Pulverized Coal Ignition Delay under Conventional and Oxy-Fuel Combustion Conditions

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Motivation for Coal Stream Ignition Study

• Several studies have shown poorer ignition quality in oxy-fuel flames (depending on O_2 level, type of coal, type of burner, etc.)

• Gas stream momentum differences, C_p differences, and inherent ignitability differences (relative to air-fired) complicate understanding of flame-holding in oxy-fuel combustion

• Very limited data available on coal stream ignition in laminar flow (and no data under oxy-fuel conditions), for development/validation of CFD models
  - Ruiz, Annamalai, and Dahdah, HTD 1990
  - hv bit coal (Pee Wee), 53-75 µm
  - 9 vol-% O_2
  - ignition point via thermal image on camera
Theoretical Influence of Particle Loading on Ignition of Pulverized Coal Particles

• Characterize particle loading with Group No. (concept borrowed from droplet combustion theory)
  \[ G \sim n_p \cdot d_p \cdot r_{cloud}^2 \]

• Competing effects as particle loading increases
  - presence of merged volatiles clouds promotes mixing of volatiles with hot ambient (decreasing ignition delay)
  - at high particle loading, sheltered inner region of particles absorbs heat without yielding substantial volatiles (increasing ignition delay)
  - minimum in ignition delay as function of Group number
Experimental Setup: Combustion-Driven Optical Entrained Flow Reactor

- 5 cm X 5 cm x-section
- 1 atm
- furnace flow from compact, diffusion-flamelet burner
- coal particles introduced along centerline
- quartz chimney
- CCD for imaging of furnace central plane
- 431 nm bandpass filter to accentuate CH* detection
Steady Coal Feed: Requirement for Accurate Ignition Delay Measurement

• Enabled by installation of new coal particle feeder that produces steady coal flow rates up to 3 g/min through 0.75 mm ID steel tubing
  - design is modified version of concept developed in Prof. Sarofim’s lab at MIT
  - feed rate determined by rate of displacement of coal-containing test tube
  - similar feeders in use at Univ. of Utah and U.S. EPA
  - coal entrained by 0.033 slpm feed gas (diluent)
# Coals Investigated

**Popular U.S. and Chinese steam coals: 3 hv bituminous, 1 subbit.**

<table>
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<th>Proximate</th>
<th>Pittsburgh wt% as rec’d</th>
<th>Pittsburgh wt% dry</th>
<th>Black Thunder wt% as rec’d</th>
<th>Black Thunder wt% dry</th>
<th>Shenmu wt% as rec’d</th>
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* by difference
Furnace Conditions Investigated

• **Primary study (with coal feed rate variations)**
  - 12 vol-%, 16 vol-%, or 20 vol-% O₂
  - 1230 K furnace and 1320 K furnace with N₂ diluent
  - 1280 K furnace with CO₂ diluent
  - 12 vol-% H₂O in furnace gas
  - all 4 coals
  - mostly with 75–105 µm size cut, some with 54–74 µm and 106–125 µm size cuts

• **Secondary study (with fixed coal feed rate)**
  - explicit study of influence of N₂ vs. CO₂ diluent at identical temperatures
  - 20 vol-% O₂
  - 1200 K, 1340 K, and 1670 K furnace temperatures
  - 2 U.S. coals only
Why Use Moderate Oxygen Concentrations at High Temperatures for Ignition Studies

Coal stream ignition occurs in presence of mixture of hot flame products and air (or oxidizer mix, for oxy-fuel combustion)

Gas T must be 1100 K for rapid ignition
- for air preheated to 400 K, implies flame product/air mixture with 12 vol-% O₂
- For ignition in 20 vol-% O₂, implies oxidizer source with 40 vol-% O₂
Furnace Gas Temperature Profiles
(on centerline, with feed gas flowing)
Photographs of Coal Flow Ignition

Black Thunder coal, 12 vol-% O\textsubscript{2} in N\textsubscript{2} bulk gas

1230 K

1320 K

coal feedrate (x 0.005 g/min)
CCD Analysis of Images

Pittsburgh coal, 12 vol-% O₂ in N₂ at 1320 K, 54-74 um particles

- spread of particles at high feed rates (ambiguity in defining ignition)
- for simplicity, radially bin image data to single vertical profile
Samples of Processed Image Data

Pittsburgh coal, 12% O₂ in N₂, 1320 K
Shenmu coal, 20% O₂ in CO₂, 1280 K

• chosen ignition criteria: location where binned signal = ½ of max signal
• max upslope criteria gives same trends, slightly lower values
Ignition Delay Results: Influence of Feed Rate and Temperature

Pittsburgh coal, 12% O\textsubscript{2} in N\textsubscript{2}

- at intermediate T, ignition delay highly sensitive to T
- minimum ignition delay occurs for feed rate of 0.05 - 0.10 g/min (for Ruiz expt, min. occurred at 3 - 6 g/min)
Ignition Delay Results:
Influence of Coal Type

12% O₂ in N₂, 1320 K

- 3 high-volatile bituminous coals show nearly identical ignition delay, except at high particle loadings
- apparent ignition delay of subbituminous coal is slightly longer
Ignition Delay Results: Influence of Particle Size

Pittsburgh coal, 12% O₂ in N₂, 1320 K

- ignition delay is a strong function of particle size
- minimum ignition delay correlates better with particle number density than particle mass feed rate
Industrial Relevance of Coal Feed Densities

![Graph showing the relationship between particle number density and ignition delay, with a shaded area indicating the reported range for coal in pipes.](image-url)
Ignition Delay Results: Group Number Analysis

- per past practice, calculate $G$ based on conditions in feed tube
- $G$ appears to give better correlation for min. ignition delay than $n$
- $\tau_{\text{min}}$ occurs for $G \sim 0.3$, whereas Ruiz found $\tau_{\text{min}}$ for $G \sim 10$

\[
G = \frac{3 \rho_g R_c^2}{a^2 \rho_p \left( \frac{m_g}{m_p} \right)} = 3 \left( \frac{R_c}{a} \right)^2 \quad f_v = 2\pi n R_c^2 d_p
\]

Pittsburgh coal, 12% $O_2$ in $N_2$, 1320 K
Ignition Delay Results: Influence of Oxygen in Bulk Gas

Pittsburgh coal, N₂ diluent, 1320 K

- for T = 1320 K, weak dependence of ignition delay on O₂ content (if [O₂] ≤ 12 vol-%), except for when high particle loading
Ignition Delay Results: Influence of CO$_2$ in Bulk Gas

Pittsburgh coal, 20 vol-% O$_2$

- variation in ignition delay with particle loading is ~ same for N$_2$ and CO$_2$ diluents
- presence of CO$_2$ adds small ignition delay relative to N$_2$ environments
Conclusions

• PC coal stream ignition delay is highly sensitive to particle size and gas temperature

• Oxygen concentration (at least if 12 vol-%) has minor impact on ignition delay

• Large CO₂ concentration adds small additional delay (order of 10%)

• Ignition delay first decreases slightly as particle loading increases, then rises rapidly for high particle loadings

• Group number correlates results for different size bins very well, but G for min. ignition delay is very different than Ruiz result
Acknowledgments

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End of Presentation

Questions?