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Numerical study of oxy-fuel MILD (moderate or intense low-oxygen dilution combustion) combustion for CH_4–H_2 fuel

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This paper demonstrates a numerical study on the combination of Oxy-Fuel and MILD (moderate or intense low-oxygen dilution combustion) combustions, i.e. OXY-MILD. The N_2 of a hot oxidizer was replaced with CO_2 and H_2O in a MILD combustion test case. The study was conducted using a CFD analysis, a zero-dimensional well-stirred reactor analysis, and a reactors network analysis. In the CFD analysis, RANS equations with modified $k-\varepsilon$ equations were solved for a 2D-axisymmetric computational domain. Results showed a decrease in temperature gradient, reaction rate, and Damköhler number under the OXY-MILD condition in comparison with the MILD one. It seems the higher the oxygen level in the preheated oxidizer, the more effective the removal of N_2 from the hot oxidizer was on the uniformity and extending of the reaction zone. Under OXY-MILD condition, an increment of inlet oxygen level decreased concentrations of CO, NO, CH_2O, and HCO and increased temperature in the reaction zone. Furthermore, the effect of fuel hydrogen content on the reaction zone was investigated. A reduction of fuel hydrogen content led to an increase in both the uniformity of temperature field and the area of the reaction zone, and a decrease in formations of NO and CO for the OXY-MILD combustion.

1. Introduction

The elimination of air pollutant products of combustion processes is an important issue and absolutely vital for the environment. In this framework, focusing on emission standards for regulating the pollutants released by combustion processes is forcing the combustion systems toward more efficient and novel technologies that result in lower fuel consumption and suppression of greenhouse effects. On the other hand, nitrogen oxides are air pollutants whose production can be suppressed by preventing their essential formation conditions in the combustion chamber. The elimination of the NO_x formation could be made by preventing the mixture of nitrogen and oxygen for a high residence time or decreasing the concentrations of oxygen and nitrogen in the reaction zone. In this regard two technologies of Oxy-fuel and highly preheated diluted combustions could be considered as the solution.

Oxygen as pure oxidizer or additive has been mentioned in many combustion process so far. For example Fehling et al. [1] reported the products of combustion with oxygen and O_2/N_2 at high temperature in 1948. Harris et al. [2], in 1976, investigated the combustion of methane with oxygen in a jet-mixing burner. They measured the noise levels, combustion intensities, and species concentrations over a range of equivalence ratio. Abraham et al. [3,4] in 1982 reported using O_2 as oxidizer of coal combustion to provide a CO_2-rich flue gas for enhanced oil recovery. The idea of replacing some or all of the air with oxygen as an oxidant for the combustion chamber was introduced by Oxy-Fuel technology. The Oxy-Fuel combustion process was announced as an example of novel combustion technologies. This technology is an option for CCS (carbon capture and storage), and accompanying by internal flue gas recirculation exhibits superior combustion characteristic in terms of high energy efficiency, uniform heat flux distributions, and low NO_x emissions [5]. However, there are some challenges such as penalty efficiency due to costs of separating oxygen from the air or some other shortcomings [3] in the original Oxy-Fuel combustion strategy like flame instability and locally high temperature gradients [6]. For example, an investigation of Nemitallah et al. [7] on an atmospheric diffusion oxy-combustion flame in a gas turbine model combustor with CH_4 for fuel and a mixture of CO_2 and O_2 as oxidizer showed that the flame was extinct for conditions of less than 21% oxygen in the oxidizer mixture.

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MILD (moderate or intense low-oxygen dilution combustion) combustion is another option to improve the environmental friendly standards of combustion systems with regard to pollutants. MILD (moderate or intense low-oxygen dilution combustion) [8] is combustion of a fuel-oxidizer mixture under high diluted and preheated conditions, in such a way that the mixture's initial temperature is higher than its auto-ignition temperature and the temperature increase is lower than the preheated temperature. This combustion regime has been studied by many researchers. Following are just a few to provide a broad overview of this new technology. Advantageous of HiTAC (high temperature air combustion) in energy saving and pollutant reduction in an industrial furnace was discussed by Hasegawa et al., in 1997 [9]. Niioka has introduced the fundamentals and applications of combustion under highly diluted and preheated conditions in 1999 [10]. He released results of two projects conducted for six years in Japan starting from 1993 to clarify the phenomena in combustors equipped with regenerative burners. Highly improvement in the thermal conversion efficiency as large as 53% in average, a homogeneous distributed heat release in furnaces, and a drastic reduction of NOx were mentioned in this report. In 2005 he investigated the development of combustors under new combustion conditions [11]. He predicted HiCOT (high-temperature air combustion technology) would bring about remarkable achievements in pulverized coal boilers, incinerators, and steam reformers, in addition to developed industrial furnaces. The science and technology of combustion under HiTAC condition was reviewed by Katsuki in 1997 [12]. A low temperature oscillation in the reaction zone was an important feature shown in this report. Flame characteristics and challenges with this combustion technology and effect of fuel property on combustion structure were studied by Gupta et al., in 1997 [13] and 2000 [14]. These reports mentioned an invisible and colorless oxidation of fuel could be achieved in a HiTAC furnace. NO_x formation under HiTAC was investigated separately by Guo et al., in 1998 [15] and Fuse et al., in 2002 [16]. Focusing on the competitive effects of high-temperature air and air with a low concentration of oxygen on NOx formation, they concluded that the combination of both improves the combustion efficiency and also suppresses NOx emission in the combustion process. Combustion characteristics of low calorific value gases under MILD condition were investigated by Ito et al., in 2002 [17]. Increase in the flame volume and thermal field uniformity with high temperature combustion air were mentioned in their report. Flame characteristics of a cross flow jet emerging in a highly preheated and diluted air stream were investigated by Mortburg in 2007 [18]. They reported a flame volume enhancement and flame fluctuations reduction under HiTAC due to prolong mixing in the combustion zone. A laboratory-scale furnace under MILD condition was investigated by Cavigiolo in 2003 [19]. In their work, operating parameters maps were obtained to achieve stable MILD combustion with methane and ethane as fuels. Christo et al. [20] studied different models for numerical simulation of MILD combustion in 2005. Entrainment of burned gas to inlet flow stream was investigated by Abtahizadeh [21] in 2012. They clarified the role of chemical and diffusion effects in autoignition behavior of MILD combustion. MILD combustion characteristics for syngas were the focus of Huang et al. [22] in 2014. They identified that air preheating resulted in higher NO_x but lower CO emissions. MILD combustion for premixed flames were aimed to study by Li et al. [23] in 2014. In their work the highest values of both furnace temperature and NO_x emission were reported in the partially premixed case, while the lowest values were found in the fully premixed pattern.

As a whole it can be concluded from the above reports that the well-known new technology of MILD combustion is broadly similar to HiTAC (high temperature air combustion) [8,11,12], HiCOT (high temperature combustion technology) [6,9], and Flameless Combustion [24]. The interesting characteristics of this new combustion regime are lower emission production and fuel consumption [7,13,14], a larger reaction zone [15,16], more uniform and lower fluctuations in the temperature field [10,22], kinetic-controlled low Damköhler number combustion [25], more stressed importance of molecular diffusion [26], and lower noise [22] with respect to the “traditional” combustion process.

The general benefits of MILD and Oxy-Fuel combustion technologies have stimulated the present authors to think that the advantages of these different combustion processes could be coalesced into a more efficient and cleaner combustion process. The Oxy-Fuel and MILD combustion technologies may be combined by replacing high temperature preheated air in the MILD combustion regime with high temperature preheated oxygen. In other words, the author's idea is to study MILD combustion while nitrogen is deleted from the preheated oxidizer inlet. This idea has been the subject of only a few works until now. MILD Oxy-Fuel combustion for a counter flow diffusion flame of hydrogen-enriched biogas was studied numerically by Chen et al. [27] in 2011. They discussed the feasibility of utilizing biogases under MILD Oxy-Fuel combustion. In 2011 PengFei et al. [28] concluded that the problems of Oxy-Fuel technology could be resolved by combing it with MILD technology and introduced an Oxy-Fuel combustion system with zero emission combustion. The dimensions of a CH_4-Jet Flame in Hot O_2/CO_2 Co-flow (JHC) were investigated numerically by Mei et al. [29] in 2012. They found that the volume of the JHC reaction zone increases with a decrease in preheated oxidizer oxygen concentration or velocity or an increase in its temperature. In another report, MILD oxy-combustion in an inner recirculation laboratory-scale furnace was investigated experimentally and numerically for NG (natural gas), LPG (liquefied petroleum gas), and C_2H_4 (ethylene) by Pengfei et al. [30] in 2013. They reported that MILD combustion occurs for the three fuels even when using pure oxygen as an oxidant. Dynamic Behaviors in Methane MILD and Oxy-Fuel Combustion were studied in a perfectly stirred flow reactor at atmospheric pressure by Sabia et al. [31] in 2015. The effect of CO_2 on oxidation routes was focused on and a complex dynamic behavior in terms of temperature oscillations was reported. Recently Liu et al. [32] investigated the performance of biogas MILD oxy-fuel combustion moderated by CO_2 or H_2O from the viewpoint of both the first law and the second law of thermodynamics. They recommended that the performance of biogas MILD oxy-fuel combustion under H_2O moderation operation was always worse than its CO_2 counterpart according to entropy generation analysis, safety, and complication of reaction zone. From a practical point of view Scheele et al. [33] reported the using flameless Oxy-Fuel combustion in furnaces in the steel industry with the outstanding results of increased throughput, reduced fuel consumption, and decreased emissions of CO_2 and NO_x.

Although both MILD and Oxy-Fuel technologies were studied separately [1–6,8–21], combination of both technologies is less mentioned with more detail from a flame structure point of view. The aim of this paper was to study Oxy-Fuel condition in an academic well defined MILD burner, i.e. JHC burner. Recently the authors investigated the Christo's report [18] on an unexpected behavior of the CO profile by O_2 concentration reduction in the JHC burner. Results showed that chemical pathways, including methane oxidation to CO, were affected by O_2 concentrations under MILD condition [34]. Due to the close relationship between CO and CO_2 it may be concluded that the CO_2 concentration in the inlet could have a considerable effect on MILD combustion characteristics and its contribution is probably chemical and not only physical as an inert species. Moreover, Glarborg et al. [35] and Picarelli et al. [36] showed the chemical pathways involved in oxidation processes