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Impact of injection conditions on flame characteristics from a parallel multi-jet burner

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ABSTRACT

This numerical study systematically investigates the influence of initial injection conditions of reactants on flame characteristics from a parallel multi-jet burner in a laboratory-scale furnace. In particular, varying characteristics from visible flame to invisible Moderate or Intense Low-oxygen Dilution (MILD) combustion is explored. Different parameters examined include the initial separation of fuel and air streams (S), air nozzle diameter (D_a), fuel nozzle diameter (D_f), and air preheat temperature (T_a). The present simulations agree qualitatively well with previous measurements reported elsewhere for two reference cases investigated by experiment. A number of new and significant findings are then deduced from the simulations. For instance, all S, D_a and D_f are found to play significant roles in achieving a proper confluence location of air and fuel jets for establishing the MILD combustion. Particularly, varying D_a is most effective for controlling the combustion characteristics. It is also found that the stability limits of the non-premixed MILD combustion varies with different combustor systems and inlet reactant properties. Moreover, for the first time, several analytical approximations are obtained that relate the flue-gas recirculation rate and the fuel-jet penetration to D_a, D_f, S and also reactant properties.

1. Introduction

The method of MILD (moderate or intense low-oxygen dilution) combustion has been recognized as one of the most successful combustion technologies, developed in past two decades, which can save energy and simultaneously reduce emissions of NO_x (nitric oxide) in particular. This technology, sometimes also termed as 'HiTAC or HTAC' (high temperature air combustion) [1], 'FLOX' ('flameless combustion' or 'flameless oxidation') [2], has been rapidly transferred from laboratory tests to industrial applications, in particular, for steel reheating and steel heat treatment furnaces. It has played a significant role in the mitigation of combustion-generated pollutants (particularly NO_x) and also of greenhouse gases by achieving high thermal efficiency in metallic industry. There is no reason that the technology is just limited within the above industry field; instead, it has an exceptionally great potential to benefit other industries in future.

The MILD combustion occurs volumetrically and is controlled by strong flue-gas recirculation. More specifically, fuel is slowly oxidized in an environment where oxygen is highly diluted by recirculated exhaust gases while temperature is beyond the local auto-ignition point of fuel. Under such conditions, traditional flames cannot sustain and are always blown-off due to either high jet velocity or strong internal flue-gas recirculation. Chemical reactions occur in a distributed zone with significantly reduced peak temperatures [2,3]. As a consequence, the flame is hardly visible, the temperature distribution is rather uniform, the net radiation flux increases by as much as 30%, and NO_x emissions reduce dramatically [1–3].

The MILD combustion has been a favourite subject of R&D (research and development) in the last two decades, see, e.g., [4–7]. Weber et al. [4,5] performed a series of experiments on the MILD combustion of gaseous, liquid and solid fuels. Their measurements were conducted inside a furnace operating with highly preheated air regime (1300 °C). Their data for NG (natural gas) showed that a substantial improvement in net flux of the thermal radiation can be achieved under the MILD combustion. Both the mixing pattern and intensity have significant effects on the overall performance of the furnace firing with NG, specifically on the thermal efficiency part. The combustion process of light oil is very similar to that of

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natural gas, with invisible flames. However, combustion of heavy fuel oil and coal is significantly different, and the flames are always visible in their tests. Weber et al. [5] pointed out that further research is still needed to optimise the burner designs for maximising the recirculation and mixing inside the furnace. Note that their test furnace of square cross-section is characterized by a burner with a central (vitiated) air nozzle and two small off-axis fuel injectors, and an exhaust outlet opposite to the burner inlets. Experimental investigations of the MILD combustion using this burner-furnace configuration have been performed also by other investigators, e.g., Rottier et al. [8,9].

Szegö et al. [7] tested a furnace of different configuration for MILD combustion. In their setup, the fuel is injected through four off-axis holes and the air enters through a central nozzle, while four exhaust ports are located in between. These investigators reported measurements of temperature and flue-gas composition from conventional and MILD combustions using NG and LPG (liquefied petroleum gas) as fuels. They, as well as Kumar et al. [10], found that air preheating is not required to achieve MILD combustion. Their investigation [7] on the stability and operational condition found that diluting the fuel with an inert gas helps achieve the MILD condition. This is because the dilution shifts the stoichiometric contour to the high scalar dissipation region which suppresses flame propagation and leads to a distributed reaction further downstream [11]. A certain threshold of the fuel-air momentum ratio G_f/G_a (≈ 0.006 for their test system) was claimed to be necessary for the MILD combustion to occur. This momentum rate was considered to ensure the penetration of fuel jets to a region classified as the oxidation zone.

Mi et al. [12,13] used a different burner configuration at the furnace indicated above in Refs. [6,7] to investigate, both experimentally and numerically, the effects of the air-fuel injection momentum rate and premixing the two on the MILD combustion. A number of different patterns of partially and fully premixed reactants were found to work very well for MILD combustion. Their numerical study suggested that there is a critical momentum rate of the inlet fuel-air mixture below which the MILD combustion does not occur. In the MILD regime, both the inlet fuel-air mixedness and momentum rate impose insignificant influence on exhaust emissions of the MILD combustion. It is worth noting that their fuel and air jets issued respectively from a central and an annulus nozzle (non-premixed) or both from an annulus nozzle (premixed). Later, Li et al. [14,15] further investigated impacts of various particular injection conditions on the characteristics of fully premixed MILD combustion from a single jet burner in the same furnace. The injection conditions include the area of the nozzle, equivalence ratio, thermal input, and initial dilution of reactants. They found that all these parameters have significant influence on the MILD combustion. It was also revealed that the premixed combustion can occur only when the injection Reynolds number exceeds its critical value. Moreover, very low emissions of NO_x, CO and H_2 were measured for the premixed MILD combustion under various conditions.

Very recently, Schaffel-Mancini et al. [16] have developed several concepts of the power station boiler firing pulverized-coal in the context of the three key points of MILD combustion: existence of an intensive in-furnace recirculation, homogeneity of both the temperature and the chemical species fields, and uniformity of heat fluxes. In order to determine the boiler shape and its dimensions, these authors performed CFD-based numerical simulations to optimise both the distance between burners and location of the burner block. It was demonstrated that the momentum of the combustion air stream is an essential design parameter driving the in-furnace recirculation. Also, the impact of the combustion air temperature on boiler performance was found less critical providing that the intensive in-furnace recirculation has been created. Schaffel-Mancini et al. [16] finally concluded that MILD technology could be a realizable, efficient and clean technology for pulverized coal fired boilers.

In the context of the previous work indicated above, the present study has been undertaken to systematically investigate the influence of injection conditions of separate methane and air streams on the establishment of diffusion MILD combustion in a furnace similar to that of Refs. [4,5,8]. The investigation is performed through RANS (Reynolds-averaged Navier–Stokes equations) modelling. Several injection conditions are selected that include the air preheat temperature (T_a), separation distance between fuel and air exits (S), air nozzle diameter (D_a) and fuel nozzle diameter (D_f). The main objective of the study is threefold:

(1) To qualitatively verify our simulations for MILD combustion by RANS-modelling with previous measurements of Rottier et al. [8,9];
(2) To explore whether the geometric parameters S, D_a and D_f or the initial properties of reactants are important for the occurrence of MILD combustion; and
(3) To identify the key factor(s) that determine the MILD combustion.

2. Computation details

2.1. Furnace configuration and reference cases for MILD combustion

The present study simulates various combustion cases occurring in a laboratory-scale furnace, some of which have been tested experimentally in a previous study of Rottier et al. [8,9]. The detail of the furnace is given in Refs. [8,9] and here only a brief description is provided on it. Fig. 1 shows a schematic of the furnace. The combustion chamber is square in cross-section of 500 mm by

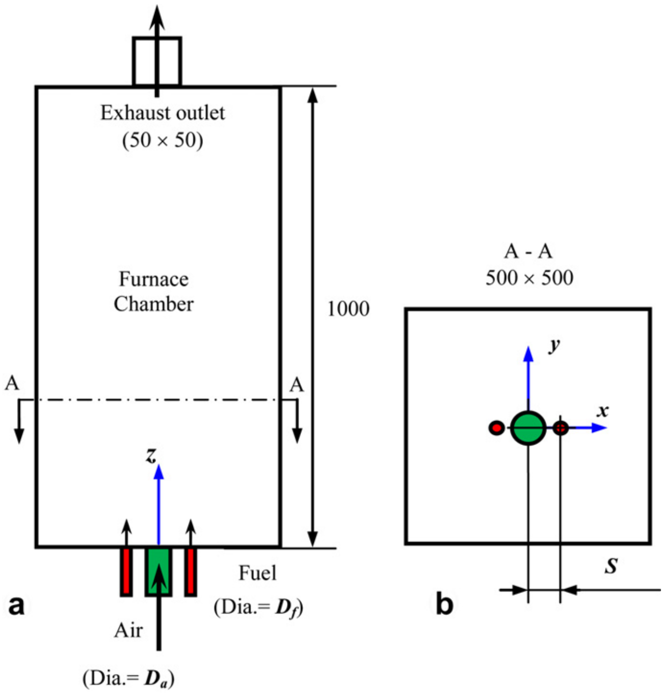

Fig. 1. Schematic of the furnace and burner configuration, simulated presently and measured previously in Rottier et al. [8]. (a) furnace and burner configuration; (b) nozzle arrangement. Dimensions are in mm.