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Numerical investigation of the effects of different injection parameters on Damköhler number in the natural gas MILD combustion

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ABSTRACT

Moderate or intense low-oxygen dilution (MILD) combustion is deemed as a promising technology due to its low pollution emissions and high thermal efficiency. To evaluate MILD combustion performance, the dependences of the Damköhler number *Da* on different injection parameters (i.e., the jet velocity, CO_2 dilution concentration, and preheating temperature) for MILD combustion in a pilot-scale furnace are investigated in this study. Subsequently, several microscopic-scale parameters of the combustion state are analyzed. Results indicate that the peak value of *Da* generally exceeds unity under non-premixed MILD combustion. However, the *Da* value remarkably decrease with an increase in jet velocity, which can be approximate to unity when its value is sufficiently high (up to 190 m/s). An increase in CO_2 dilution concentration also tends to reduce the magnitude of *Da*, because the chemical and physical properties of CO_2 and N_2 differ. When the CO_2 dilution concentration is up to 60 vol%, the peak value of *Da* is below 10 but hardly approaches unity. Furthermore, low preheating temperatures reduce the effect on the turbulent magnitude and slows down the reaction rate, thereby leading to a slight reduction on the *Da* value. Compared with the reduced effects of CO_2 dilution and preheating temperature on the value of *Da*, the dependence of jet velocity is more remarkable.

1. Introduction

Moderate or intense low-oxygen dilution (MILD) combustion is a volumetric and slow combustion regime that can achieve high thermal efficiency and low pollution emissions simultaneously [1,2]. The reaction regions for an ideal MILD combustion regime are homogeneously distributed in an entire furnace, where the reactants (oxidizer and fuel) are well diluted and the rates of chemical reactions are lower compared with those in the conventional air combustion [3]. Consequently, the temperature distribution becomes uniform and peak temperature remarkably decreases [4]. Wünning et al. [5] proposed the flue the use of the gas internal recirculation rate (*Kv*) to characterize MILD combustion regime. *Kv* is calculated as $Kv = m_r/(m_f+m_o)$ where m_r, m_f and m_o represent the mass flow rates of entrained flue gas, fuel stream, and oxidant stream, respectively. They suggested that MILD combustion of the methane could be realized when the internal recirculation rate *Kv* exceeded 3.0. Cavigiolo et al. [6] determined that the critical values of *Kv* were different to realize the MILD combustion of the different fuels (i.e., $Kv > 2.3$ for methane, $Kv > 3.5$ for ethane). Minamoto et al. [7] suggest that the oxygen mole concentration was < 5% in the reactant mixture under a MILD combustion regime. In addition, high preheating temperatures require the selection of a suitable non-premixed combustion regime to ensure safety in conventional industry applications. The separation of fuel and oxidant blocks the mixing of the reactants, and chemical reactions occur where the fuel and oxidant streams merge. Thus, a complete volumetric reaction is difficult to achieve but can only be approximated under a non-premixed combustion strategy. An effective and economical MILD combustion should thus be determined.

An increase in strengthens flue gas recirculation, which contributes to the initiation of MILD combustion. Weber et al. [8] experimentally investigated MILD combustion on liquid and solid fuels in a pilot-scale furnace. The researchers concluded that the distributions of both reactants and temperature were uniform throughout the furnace chamber on the basis of high jet velocity. Weidmann et al. [9,10] evaluated a series of jet velocities on a down-fire furnace for coal MILD combustion. Their study showed that the flue gas internal recirculation could be remarkably enhanced when the jet velocity of air stream ranged between 100 and 200 m/s, and the MILD combustion could be established without the need to preheat the reactants (atmospheric temperature).

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Nomenclature

$(C_i)^n$	reaction order
D	mass diffusivity
Da	Damköhler number
D_t	turbulent diffusivity
Ka	Karlovitz number
Le	Lewis number
l_F	flame length scale
Ret	turbulent Reynolds number
$R_{kin,i}$	consumption rate of species i
r_{kin}	elementary reaction kinetic rate
[i]	molar concentration

Greeks

A	thermal diffusivity
τ_f	flow time scale
τ_R	reaction time scale
τ^*	mean resident time
ξ^*	length scale for fine structure
η	Kolmogorov length scale

Our previous studies [11,12] reported that the pulverized coal MILD combustion could be realized by high jet velocity in a 0.3 MW_{th} pilot-scale furnace. Furthermore, MILD combustion regime occurs with jet velocities of 100 m/s and 112 m/s under oxy-coal and air-coal atmospheres, respectively. Mi et al. [13] investigated the effect of injection momentum on MILD combustion at a pilot-scale furnace. They concluded that MILD combustion was hardly established once the initial momentum rate exceeded a critical value. Li et al. [14] indicated that the occurrence of MILD combustion for different fuel types might lead to the different injection momentum rates.

Researchers have determined that CO_2 dilution can affect the establishment of MILD combustion. Dally et al. [15] used a recuperative MILD combustion furnace to investigate the burning of sawdust diluted by CO_2 and N_2. They concluded that the optimal equivalence ratio for MILD combustion was in range of 0.71–0.75 for CO_2 dilution but 0.75 for N_2 dilution. Similarly, Zhang et al. [16] investigated MILD combustion regimes that were diluted with CO_2 and N_2 by experiment and kinetic calculation. Their results indicated that CO_2 dilution was favorable to the reduction of the flame temperature. Furthermore, they concluded that oxy-fuel combustion (O_2/CO_2 atmosphere) could facilitate the establishment of MILD combustion. Sabia et al. [17,18] conducted the numerical and experimental studies on MILD combustion with CO_2 dilution, and determined that CO_2 dilution was superior to N_2 dilution in delaying the reactants' reactivity. Mardani et al. [19] conducted a numerical comparison to determine the difference in the peak temperatures between MILD-oxy and MILD combustions. Their findings showed that CO_2 dilution would cause a reduction on the flame temperature.

High preheating temperature of reactants is a significant feature for the initiation of MILD combustion. Suda et al. [20] experimentally evaluated the effect of preheating temperature (623 K and 1073 K) under the MILD combustion of pulverized coal; and found that high preheating temperature could shorten the ignition time delay. Gao et al. [21] simulated the effect of preheating temperature (1300 K –1700 K) on the MILD combustion of hydrogen–methane mixtures. They also concluded that high preheating temperature could significantly change the kinetic reaction rate. Similarly, Huang et al. [22] investigated the effect of preheating temperature on the MILD combustion of syngas. Their results showed that an increase in the preheating temperature could result in the growth of peak flame temperature.

As the above mentioned, many researchers have investigated the macroscopic characteristics (temperature, velocity, and species) of MILD combustion with the different injection parameters (jet velocity, CO_2 dilution, and preheating temperature) by experiments and numerical simulations. The microscopic characteristics of MILD combustion, e.g., flow time scale τ_f, reaction time scale τ_R, Damköhler number Da, and Lewis number Le, are rarely involved. Specifically, the Damköhler number Da, which is a key parameter used to evaluate the combustion regime, is defined as the ratio of flow to the reaction time scale ($Da = \tau_f / \tau_R$) [23–26]. Isaac et al. [27] suggested that Da was conductive to identifying combustion regimes and appropriate modeling strategies. By observing the distribution of OH radical concentration, Ozdemir et al. [28] found that the kinetic rate of chemical reaction was sufficiently slow, and the chemical time scale was comparable with the flow time scale under MILD combustion conditions. Thus, $Da = 1$ signifies the appearance of an ideal MILD combustion. The present work numerically investigates the effects of different jet velocities, preheating temperatures and CO_2 dilution concentrations on the Damköhler number Da during the MILD combustion of natural gas. The results can provide several suggestions for the establishment of the non-premixed MILD combustion via the optimization of injection parameters in terms of the reduction of the Da value.

2. Mathematical model

2.1. Operational conditions

The experiments of MILD combustion on the natural gas [8,29] is considered as the base-case for present simulation. A brief description of the International Flame Research Found (IFRF) furnace is provided here. As Fig. 1 displays, the dimension of the furnace is 2000 × 2000 × 6250 mm. The primary stream and secondary stream are injected into furnace through the two side channels (D_{pri} = 50 mm) and the central channel (D_{sec} = 124 mm), respectively. Table 1 lists the operational conditions of fuel and air streams of the base-case. In the present study, the effects of the different injection parameters on the

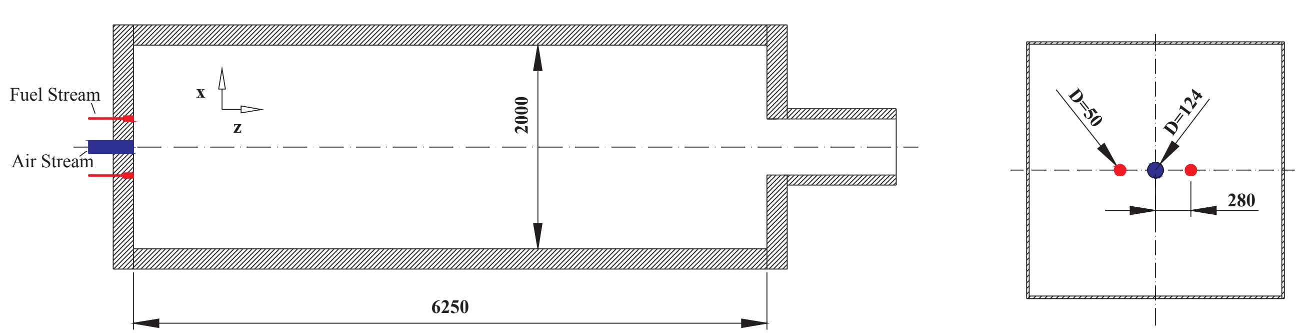

Fig. 1. The schematic diagram of the IFRF furnace.