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Experimental analysis of oxygen-methane combustion inside a gas turbine reactor under various operating conditions

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ABSTRACT

The oxygen-methane diffusion flame taking place in a gas turbine reactor was investigated experimentally with emphasis on flame stability. The oxidizer is a mixture of O_2 and CO_2 and the oxy-combustion process was studied at different equivalence ratios ranging from $\Phi = 0.5$ to 1.0 and different O_2/CO_2 mixture composition (100/0, 80/20, 60/40, 50/50, 40/60, 30/70 and 25/75). The flame blowout condition was achieved through the reduction of oxygen percentage in the oxidizer mixture. Measurements were obtained for the flue gas temperature and concentration as well as flame visualization. It was found that the flame is very stable at the equivalence ratio of 0.65. At this ratio, the flame blows out at an O_2/CO_2 blending ratio of 22/78 for the case of fuel flow rate of 6 L/min and at a blending ratio of 21/79 for the case of fuel flow rate of 9 L/min. Attempts for operating the burner with less than 21% O_2 were unsuccessful at all ranges of the operating parameters and resulted in unstable operation and blowout. Moreover, it was observed that the stabilization behavior did not change significantly with the variation of the fuel volume flow rate. It was also found that both flame and flue gas temperatures are reduced with the increase of the equivalence ratio.

1. Introduction

The use of fossil fuels in many power plants presents the largest threat for global warming as they are the main sources of CO_2 emissions. CO_2 capture from these sources offers a feasible solution for the endangered climate change with reduced cost. As forecasted by the IEA (international energy agency), coal will continue to be used as an energy source for electric power generation up to 2020 and beyond [1]. In addition, cycle integration combined with energy storage is one very important option to utilize low grade energy and reduce CO_2 emissions for lower environmental impact. Many approaches including CCS (carbon capture and sequestration) have so far been presented, evaluated and reviewed by researchers in the past [2]. In addition, energy storage method has already been a good option in various areas [3–8] for reducing energy consumption and the environmental impact resulting from CO_2 emissions. Among the proposed methods [9], oxy-fuel combustion capture presents a promising technology that can be incorporated without adverse complication to the existing power plants. In this process, a mixture of oxygen and fuel is burned along with a percentage of recycled flue gases, and the end products of which are mostly CO_2 and H_2O. H_2O can be removed easily by condensation leaving CO_2 for capture, thus eliminates the difficulty of separating nitrogen as in case of air-fuel combustion. On the other hand, Oxy-fuel combustion results in high flame temperatures and part of the exhaust gases are recycled to compensate for the absence of nitrogen.

The gas turbine processes using oxy-fuel combustion technology have several combined cycle concepts such as O_2/CO_2 [10–12], COOLENERG (CO_2 Loop for Energy and Nature, Enhanced by Refrigeration and Gas-turbines) [13], COOPERATE (CO_2 Prevented Emissions Recuperative Advanced Turbines Energy) [14] and MATIANT (contraction of the names of the two designers: MATHIEU and IANTOVSKI) [15] cycles. These cycles are called SCOF-CC (semi-closed oxy-fuel combustion cycles) and are likely to require modified design of the turbo-machineries along with high temperature turbines. The application of the oxy-fuel combustion technology into gas turbine combustors enables the same post-combustion capture techniques to be utilized as those of oxy-fuel process [16]. Much research in the past has been focused on the thermodynamic analysis of the system with regard to oxy-fuel combustion in gas turbine cycles. In realistic combustion

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systems, swirl-stabilized flames are used to a large extent as they are able to produce high combustor power per unit volume. These types of flames exhibit efficient ignition and good flame stability under different operating conditions [17–20].

Jericha and Gottlich [21] demonstrated a burner and combustor arrangement where oxygen, fuel, and steam were supplied through different inlets. In their experiments, steam was passed through an outer swirler inlet so as to form a swirling flow motion in order to cloak the flames and to reduce the flue gas temperature. This combustor arrangement generates high flame temperature in the vicinity of the reaction zones that increases the dissociation of H_2O and CO_2. Consequently the composition of the flue gas is affected due to the increase of un-consumed oxygen in the flue gas. It is advantageous to premix the oxygen and CO_2 (or steam) before introducing the mixture into the combustor so that the un-consumed oxygen is utilized efficiently in the combustion process. Different levels of premixing and different mixing patterns of oxygen and CO_2 need investigations. The thermodynamic analysis of the flue gas in the post flame zone gives the same result if the inlet boundary conditions such as temperature, pressure and mass flow rates of gas streams are kept unchanged [21]. However, the combustor configuration and the inlet conditions of the mixture govern the flame dynamics and reaction zone structures.

In order to sustain a stable oxy-fuel combustion flame in a gas turbine combustor, certain minimum amount of oxygen has to be maintained in the oxidizer. This helps in generating sufficient high temperature inside the reaction zone allowing the chain reactions to proceed. Flame instability and poor burnout were encountered when O_2/CO_2 are premixed and supplied as oxidizer [22]. In their experiments, Heil et al. [23] demonstrated that poor burnout and unstable lifted flames appear when the oxygen mole fraction in the O_2/CO_2 stream was set to 21%. However, full burnout and stable flames were obtained when the oxygen volume fraction was increased to 27% and 34% respectively. Moreover, modifications to the burner inlet section should be carried out in order to allow for exhaust gas recirculation. On the other hand, the use of high percentage of oxygen in the oxidizer mixture increases the temperature of the combustion products. In addition, the amount of oxygen in the exhaust gases may also be increased at high operating temperatures due to the dissociation reactions. Therefore, in order to have a stable and efficient combustion, an optimal O_2/CO_2 ratio in the oxidizer stream should be maintained [24]. The results of Liu et al. [24] showed that the primary oxidizer which was supplied at a temperature of 520 K in the upstream should have a minimum amount of oxygen level of 24%. The excess CO_2 was supplied downstream of the reaction zone through the holes in the liner. This should result in a reduction in the combustion product temperature. The stability of swirl stabilized O_2/CH_4 flames was investigated by Peter Kutne et al. [16]. They concluded that the O_2/CO_2 ratio can be optimized to produce stable combustion. Nemitallah and Habib [25] studied the effect of O_2/CO_2 ratio in the oxidize mixture on the stability of a diffusion flame in a gas turbine combustor. Their results showed that the stability of the flame is greatly affected when the oxygen percent is reduced below 30%.

Recently, the idea of integrating ceramic membranes (for oxygen separation) with gas turbine combustors attracted many researchers. This idea is supported by the attractive performance of membranes in terms of energy efficiency [26]. Gunasekaran et al. [27] performed a detailed optimization study on the design and operating parameters of a membrane-based oxy-combustion power plant. The optimization resulted in considerable improvements in the efficiency and emissions of the power plant. Mancini and Mitsos [28,29] performed a detailed optimization study of a membrane-based oxy-combustion power plant. They came up with a design that can replace the conventional gas turbine power plant. Their new design is capable of delivering power in the range of 300–500 MWe, based on the cycle first law efficiency. Kotowicz and Michalski [30] conducted an efficiency analysis of a supercritical power plant fueled by hard coal utilizing high temperature membranes for air separation. The results showed significant improvement in the net efficiency of the analyzed supercritical power plant. Nemitallah et al. [31] presented an optimized monolith structure design of an ion transport membrane reactor for the replacement of conventional gas turbine combustor in the power range of 5–8 MWe, based on the cycle first law efficiency. Very recently, Habib and Nemitalah [32] came up with a design of an ion transport membrane reactor for the replacement of conventional fire tube boiler based on three-dimensional numerical simulations. The resultant reactor design is capable of replacing fire tube boilers in the power range up to 8 MWe.

The use of premixed flames has found great interest in the last few decades in order to control the associated emissions of high temperature diffusion flames. However, the stability of such flames is much affected as compared to diffusion flames [33,34]. The effect of premixed swirl on stabilizing syngas and methane flames was investigated by William et al. [35] using two different oxidizers of air and $O_2/CO_2/N_2$. They presented simple flame images in addition to exhaust gas emissions for different operating conditions. Their results predict low nitrogen oxide (NO_x) and high carbon monoxide (CO) concentrations thereby suggesting stoichiometric operation at 20–24% O_2 which is considered ideal amount for low emissions. The length of CH_4/O_2 diffusion flames for free and confined configurations of a jet burner were investigated by Sautet et al. [36]. Five different flames were studied by varying the fuel jet Reynolds number from 8362 to 16,300 out of which two were buoyancy controlled. The results indicated that the flame lengths were much shorter than flames resulting from air combustion. Thermo-acoustic flame instabilities were reported in the work by Ditaranto and Hals [37] who concluded that increment of O_2 content in the oxidizer causes these instabilities. In their numerical and experimental investigations on the chemical effects of CO_2, Liu et al. [38] indicated that CO_2 properties are not enough to explain the reduction of flame speed in oxy-fuel combustion. Experiments of O_2/CO_2 mixture combustion on a 100 kW test unit with the incorporation of flue gas recycling unit were performed by Anderson et al. [39]. Their experiments comprised of a reference test with air and two O_2/CO_2 test cases (OF-21 at vol.% O_2/CO_2: 21/79 and OF-27 at vol.% O_2/CO_2: 27/73). In their results, the delay in the fuel burnout in case of OF-21 compared to air-fuel case was attributed to the reduced temperature levels. On the other hand the OF-27 case exhibited similar combustion characteristics compared to the reference conditions in terms of in-flame temperature and gas concentration levels. However, radiation intensity of the flame was increased significantly.

In the present study, experimental investigations on an atmospheric diffusion oxy-fuel combustion flame in a gas turbine model combustor are presented. The combustor is fueled with CH_4 and a mixture of CO_2 and O_2 as oxidizer. Different operating parameters are considered in this investigation including equivalence ratio (0.5–1), blending ratio of O_2/CO_2 in the oxidizer mixture, and fuel volume flow rate. The study aims to check the stability of the oxy-fuel combustion diffusion flame and the minimum percentages of O_2 in the oxidizer mixture required to get a stable oxy-fuel flame without a turn-off. Flame and exhaust gas temperatures are measured at different operating conditions together with visualization of the flame.