Insight on Required Conditions to Achieve MILD Coal Combustion

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Abstract: In Moderate or Intense Low-Oxygen Dilution (MILD) Combustion, well-mixed reactants are required to have a uniform reaction field so the perfectly-stirred reactor (PSR) model is an ideal model to investigate the thermochemical characteristics in the MILD regime. However, it is difficult to achieve well-mixed reactants around the particles for pulverized coal combustion. We present a comparison of PSR and flamelet models that suggests well-mixed reactants may not be necessary to achieve MILD regime as long as the scalar dissipation rate is high enough. We also present a theoretical basis for MILD combustion in the context of coal combustion where fuel is delivered as distributed point sources. Results suggest that mixing length scales must be smaller than the particle diameter and that the Damköhler number should be order unity or smaller. The criteria on mixing length scales are particularly useful as they can serve as a practical guide for experiments to attain MILD conditions.

Keywords: MILD coal combustion, mixing length scale, well-mixed reactants

1. Introduction

Moderate or Intense Low-Oxygen Dilution (MILD) combustion is a relatively new combustion technology that has attracted attention due to its high thermal efficiency and low NOₓ emissions. The MILD combustion regime is characterized by a highly-distributed reaction zone in which a flame is visibly absent. To achieve MILD combustion, the reacting mixture is combined with combustion products under highly-turbulent conditions which acts to preheat the oxidizer-fuel mixture, facilitates mixing, and reduces the reactivity of the system through dilution. In previous work, Cavaliere and De Joannon [1] proposed that a combustion system is of MILD of classification if the inlet temperature is larger than the auto-ignition temperature, and difference between maximum temperature and the inlet temperature is smaller than the auto-ignition temperature (in Kelvin). At the time, these criteria only considered homogeneous combustion. However, studies performed more recently have focused combustion of solid fuels under MILD conditions. Saha, et al. [2–6] have performed a number of studies investigating the effect of particle size, turbulence intensity, and coal type on MILD combustion using pulverized coal as a fuel. Tu et al. [7, 8] recently investigated the impact of oxygen concentration as well as the addition of H₂O to oxy-coal systems under MILD conditions and found that enrichment of either O₂ or H₂O results in decreased NOₓ concentrations in the flue gas. A study by Liu et al. explored the effect of varying particle size as well as inlet jet configuration and attempted to find optimum operating conditions for a bench-scale oxy-coal MILD system. In a number of studies [5, 9, 10], “ghost” flames and sparks
were observed under MILD conditions in multiphase combustion, suggesting the possibility of poor mixing which conflicts with the flameless characteristic of MILD combustion. This perhaps indicates that a different set of criteria is needed for classifying multiphase combustion systems as MILD.

In this study, the required conditions to achieve MILD coal combustion are concluded by analyzing the mixing process in the reactor. The data from literature are applied to confirm the correctness of these conditions. In addition, we numerically investigate the characteristics of coal combustion in the MILD regime using the perfectly-stirred reactor (PSR) model as well as the steady laminar flamelet (SLF) model. The effects of the recirculation rates, heat loss and mass fraction of light volatile gas in the fuel mixture are investigated. And the results from PSR and SLF models are compared to explore the necessity of well-mixed reactants to achieve MILD regime.

2. Conditions for MILD Coal Combustion

2.1 Definition of MILD Combustion

MILD combustion is defined as a combustion process where the inlet temperature of the reactant mixture is higher than the mixture self-ignition temperature whereas the maximum temperature increase with respect to the inlet temperature in the reactor is lower than the mixture self-ignition temperature by Cavaliere [1]. This is the most common criterion for the achievement of MILD regime.

\[ T_{\text{inlet}} > T_{\text{self-ignition}}, \]
\[ (T_{\text{max}} - T_{\text{inlet}}) < T_{\text{self-ignition}}, \]

For coal combustion, both the temperature and composition of the reactant mixture are ambiguous as both vary through the devolatilization process. In the experiments, the temperature is considered high enough as long as the initial temperature of the reactor, usually preheated by combustion of natural gas, is higher than the reactant self-ignition temperature [2, 3]. And none of the papers have declared the method and composition of the reactants used to get self-ignition temperature, which is always set approximately based on the coal type or experience (usually 1100K). In this work, the light gas and tar products in volatiles from devolatilization is considered as fuel. The temperature and composition of light gas in volatiles are defined as the particle temperature and species production rates during devolatilization normalized by the total light gas production rate [1].

\[ T_{\text{lg}} = \frac{\sum_{0}^{n_p} \int T_{p} m_{\text{lg}} dt}{\sum_{0}^{n_p} \int m_{\text{lg}} dt}, \]
\[ Y_{i\text{lg}} = \frac{\sum_{0}^{n_p} \int m_{i\text{lg}} dt}{\sum_{0}^{n_p} \int m_{\text{lg}} dt}, \]

where \( T_{\text{lg}} \) and \( T_{p} \) are the temperatures of light gas and particles, respectively, \( m_{\text{lg}} \) and \( m_{i\text{lg}} \) are the total light gas production rate and \( i^{th} \) species production rate from devolatilization, respectively, \( Y_{i\text{lg}} \) is the mass fraction of \( i^{th} \) species in light gas, \( n_p \) is the number of particles and \( t \) is time. The
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tar product temperature is defined as the gas temperature normalized by the mass source term from tar and soot to gas phase \([11]\).

\[
T_{tp} = \frac{\int T_g \dot{m}_{\text{gas}}^{\text{tar+soot}} dt}{\int \dot{m}_{\text{gas}}^{\text{tar+soot}} dt},
\]

where \(T_{tp}\) and \(T_g\) are the temperatures of tar products and gas phase. \(\dot{m}_{\text{gas}}^{\text{tar+soot}}\) is the mass source term from tar and soot to gas phase.

The inlet temperature used in the definition is obtained by mixing the light gas, tar product, oxidizer and recirculated flue gas under constant enthalpy and pressure using Cantera \([12]\).

2.2 Theoretical Analysis of the Mixing Process for MILD Coal Combustion

High recirculation rate of flue gas is necessary in MILD combustion to dilute the oxidizer, preheat the reactants, and mix them rapidly to avoid formation of a flame front. This reduces the peak temperature and chemical reaction rates in the reactor. The reduced chemical reaction rates are always smaller than the high mixing rates. Perfectly-stirred reactor (PSR) becomes a good model to mimic this process \([1, 13]\). Such model relies on the assumption that the mixing time scale needs to be smaller than the chemical time scale \(Da < 1\), which is needed in MILD combustion.

\[
\tau_{\text{mix}} < \tau_{\text{rxn}}.
\]

However, it is difficult to get well-mixed reactants around the pulverized coal particle. Because of the interaction between gas phase and particles, a heat and mass transfer boundary layer is formed around the particles. To get well-mixed reactants around these particles, the mixing structure needs to be small enough to breakup this boundary layer. In turbulent flow, the turbulent eddies represent the mixing structure. To analyze this, the turbulent eddy cascade is used. Figure 1 gives the scalar spectra and the position of different particle sizes, where \(\eta_{\text{mix}}\) represents the smallest scalar mixing length scale. When the particle size is bigger than the smallest mixing length scale, \(\eta_{\text{mix}} < d_p\), as shown by the left particle in the figure, the smallest mixing structure around the particle could breakup the boundary layer and perfectly mix the reactants. When the particle size is much smaller than the smallest mixing length scale, \(\eta_{\text{mix}} > d_p\), as shown by the right particle in the figure, the
particle may sit inside the mixing structure, and a distinct boundary layer will develop around the particle. This analysis suggests that the smallest mixing length scale needs to be smaller than the particle size to get well-mixed reactants around the particles:

$$\eta_{\text{mix}} < d_p \quad \text{(Additional MILD criterion).}$$  \hspace{1cm} (7)

The scalar mixing structure is affected by turbulent cascade and the smallest scalar length scales can be related to the integral ($L$) and Kolmogorov ($\eta$) length scales and Schmidt number, $Sc = \nu/D$

$$\eta_{\text{mix}} = \begin{cases} 
\eta_c = \eta Sc^{-3/4}, & Sc < 1 \\
\eta = L Re_L^{-3/4}, & Sc = 1 \\
\eta_B = \eta Sc^{-1/2}, & Sc > 1
\end{cases}$$

Here $Re_L$ is the Reynolds number based on integral length scale. The Obukhov-Corrsin length scale $[14]$, $\eta_C$, is the mixing length scale for the species with $Sc < 1$. The Batchelor length scale, $\eta_B$, is the mixing length scale for the species with $Sc > 1$.

Based on the above discussion, equations (1)-(2) and (6)-(7) are used as the criteria for MILD regime in this work.

3. Theoretical Formulation

3.1 Gas Phase Fuel Composition

In this work, the fuel stream for the perfectly-stirred reactor and steady laminar flamelet models is a mixture of devolatilized light gases and products of partially-combusted tar and soot. Illinois Bituminous coal with initial temperature of 350K, is considered here, the properties of which are provided in Table 1. The composition of its devolatilization products is obtained from the Chemical Percolation and Devolatilization (CPD) model, the details of which are provided in [15–17]. This work assumes coal volatiles are composed of light gases (CH$_4$, CO, CO$_2$, H$_2$, H$_2$O, NH$_3$, and HCN) and a high molecular weight hydrocarbon, i.e., tar, as shown in Table 2. The light gas components of the coal volatiles participate in reactions according to the chosen chemical mechanism, GRI 2.11 mechanism [18], while tar and soot are considered only through their products of combustion. Herein, we assume tar is naphthalene (C$_{10}$H$_8$), and that soot has the same empirical formula as tar in order to reduce the number of mixture fractions required to parameterize products of tar and soot reactions, which results in the following reaction scheme

$$\text{tar} \rightarrow \text{soot}.\quad \text{(8)}$$

As a result, the “tar and soot products” portion of the fuel stream is composed of CO, H$_2$O and inert components of the oxidizer. Air at 500K is used as the oxidizer. Therefore, the inert components in the “tar and soot products” portion of the fuel stream is N$_2$ here. The composition and adiabatic temperatures of the light gases and tar products, calculated using equations (3), (4), (5) and (8), are provided in Table 3. In both PSR and SLF model, the products from the stoichiometric combustion of this fuel steams with air as the oxidizer is used as the recirculated flue gas. Besides, heat loss during this combustion process is considered, which reduces the product temperature to be 1800K.
Table 1: Proximate and ultimate analyses of the Illinois Bituminous coal.

<table>
<thead>
<tr>
<th>Proximate %</th>
<th>Ultimate (dry) %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture</td>
<td>0.0</td>
</tr>
<tr>
<td>Ash</td>
<td>8.02</td>
</tr>
<tr>
<td>Volatiles</td>
<td>31.60</td>
</tr>
<tr>
<td>Fixed C</td>
<td>69.10</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2: Composition of volatiles for Illinois Bituminous coal(%)

<table>
<thead>
<tr>
<th>Tar</th>
<th>CH₄</th>
<th>CO</th>
<th>CO₂</th>
<th>H₂</th>
<th>H₂O</th>
<th>HCN</th>
</tr>
</thead>
<tbody>
<tr>
<td>19.8</td>
<td>10.8</td>
<td>30.1</td>
<td>18.0</td>
<td>3.91</td>
<td>11.0</td>
<td>6.36</td>
</tr>
</tbody>
</table>

Table 3: Compositions and temperatures of light gases and tar products.

<table>
<thead>
<tr>
<th>Stream</th>
<th>CH₄</th>
<th>CO</th>
<th>CO₂</th>
<th>H₂</th>
<th>H₂O</th>
<th>HCN</th>
<th>N₂</th>
<th>T_ad (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>lg, (ζ = 1)</td>
<td>0.134</td>
<td>0.375</td>
<td>0.226</td>
<td>0.049</td>
<td>0.137</td>
<td>0.079</td>
<td></td>
<td>1127</td>
</tr>
<tr>
<td>tp, (ζ = 0)</td>
<td>0.257</td>
<td>0.0661</td>
<td>0.0661</td>
<td>0.0661</td>
<td>0.677</td>
<td>1604</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3.2 Perfectly-Stirred Reactor (PSR) Model

As shown in Figure 2, a perfectly-stirred reactor under constant pressure with external recirculation stream is used in this work.

The equations governing the evolution of species mass fractions ($Y_i$) and specific enthalpy ($h$) in this reactor are

$$\frac{dY_i}{dt} = \frac{\rho_{in}}{\rho \tau_{mix}} (Y_{i,in} - Y_i) + \frac{\dot{\omega}_i}{\rho}$$

$$\frac{dh}{dt} = \frac{\rho_{in}}{\rho \tau_{mix}} (h_{in} - h) - \frac{3k}{\rho r} (T - T_{inf})$$

where $\rho$ is the density, $T$ is the gas phase temperature, $\dot{\omega}_i$ is the species volumetric chemical reaction rate, and $r$ is the reactor radius. The last term on the right hand side of equation (10) represents the convective heat transfer between gas and surroundings with temperature $T_{inf}$ with convective coefficient $k$. The "in" subscript indicates an inlet (feed) condition.

To mimic the recirculation process in MILD combustion, part of the product (flue gas), $\dot{m}_e$, is mixed with the oxidizer and injected into the reactor carrying coal particles, $\dot{m}_f$. The ratio between the mass of recirculated flue gas and the total mass of oxidizer and fuel is defined as the recirculation rate, $K_v$.

$$K_v = \frac{\dot{m}_e}{\dot{m}_o + \dot{m}_f}$$

where $\dot{m}_e$, $\dot{m}_o$ and $\dot{m}_f$ are the mass flow rate of entrained flue gas, initial oxidizer and initial fuel, respectively.

3.3 Steady Laminar Flamelet (SLF) Model

The steady laminar flamelet (SLF) model assumes that the structure of a flame is locally one-dimensional and that steady balance exists between reaction kinetics and diffusive fluxes. Flamelet
solutions for temperature, \((T)\) and and mass fractions for each species \((Y_i)\) are determined by solving the following system of ODEs

\[
\frac{\chi}{2Le_i} \frac{d^2 Y_i}{dZ^2} = -\frac{1}{\rho} \omega_Y, \quad (12)
\]

\[
\rho c_p \frac{d^2 T}{dZ^2} = \sum_{j=1}^{n_i} h_j \omega_Y, \quad (13)
\]

where \(\chi\) is the scalar dissipation rate, \(Le_i\) is the Lewis number for species \(i\), \(\rho\) is the fluid density, \(\omega_Y\) is the net reactive source term for species \(i\), \(c_p\) is the fluid heat capacity, and \(h_i\) is enthalpy of species \(i\). The quantity \(\chi_{\text{max}}\) is the maximum scalar dissipation rate and is set from an expression suggested by Peters [20]

\[
\chi = \chi_{\text{max}} \exp \left( -2 \left[ \text{erf}^{-1}(2Z - 1) \right]^2 \right). \quad (14)
\]

In this study, flamelet solutions are parametrized by five variables; an overall mixture fraction, \(Z\), a fuel-side mixture fraction, \(\zeta\), maximum scalar dissipation rate, \(\chi_{\text{max}}\), normalized heat loss, \(\gamma\), and recirculation rate of flue gas, \(K_v\). The overall mixture fraction, \(Z\) is expressed as

\[
Z = Z_{\text{lg}} + Z_{\text{tp}}, \quad (15)
\]

where mixture fractions for devolatilized light gases, \(Z_{\text{lg}}\), products of tar and soot reactions, \(Z_{\text{tp}}\), are given by

\[
Z_{\text{lg}} = \frac{M_{\text{lg}}}{M_{\text{lg}} + M_{\text{tar}} + M_{\text{ox}}}, \quad (16)
\]

\[
Z_{\text{tp}} = \frac{M_{\text{tp}}}{M_{\text{lg}} + M_{\text{tar}} + M_{\text{ox}}}. \quad (17)
\]

The values \(M_{\text{ox}}, M_{\text{lg}}, M_{\text{tar}}\) appearing in (16) and (17) are masses originating from the oxidizer, devolatilized light gases, and tar, respectively. The fuel-side mixture fraction, \(\zeta\), is defined as

\[
\zeta = \frac{Z_{\text{lg}}}{Z_{\text{lg}} + Z_{\text{tp}}}, \quad (18)
\]
and normalized heat loss, $\gamma$ is expressed as

$$
\gamma = \frac{h_{ad}(Z, \zeta) - h(T, Z, \zeta)}{h(T, Z, \zeta) - h(T_{ref}, Z, \zeta)},
$$

(19)

where $h(T, Z, \zeta)$ is the mixture enthalpy, $h_{ad}(Z, \zeta)$ is the mixture enthalpy under adiabatic conditions, and $T_{ref} = 298.15K$ is a reference temperature.

Fuel-side boundary conditions for the composition are determined by evaluating the following expression

$$
Y_i(Z = 1) = \zeta Y_{lg,i} + (1 - \zeta) Y_{tp,i},
$$

(20)

Oxidizer-side boundary conditions are set based on the value of $K_v$ by mixing the oxidizer and recirculated flue gas under constant enthalpy and pressure using the Cantera software package [12]. Boundary conditions for (13) are set first by calculating stream enthalpies by evaluating

$$
h_k(\gamma) = \frac{1}{1 + \gamma} h_{k,ad} + \frac{\gamma}{1 + \gamma} h_{k,ref},
$$

(21)

where $k = \{ox, lg, tp\}$. The adiabatic enthalpy of stream $k$ is obtained via

$$
h_{k,ad} = h_k(T_{k,ad}),
$$

(22)

where $T_{k,ad}$ is the adiabatic temperature of stream $k$. The oxidizer stream is the mixture of oxidizer and recirculated flue gas when there is recirculation. Boundary temperatures are set using

$$
T(Z = 0) = T \text{ such that } h(T) = h_{ox}(K_v, \gamma),
$$

(23)

$$
T(Z = 1) = T \text{ such that } h(T) = \zeta h_{lg}(\gamma) + (1 - \zeta) h_{tp}(\gamma).
$$

(24)

Solutions to equations (12) and (13) are obtained using the numerical methods described in [21, 22].

4. Results and Discussion

4.1 Mixing Criteria for MILD

To test the criteria proposed in §2.2, $\eta_{mix} < d_p$, we consider data from the literature. The Reynolds number is calculated using the jet diameter and gas parameters through jet. The mixing length scale is calculated based on the jet Reynolds number and species Schmidt numbers. Figure 3 shows the scalar spectra from two studies [5, 23]. The particle size is indicated by a dashed red in the figure to compare with the mixing length scale. Three mixing length scales, $\eta$, $\eta_C$ and $\eta_B$, are shown as dashed blue lines, which gives the range of the mixing length scale for different species in the reactor.

MILD combustion was reported in cases FLOX-CO2 and FLOX-AIR, but not FLOX-FLAME. In cases FLOX-CO2 and FLOX-AIR, the condition, $\eta_{mix} < d_p$, is satisfied. For the case FLOX-FLAME, where flames (not MILD) were reported, $\eta_{mix} > d_p$ consistent with our theoretical condition. In Figure 3d - 3f the range of particle sizes is represented as the red zone between two red dashed lines. For the cases where $Re_{jet} = 20,000$ and $Re_{jet} = 11,000$, the mixing length scale
for Sc = 1 (\( \eta \)) and Sc > 1 (\( \eta_B \)) is smaller than particle size. However, the mixing length scale for Sc < 1 (\( \eta_C \)) is in the particle size range, especially for \( Re_{\text{jet}} = 11,000 \). In the paper, MILD combustion is reported for cases \( Re_{\text{jet}} = 20,000 \) and \( Re_{\text{jet}} = 11,000 \). No visible flame is found in these two cases. However, images of the furnace interior indicate that the luminous intensity is higher for the \( Re_{\text{jet}} = 11,000 \) case compared to the \( Re_{\text{jet}} = 20,000 \) case. Analysis of the kinetic energy spectra provides a possible explanation for the observed disparity in luminous intensity. According to Figure 3d and 3e, some species do not mix perfectly within the vicinity of the particles because of a high Schmidt number.

---

**Figure 3:** Particle position in scalar spectra from literature data. Figures 3a-3c use data from [23] while Figures 3d-3f use data from [5]. Three blue dashed lines represent the mixing length scales based on different species Sc numbers. The red dashed line in 3a-3c represents the particle size. The red zone between two red dashed lines in 3d-3f represents the range of particle sizes.

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Figure 4 gives additional comparisons between particle size and mixing length scales. The first four cases in the figure, namely "OM_dry(ideal)", "OM_dry", "OM_wet" and "OM_stream", represent cases with different proportions of CO\(_2\) and H\(_2\)O in oxidizer from paper [7]. Other five cases, namely "AM", "OM21", "OM24", "OM27" and "OM30", represents cases with different proportions of O\(_2\) and CO\(_2\) in oxidizer from paper [8]. The red dashed line represents the particle size while gray zone enclosed by the black data points represent the range of the mixing length scales of all species for all cases. In all the cases considered in Figure 4 MILD combustion is attained. According to Figure 4, the mixing length scales are smaller or slightly bigger than the particle size, which is consistent with our proposed criterion, \( \eta_{\text{mix}} < d_p \).
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OM_dry
OM_wet
OM_stream
AM
OM21
OM24
OM27
OM30

Figure 4: Comparison between mixing length scale and particle size. The red dashed line represents the particle size. The blue zone represents the mixing length scale of all species. The data are from [7, 8]

4.2 Parametric analysis of MILD combustion using PSR model

The PSR model is used in this work to analyze the effects of recirculation rates, $K_v$, fuel-side mixture fraction, $\zeta$, and heat loss, $\gamma$. Figure 5 plots three temperatures for conditions shown in equations (1) and (2), including $T_{\text{inlet}}$, $T_{\text{max}} - T_{\text{inlet}}$ and $T_{\text{self-ignition}}$, for different recirculation rates, $K_v$, with $\zeta = 0.4$ and no heat loss, $\gamma = 0$. Based on the conditions shown in equations (1) and (2), the red dashed lines ($T_{\text{inlet}}$) and the blue dashed lines ($T_{\text{max}} - T_{\text{inlet}}$) in the figure should sit above and below the black dashed line ($T_{\text{self-ignition}}$), respectively, in order to obtain MILD combustion.

From Figure 5, we see that the inlet temperature, $T_{\text{inlet}}$, near the oxidizer side ($Z = 0$) increases significantly as $K_v$ increases. This leads to a decrease of temperature increment in the reactor, $T_{\text{max}} - T_{\text{inlet}}$. When there is no recirculation, $K_v = 0.0$, both $T_{\text{inlet}}$ and $(T_{\text{max}} - T_{\text{inlet}})$ are lower than $T_{\text{self-ignition}}$ near oxidizer side ($Z = 0$). The low temperature increment, $(T_{\text{max}} - T_{\text{inlet}})$, comes from insufficient amount of fuel in this fuel-lean mixtures. Both $T_{\text{inlet}}$ and $(T_{\text{max}} - T_{\text{inlet}})$ are higher than $T_{\text{self-ignition}}$ near stoichiometric conditions, as is typically observed in traditional combustion. $(T_{\text{max}} - T_{\text{inlet}})$ becomes lower than $T_{\text{self-ignition}}$ near fuel side ($Z = 1$) because of insufficient amount of oxidizer in the fuel-rich mixtures. When the recirculation rate is sufficiently large, $T_{\text{inlet}}$ is higher than $T_{\text{self-ignition}}$ for all mixture fractions, $Z$. However, $(T_{\text{max}} - T_{\text{inlet}})$ is still higher than $T_{\text{self-ignition}}$ near stoichiometric conditions for $K_v = 0.5$ and 1.0. When the recirculation rate reaches a value of 1.5, $(T_{\text{max}} - T_{\text{inlet}})$ becomes lower than $T_{\text{self-ignition}}$ for all mixture fractions. That is, MILD regime is obtained for $K_v \geq 1.5$.

Figure 6 shows temperature plotted against mixture fraction over a range of $\zeta$ values, with $K_v = 1.0$ and $\gamma = 0$. For the chosen recirculation rate ($K_v = 1.0$), $T_{\text{inlet}}$ is always higher than $T_{\text{self-ignition}}$. Additionally, the peak temperature decreases as the mass fraction of light gas in fuel side ($\zeta$) increases because of lower temperature of light gas than tar products. This leads to increment of $(T_{\text{max}} - T_{\text{inlet}})$ near stoichiometry. MILD combustion is obtained for all mixture fractions only when there is no light gases in the fuel side, $\zeta = 0.0$, with $K_v = 1.0$. Figure 6 also
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Figure 5: Temperature comparison against mixture fraction for different recirculation rates, $K_v$, with $\zeta = 0.4$ and $\gamma = 0$. Three different colors represent three temperatures and different line styles with the same color represent different recirculation rates.

Figure 6: Temperature comparison against mixture fraction for different fuel-side mixture fractions, $\zeta$, with $K_v = 1.0$ and $\gamma = 0$. Three different colors represent three temperatures and different line styles with the same color represent different fuel-side mixture fractions.

indicates that the stoichiometric mixture fraction decreases with the increasing of $\zeta$. Therefore, for fuel mixture with light gases, application of high recirculation rate is helpful to increase the inlet temperature near oxidizer side and to obtain MILD regime under adiabatic conditions.

As discussed in §2, the turbulence intensity must be large enough to ensure that the smallest mixing length scales are smaller than the particle size, $\eta_{\text{mix}} < d_p$. The SLF model allows us to examine imperfect mixing, to identify minimum mixing rates $\chi$ to ensure MILD combustion.

Figure 8 compares the temperature profiles against mixture fractions from PSR and SLF models for different recirculation rates with $\zeta = 0.4$ and $\gamma = 0$. The zone between two black dashed lines in Figure 8 represents the temperature range necessary for MILD combustion, while the top black dashed line represents the allowed maximum temperature for MILD combustion, $T_{\text{max}} = T_{\text{inlet}} + T_{\text{self-ignition}}$, and the bottom black dashed line represents the self-ignition temperature. The PSR model results are plotted using red dashed lines for reference while SLF model results are colored based on the maximum dissipation rate, $\chi_{\text{max}}$ according to the color bar. Based on the conditions shown in equation (1) and (2), MILD regime is achieved when the whole temperature profile drops into the range between two black dashed lines. The self-ignition temperature (the bottom black dashed line) does not change with recirculation rate, whereas the allowed maximum
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Figure 7: Temperature comparison against mixture fraction for different normalized heat losses, $\gamma$, with $K_v = 1.0$ and $\zeta = 0.4$. Three different colors represent three temperatures and different line styles with the same color represent different heat losses.

Figure 8: Temperature plotted against mixture fraction from PSR and SLF models for different recirculation rates, $K_v$, with $\zeta = 0.4$ and $\gamma = 0$. The top and bottom black dashed lines represent the allowed maximum temperature in the reactor, $T_{\text{max}}$, and the self-ignition temperature, $T_{\text{self-ignition}}$, respectively. The red dashed line represent the PSR results. The SLF results are colored based on dissipation rate, $\chi_{\text{max}}$. 
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temperature (the top black dashed line) increases with the increment of recirculation rates. This gives bigger temperature range for MILD combustion. The maximum temperatures from both models do not have big difference for different recirculation rates. When $K_v = 1.5$, as shown in Figure 8d, all temperature calculations are in the MILD region. This is consistent with the analysis of the results in Figure 5 discussed in §4.2. For the SLF calculations, temperature decrease with the increment of dissipation rate, $\chi_{\text{max}}$. When there is no recirculation, $K_v = 0.0$, the maximum temperature is still higher than the allowed maximum temperature, $T_{\text{max}}$, even for $\chi_{\text{max}} = 10^4$. For $K_v = 0.5$ and $K_v = 1.0$, the results move into the MILD region when the dissipation rate is sufficiently large. However, MILD regime is not achieved according to the PSR model under the two recirculation rates. This suggests that well-mixed reactants may be not needed to obtain MILD regime as long as the dissipation rate is large enough.

Figure 9: Temperature plotted against mixture fraction from PSR and SLF models for different fuel-side mixture fractions, $\zeta$, with $K_v = 1.0$ and $\gamma = 0$. The top and bottom black dashed lines represent the allowed maximum temperature in the reactor, $T_{\text{max}}$ and the self-ignition temperature, $T_{\text{self-ignition}}$, respectively. The red dashed line represent the PSR results. The SLF results are colored based on dissipation rate, $\chi_{\text{max}}$.

Figure 9 shows the temperature profiles for different fuel-side mixture fractions, $\zeta$, with $K_v = 1.0$ and $\gamma = 0$. As discussed in §4.2, the PSR model only predicts that MILD combustion is obtained for all mixture fractions with $K_v = 1.0$ and $\gamma = 0$ when no light gases are present ($\zeta = 0.0$). The allowed maximum temperature decreases with $\zeta$ because of lower temperature of light gas than tar products, which shrinks the temperature range for MILD regime. Therefore, bigger dissipation rate, $\chi_{\text{max}} > 2 \times 10^2$ is required for $\zeta = 1.0$ to get MILD combustion, which is bigger than that, $\chi_{\text{max}} > 2 \times 10^1$, needed for $\zeta = 0.4$, as shown in Figure 9b and 9c.

Figure 10 shows the temperature profiles for several heat losses, $\gamma$, with $K_v = 1.0$ and $\zeta = 0.4$. As noted in §4.2, the temperature region for MILD combustion decreases with the heat loss because of the decrease of the maximum allowed temperature, $T_{\text{max}}$. Additionally, Figure 10 suggests that the minimum scalar dissipation rate required for achieving MILD combustion increases with increasing heat loss and that extinction occurs at a lower dissipation rate as heat loss increases.
Figure 10: Temperature plotted against mixture fraction from PSR and SLF models for different heat losses, $\gamma$, with $K_v = 1.0$ and $\zeta = 0.4$. The top and bottom black dashed lines represent the allowed maximum temperature in the reactor, $T_{\text{max}}$ and the self-ignition temperature, $T_{\text{self-ignition}}$, respectively. The red dashed line represent the PSR results. The SLF results are colored based on dissipation rate, $\chi_{\text{max}}$.

5. Conclusions

In this work, we propose an additional criterion for MILD coal combustion informed by scalar mixing spectra, and evaluate this against experimental data available in the literature. Our proposed criterion that the smallest mixing length scale needs to be smaller than the particle size, $\eta_{\text{mix}} < d_p$ (to breakup the heat and mass transfer boundary layers around particles and get well-mixed reactants), is consistent with experimental observations of MILD combustion and can discriminate between cases where MILD and traditional combustion are reported. For the traditional combustion, the particle size is always much bigger than the mixing length scales as we expect.

Perfectly-stirred reactor (PSR) and steady laminar flamelet (SLF) models are used to test the effects of recirculation rate ($K_v$), fuel-side mixture fraction ($\zeta$) and heat loss ($\gamma$). The light gas and tar products are used as fuel. The increase of recirculation rate is helpful to increase inlet temperature and reduce temperature increases in the reactor, which increases the temperature range for MILD combustion. Furthermore, the SLF results suggest that MILD is achieved for finite dissipation rates (e.g., without perfect mixing), which suggests that well-mixed reactants may be not needed for MILD combustion. This is something that warrants further investigation.

Our analysis indicates that large heat loss values have a negative effect on achieving MILD combustion by decreasing the inlet temperature, and thus the range of temperatures which bound the MILD regime. We also observe that dissipation rate required to achieve the MILD regime increases slightly for large heat loss values, and that the range of dissipation rate for which MILD combustion is obtained decreases for large heat loss due to extinction.

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References


