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Counterflow diffusion flame of hydrogen-enriched biogas under MILD oxy-fuel condition

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ABSTRACT

Biogases are commonly found renewable fuels. Meanwhile they are difficult to be economically utilized because their low calorific values are very small and the induced costs of upgrading are expensive. To overcome the above deficiencies, in this paper we discuss the feasibility to utilize biogases under the MILD oxy-fuel operation recently proposed by the present authors. A popularly used counterflow configuration is adopted as the research prototype in this work. The effects of (1) the preheated temperature of the oxidizer mixtures, (2) the oxygen concentration in the oxidizer flow and (3) the hydrogen concentration in the fuel mixtures on the reaction structure of biogas under the new combustion condition are investigated with the aid of the lattice Boltzmann method (LBM). Through numerical simulation, it is found that the MILD oxy-fuel combustion fueled by biogas can be sustained even with relatively low preheated temperature of the oxidizer, extremely highly diluted oxygen concentration in the oxidizer flow and little hydrogen addition in the fuel mixtures, which provide a solid theoretical basis to develop a novel scheme to respond to the challenge caused by CO_2 emissions. Moreover, our discoveries imply the breakdown of the popularly used flamelet approach and emphasize the urgency to develop new turbulent combustion models for this novel combustion strategy.
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1. Introduction

According to the latest "World Energy Outlook" published by the International Energy Agency [1], CO_2 emitted by power plants will continue to constitute the major share of greenhouse gases in the next two decades due to the sharp increasing demand on electric power. However, the abrupt change in the Earth's climate system highlights the urgency to cut at least 50% of global greenhouse gases emissions from 2005 levels by 2050 [1]. The sharp increasing demand on electric power and the preservation of the global warming place the human being in a dilemma. In order to address this challenge, besides developing novel combustion technologies to reduce CO_2 emissions, it is desired to replace the conventional fossil fuels by renewable energy sources as far as possible. In order to curb greenhouse gases emissions to Copenhagen/Kyoto protocol compliant levels, combustion specialists have made significant efforts at least from three directions: (1) to replace conventional fossil fuels by renewable resources; (2) to retrofit/build power plants using conventional fossil fuels with the aid of novel combustion technologies; (3) to combine the former two ways organically.

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Among them, the last way is the most attractive one because it can accelerate the reduction of CO_2 emissions, although its complexity is the highest.

As Jahangirian et al. concluded in their work [2]: "Biogas", which typically originates from the anaerobic digestion of biomass and organic wastes by micro-organisms, is a renewable and biodegradable energy source that can be used for heating, lighting, transportation, small-scale power generation, and large gas turbines as a complementary fuel. The benefits of biogas are generally similar to those of natural gas. In addition, burning biogas reduces greenhouse gas emissions; it reduces the net CO_2 release and prevents CH_4 release. Thus, biogas combustion is a potential means to satisfy various legislative and ecological constraints." Up to date there have been numerous studies on the combustion characteristics of biogases. Henham and Makkar [3] discussed the combustion of biogases in a dual-fuel diesel engine over a wide range of compositions of gaseous mixtures. They focused on how to economically transform energy through biogases into the thermodynamically higher valued mechanical energy. Crookes [4] experimentally examined the emissions from spark- and compression-ignition engines using simulated biogas produced from domestic-supply natural gas. He observed that, for the simulated biogas which contained significant fractions of carbon dioxide, the emissions of oxides of nitrogen were reduced relative to natural gas, while unburnt hydrocarbons increased compared with natural gas or gasoline. The author systematically discussed the effects of adding increasing fractions of inert gases into the simulated biogas on the emissions of NO_x. Equivalent effects were also demonstrated with nitrogen replacing carbon dioxide in the simulated biogas. The influence of hydrogen addition on the performance of a biogas fueled spark ignition engine was investigated in Ref. [5]. It was observed that hydrogen significantly enhanced the combustion rate and extended the lean limit of combustion of biogases besides an improvement in brake thermal efficiency and brake power. The second-law based availability analysis in a spark ignition engine under biogas–hydrogen mixtures fueling conditions was conducted by Rakopoulos and Kyritsis [6] and Rakopoulos and Michos [7]. It was revealed that the addition of increasing amounts of hydrogen in biogases promoted the degree of reversibility of the burning process due to the incurred increase of combustion temperatures. Jahangirian et al.[2] investigated the thermal and chemical structures of biogases highly diluted by N_2 in counterflow diffusion flames. The authors found that, compared with pure methane, biogases could significantly reduce the net release of three greenhouse gases: CO_2, CH_4 and N_2O.

Among the recently emergent novel combustion technologies, the oxy-fuel [8] and MILD (moderate or intense low-oxygen dilution) [9] combustion technologies have attracted increasing attention. The oxy-fuel combustion is a process of burning fuel in a mixture of pure oxygen and recirculated flue gas [8]. Compared with convectional air-fired boilers, the exhaust gases in the oxy-fuel regime are composed mainly of CO_2 instead of N_2 since almost all atmospheric nitrogen has been removed from the input air, which makes it possible for Carbon Capture and Storage (CCS) with commercial requirements. The oxy-fuel technology was originally developed by the US Argonne National Laboratory. Within two decades, it has been developed from laboratory tests to industrial applications, which is an extraordinary progress as for an energy technology. However, the original oxy-fuel combustion strategy suffers from several shortcomings like flame instability and locally high temperature gradients [10]. The MILD combustion, usually being characterized by both an elevated temperature of reactants and low temperature increase in combustion processes, is judged as "one of the most promising combustion technologies in 21st Century" [9] due to its intrinsic advantages such as good combustion stability, enhanced heat transfer, high energy recovery and uniform distribution of chemical and thermodynamic variables. The publications on these two novel combustion technologies are nearly countless and the latest development of them can be found in some review papers [10–12]. Through high temperature recirculated flue gas, the oxy-fuel and MILD combustion technologies can be integrated seamlessly. The novel MILD oxy-fuel combustion strategy proposed by the present authors with the support from the US–China Clean Energy Research Center, is an improved variation of the original oxy-fuel combustion technology and can remedy its ancestor's deficiencies satisfactorily. The readers who are interested in this topic can refer to the review paper by the present authors [12].

Almost all existing publications on oxy-fuel and/or MILD combustion technologies are limited in discussing the performance of traditional fossil fuels under these novel combustion conditions. Up to date the corresponding literature on biogases in the new combustion regimes is still quite sparse. To the best knowledge of the present authors, until now there is only one publication [13] on this issue. In Ref. [13], the authors compared the performance of biogas and natural gas in the flameless combustion regime. Their results indicated that the flameless combustion regime eased the interchangeability between fuels of different compositions.

The above literature survey clearly shows that the investigation on the feasibility to utilize biogases under the MILD oxy-fuel condition is absent yet, whereas the potential benefits of this novel combination are obvious. It is well known that there are generally two drawbacks to utilize biogases in conventional modes: their low calorific values (LCVs) are too small and the induced costs of upgrading are very expensive. Upgrading means the removal of CO_2 from biogases to raise their LCVs. However, under the MILD oxy-fuel operation, these two disadvantages of biogases disappear naturally: the MILD combustion mode can work well even though the LCVs of used fuels are extremely small and in the oxy-fuel regime the removal of CO_2 from biogases is unnecessary because additional CO_2 is required to dilute the hot reactants. Although it is a promising way to utilize biogases more efficiently and economically, the necessary knowledge on this novel strategy is highly desired before it could be widely implemented with confidence in its performance.

The main originality of the present work is to investigate the reaction zone structure of biogas combustion in the MILD oxy-fuel regime for the first time. Hydrogen is added to sustain combustion. As a pioneering study, the influences of: (1) the preheated temperature of the oxidizer, (2) the oxygen concentration in the flow from the oxidizer side and (3) the hydrogen concentration in combustible mixtures in the fuel

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