing of MILD combustion in POX gasifiers. Colorless Distributed Combustion is achieved for POX process using preheated air as oxidant [35,36], but the establishment of MILD combustion in POX gasifiers using pure oxygen as oxidant has not been reported. The achievement of MILD combustion in gasifiers is more difficult than that in combustion chambers because the oxygen can easily react with the recirculating syngas. A recent numerical study [37] by the present author had shown that inverse diffusion configuration with high jet velocity can lead to MILD combustion in high temperature syngas coflow. While this conclusion was totally drawn by numerical analysis, no experimental validation has been conducted.

In the present work, an experimental study was conducted on a bench-scale non-catalytic partial oxidation gasifier to investigate the way to achieve MILD combustion in POX gasifiers. Numerical modeling of the gasifier was also performed to provide a deep understanding of the combustion process. Combustion regime of the process in gasifier was analyzed and mechanism of the establishment of MILD combustion in POX gasifiers was discussed.

2. Experimental setup

The diagram of the bench-scale non-catalytic partial oxidation gasifier is shown in Fig. 1. This POX gasifier is modified based on an opposed multi-burner (OMB) coal gasifier developed in East China University of Science and Technology [38]. A coaxial two-channel burner is mounted on the top of the furnace, and four coaxial two-channel burners are side-mounted oppositely in a horizontal plane with the angle of 90° between each other. The top burner is used for the injection of oxygen and fuel during the experiment. While the four opposite burners are only used to preheat the chamber, and will be shut off when the chamber is preheated to ~1373 K. It takes about 6 h to warm up from the cold state. The inner diameter of the refractory wall in the gasifier is $D = 300$ mm. The total height of the chamber is 1500 mm.

For temperature measurement, several B type thermocouples are mounted on the side wall of the furnace, as shown in Fig. 1. The four thermocouples T1, T2, T3 and T4 are located 150 mm, 350 mm, 450 mm and 550 mm downstream from the burner exit plane, respectively. The four thermocouples can move inside the furnace during the experiment to measure the temperature at different radial positions.

A side imaging system used for the visualization of the flame is installed axially close to the refractory wall. This system consists of a CESYCO Φ19 mm lateral high temperature endoscope with an optical axis-to-target angle of 90° and a 65° view field, an industrial high speed camera, a frame grabber, a graphics workstation and associated image processing software. The endoscope can move axially to capture different parts of the flame.

The detailed structure of the top burner is also shown in Fig. 1. The central channel has an inner diameter of $d = 3$ mm. The outer channel has an inner diameter of 6 mm and an outer diameter of 7 mm. The burner can be operated in either inverse diffusion configuration (IDC) or normal diffusion configuration (NDC) by adjusting the relative position of fuel and oxygen. A schematic diagram of the two configurations is shown in Fig. 2. In IDC, the oxygen flows through the inner channel and fuel flows through the outer channel. In NDC, the positions of fuel and oxygen are opposite. The exit plane of the top nozzle was fixed at 57 mm downstream of the peak of the dome to provide a reference for the imaging system.

The fuel used in the experiment was methane with a purity of 99.9%. Both fuel and oxygen were not preheated and were injected at an ambient temperature of 288 K. The operating pressure was 1 atm.

3. Numerical models

In this paper, numerical modeling of the combustion process was performed using the commercial CFD software ANSYS Fluent 12.1. The steady Favre-averaged Navier-Stokes equations were solved in finite volume scheme. The realizable k-ε model with enhanced wall function was used for the turbulent flow modeling. Since the characteristic chemical time scale is comparable to the flow time scale in MILD combustion [39], the turbulence–chemistry interaction should be treated with finite rate approaches. So the Eddy dissipation Concept (EDC) model combined with a modified GRI 3.0 mechanism [40] which eliminated all the nitrogen-related species and reactions was used for the modeling of turbulence-chemistry interaction. The EDC model assumes that reaction occurs in fine scale turbulent structures. The evolution of species concentrations is computed by integrating the chemistry within these fine scales. The EDC model has been widely used in