SAND2011-3702C

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

Christopher Shaddix, Yinhe Liu[†], Manfred Geier,
and Alejandro Molina[‡]

Combustion Research Facility
Sandia National Laboratories
Livermore, CA 94550

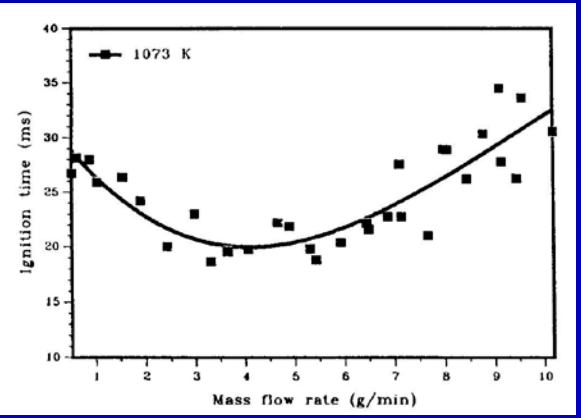
[†] Xi'an Jiatong University
Xi'an, China

[‡] Universidad Nacional de Colombia
Medellín, Colombia

2nd IEA GHG International Oxyfuel Combustion Conference
Yeppoon, Australia
September 12-16, 2011

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

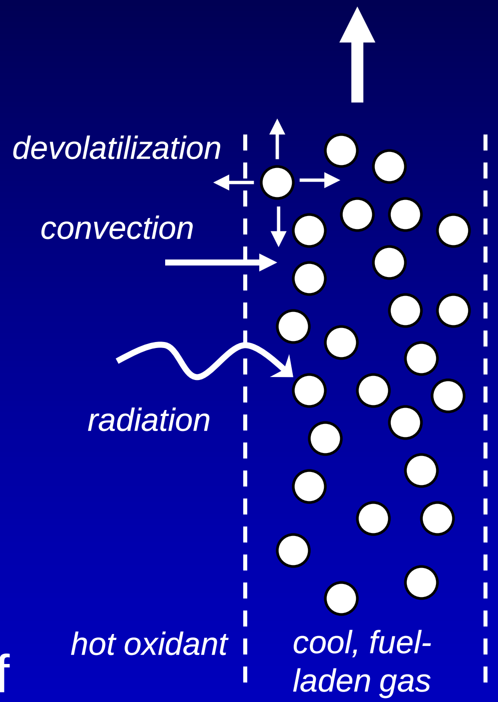


Theoretical Influence of Particle Loading on Ignition of Pulverized Coal Particles

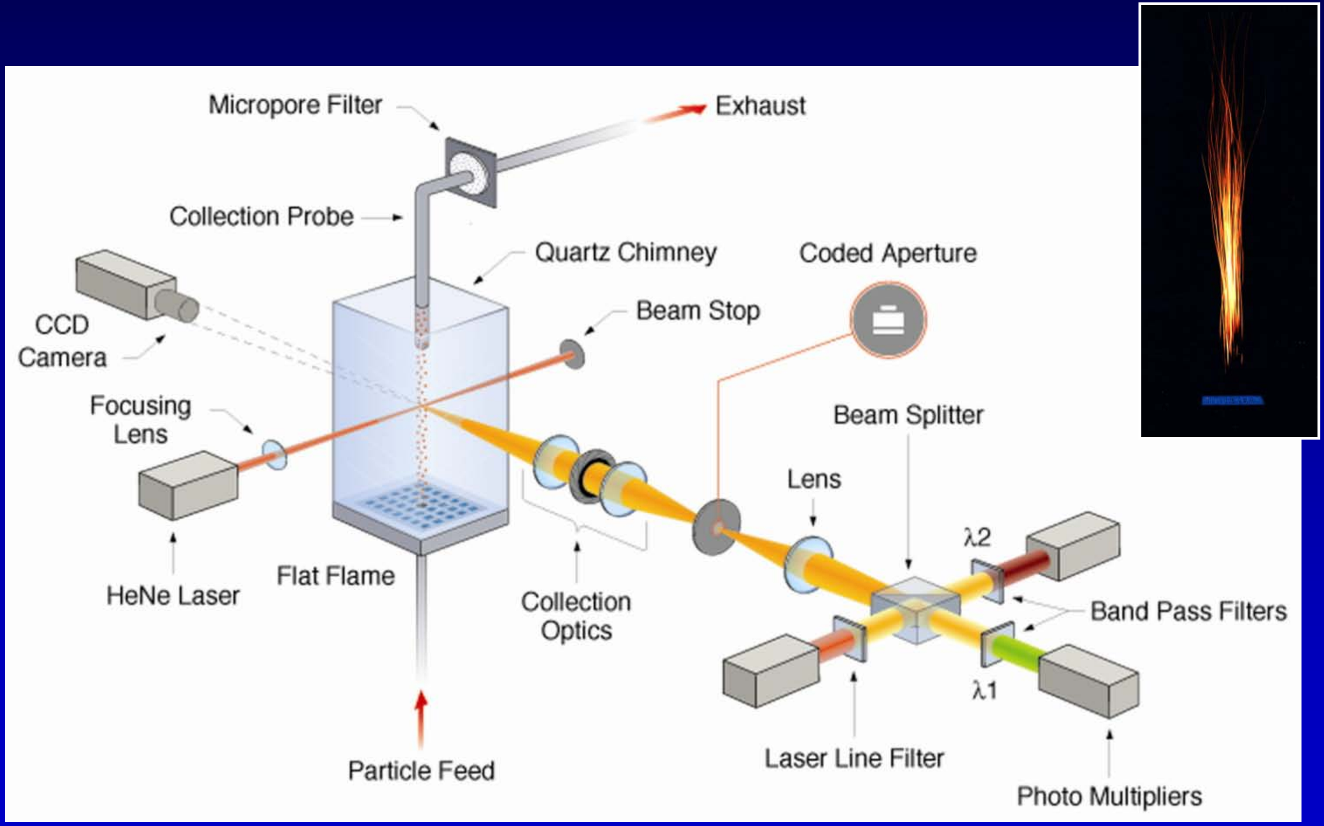
- **Characterize particle loading with Group No. (concept borrowed from droplet combustion theory)**

  $$G \sim n_p * d_p * r_{cloud}^2$$

- **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



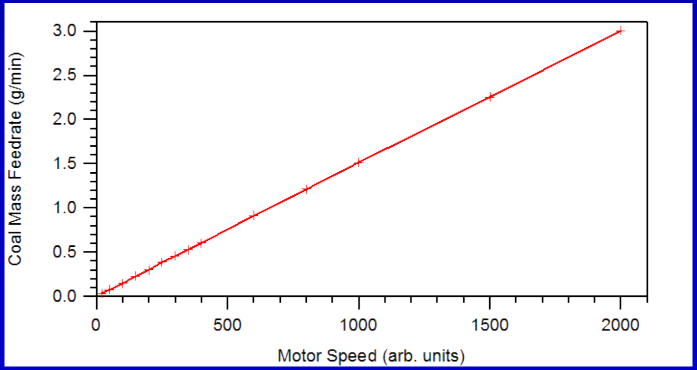
Experimental Setup: Combustion-Driven Optical Entrained Flow Reactor



- 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)



Coal feed calibration plot

Photograph of pulverized coal feeder

Coals Investigated

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

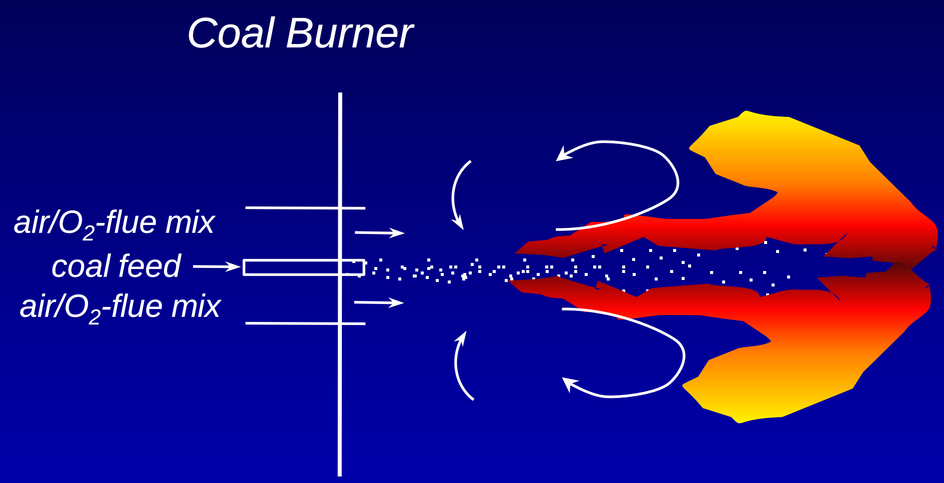
	Coal Type							
	Pittsburgh		Black Thunder		Shenmu		Guizhou	
Proximate	wt%, as rec'd	wt% dry	wt%, as rec'd	wt% dry	wt%, as rec'd	wt% dry	wt%, as rec'd	wt% dry
moisture	1.4		10.8		5.7		5.7	
ash	6.9	7.0	5.0	5.6	8.7	9.2	31.8	33.8
volatiles	35.4	35.9	40.4	45.3	35.1	37.2	22.8	24.1
fixed C	56.3	57.1	43.8	49.1	50.5	53.5	39.7	42.1
Ultimate	wt% dry	wt% daf	wt% dry	wt% daf	wt% dry	wt% daf	wt% dry	wt% daf
C	77.2	82.9	60.9	64.1	78.8	86.8	55.6	84.0
H	5.2	5.6	5.2	5.5	4.7	5.2	3.5	5.3
O [a]	7.2	7.7	27.6	29.1	4.8	5.7	5.0	7.6
N	1.5	1.6	0.9	0.9	1.2	1.4	0.9	1.6
S	2.0	2.2	0.4	0.5	0.8	1.0	1.1	1.5

[a] by difference

Furnace Conditions Investigated

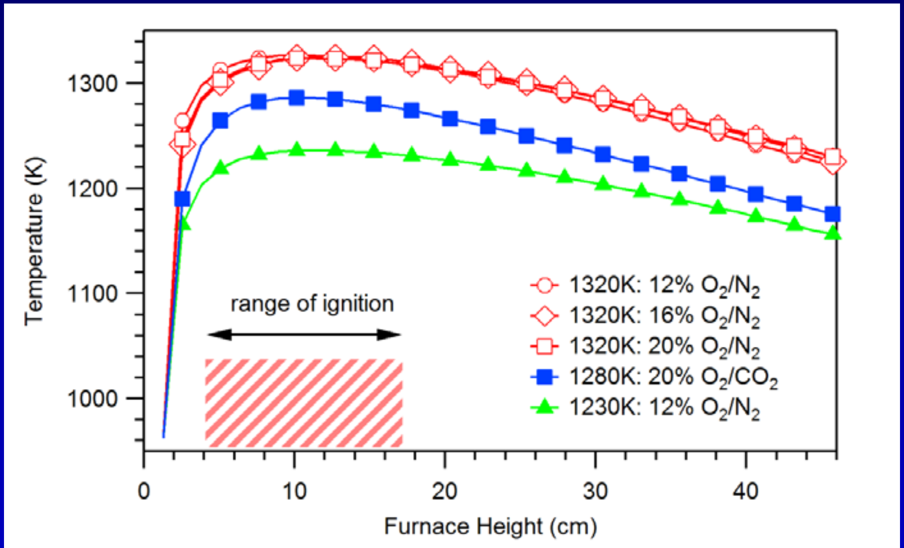
- **Primary study (with coal feed rate variations)**
  - 12 vol-%, 16 vol-%, or 20 vol-% O_2
  - 1230 K furnace and 1320 K furnace with N_2 diluent
  - 1280 K furnace with CO_2 diluent
  - 12 vol-% H_2O in furnace gas
  - all 4 coals
  - mostly with 75–105 μm size cut, some with 54–74 μm and 106–125 μm size cuts
- **Secondary study (with fixed coal feed rate)**
  - explicit study of influence of N_2 vs. CO_2 diluent at identical temperatures
  - 20 vol-% O_2
  - 1200 K, 1340 K, and 1670 K furnace temperatures
  - 2 U.S. coals only

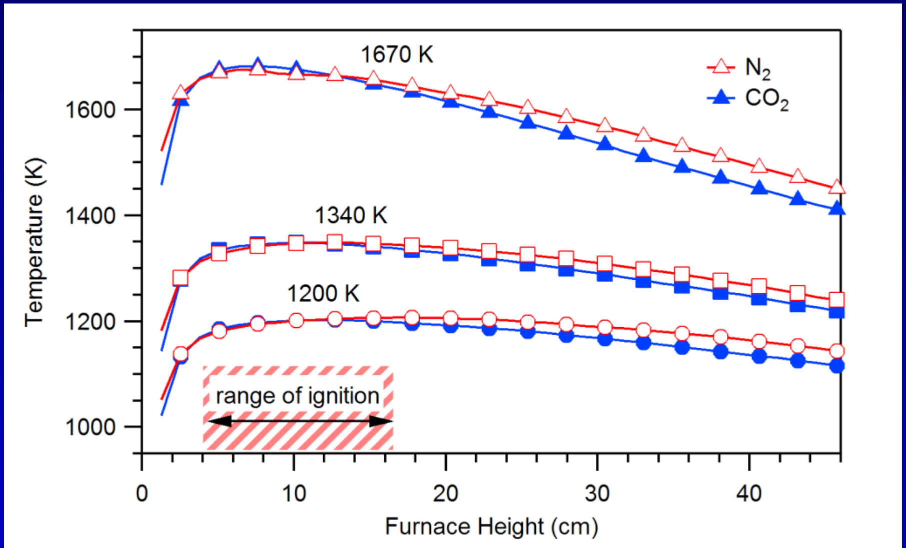
Why Use Moderate Oxygen Concentrations at High Temperatures for Ignition Studies



- **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-% O_2
  - For ignition in 20 vol-% $O_{2,}$ implies oxidizer source with ≥ 40 vol-% O_2

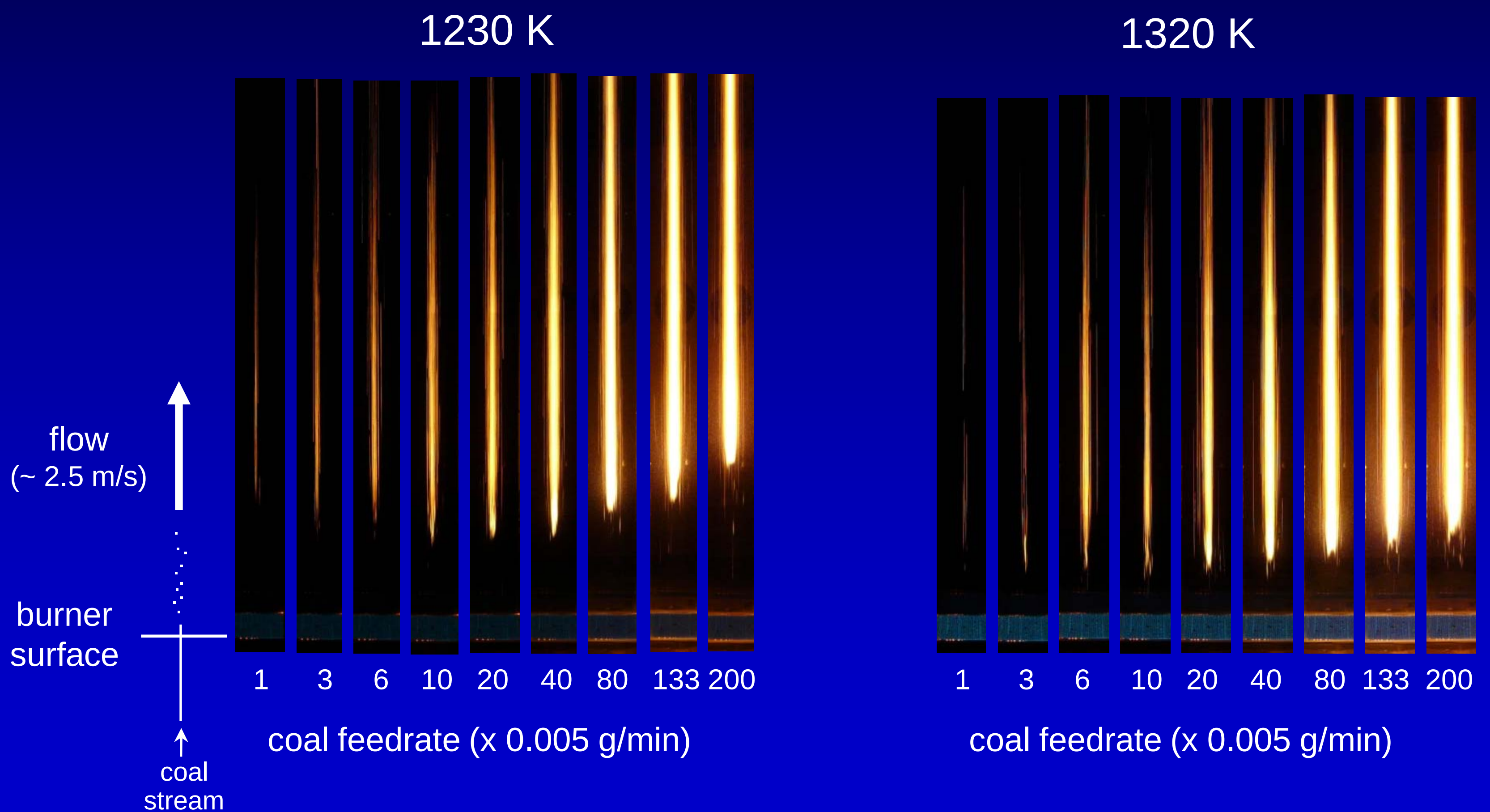
Furnace Gas Temperature Profiles
(on centerline, with feed gas flowing)





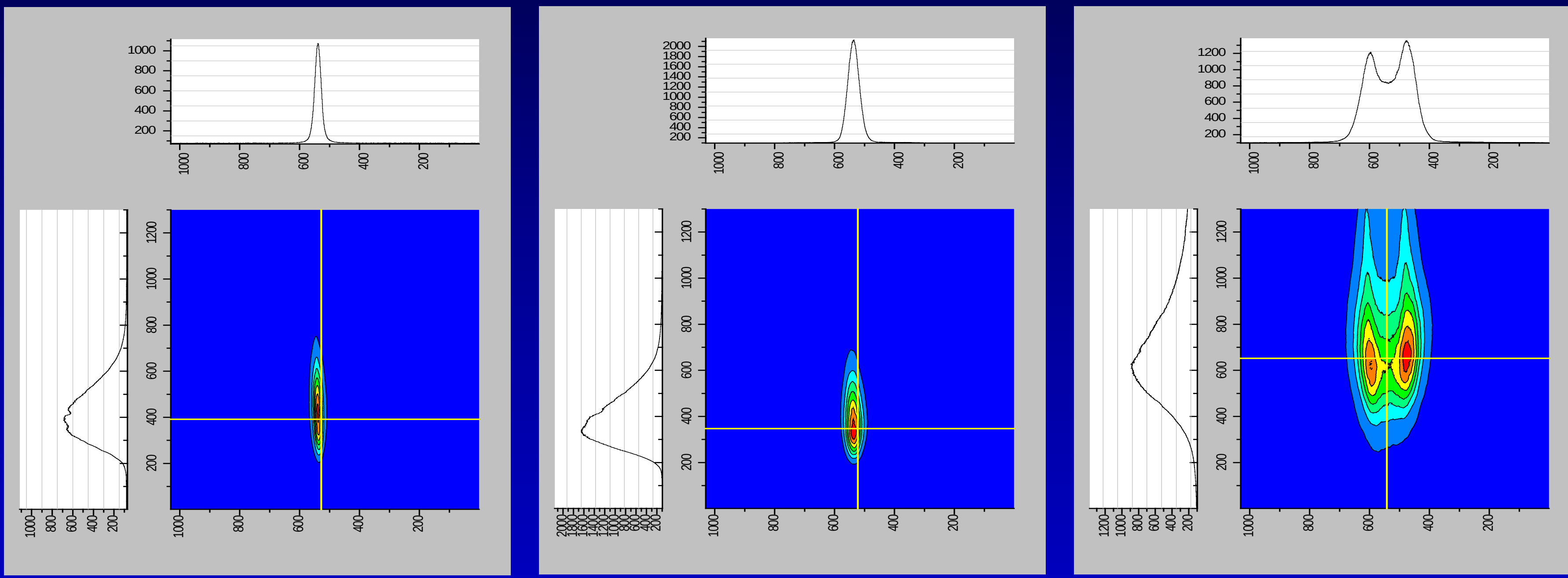
Photographs of Coal Flow Ignition

Black Thunder coal, 12 vol-% O_2 in N_2 bulk gas



CCD Analysis of Images

Pittsburgh coal, 12 vol-% O_2 in N_2 at 1320 K, 54-74 um particles



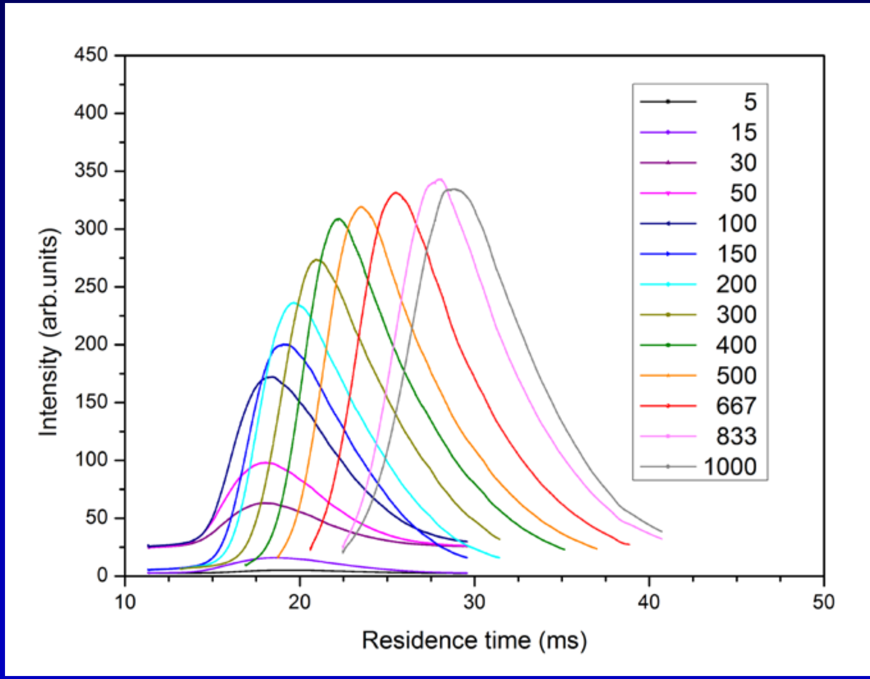
0.005 g/min   0.050 g/min   1.000 g/min

flow ↑

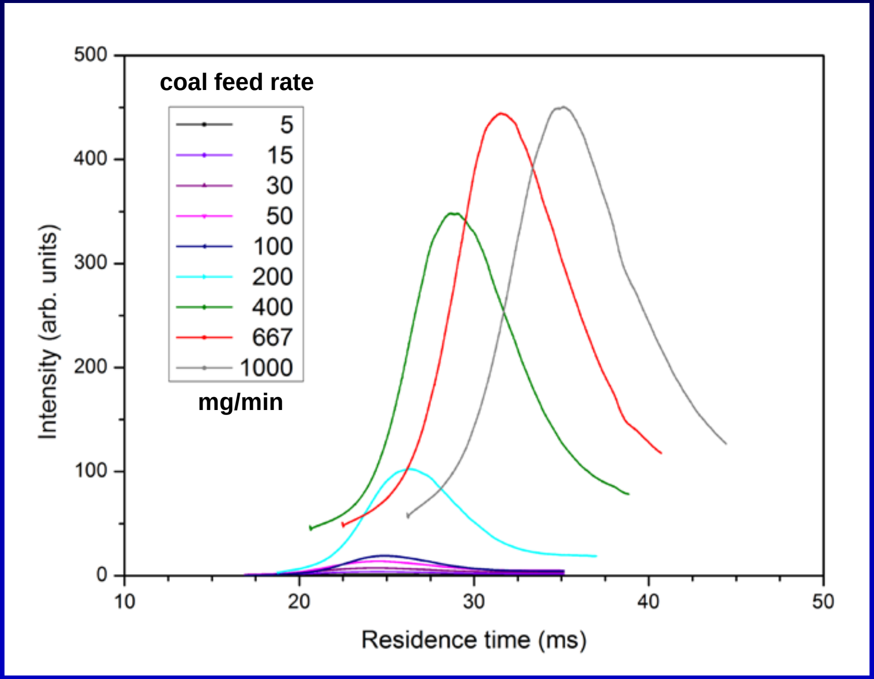
- **spread of particles at high feed rates (ambiguity in defining ignition)**
- **for simplicity, radially bin image data to single vertical profile**

Samples of Processed Image Data

Pittsburgh coal, 12% O_2 in N_2, 1320 K



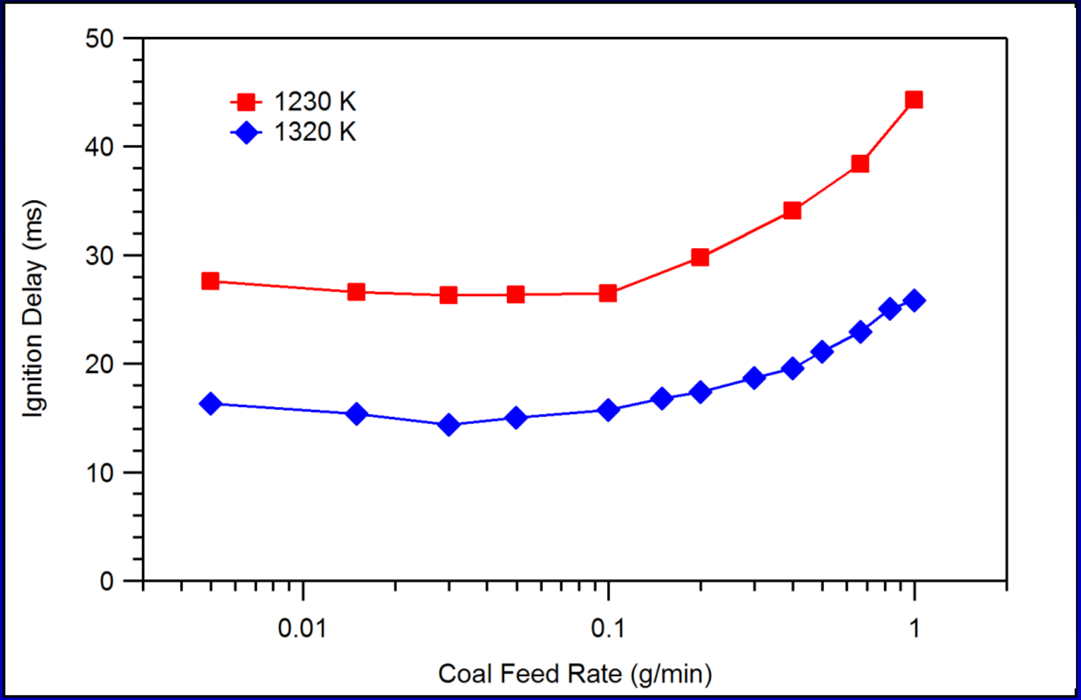
Shenmu coal, 20% O_2 in CO_2, 1280 K



- 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

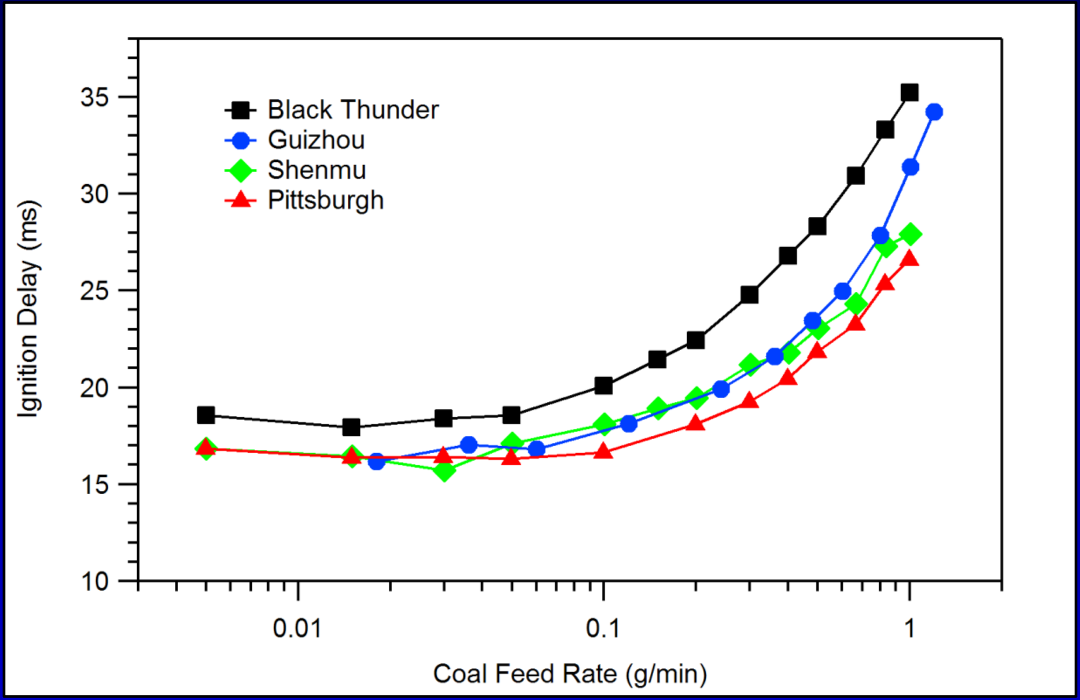
Pittsburgh coal, 12% O_2 in N_2



- **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

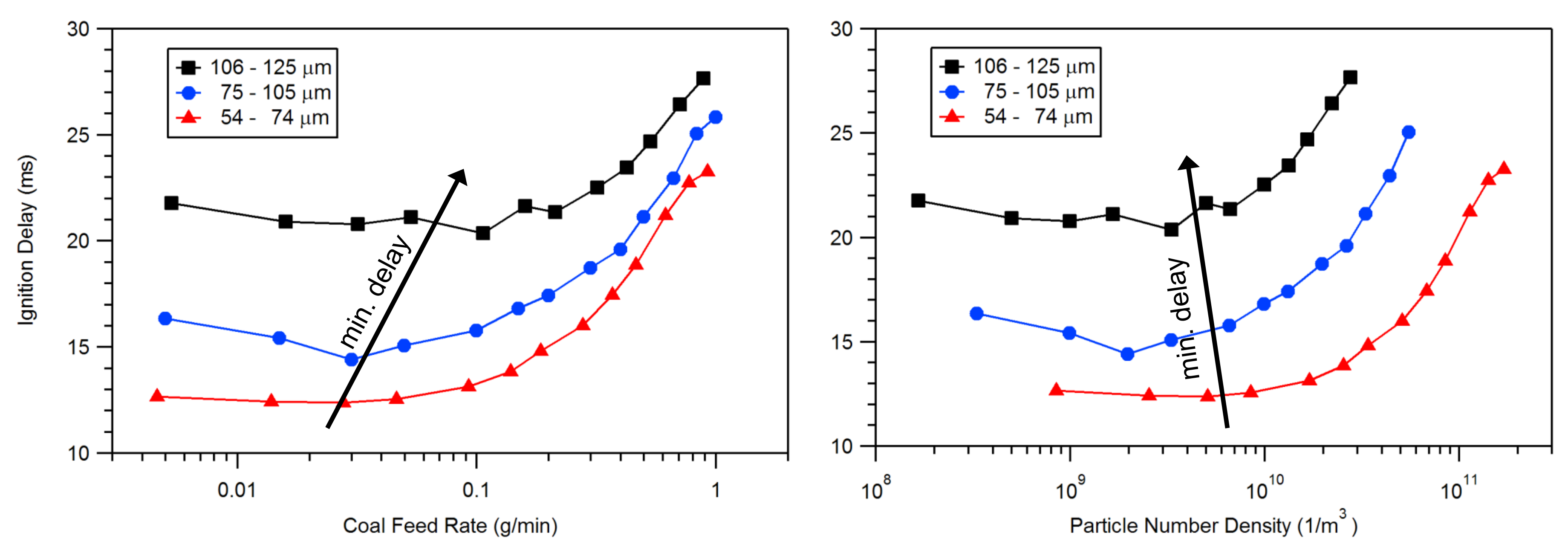
12% O_2 in N_2, 1320 K



- **3 high-volatile bituminous coals show nearly identical ignition delay, except at high particle loadings**
- **apparent ignition delay of subbituminous coal is slightly longer**

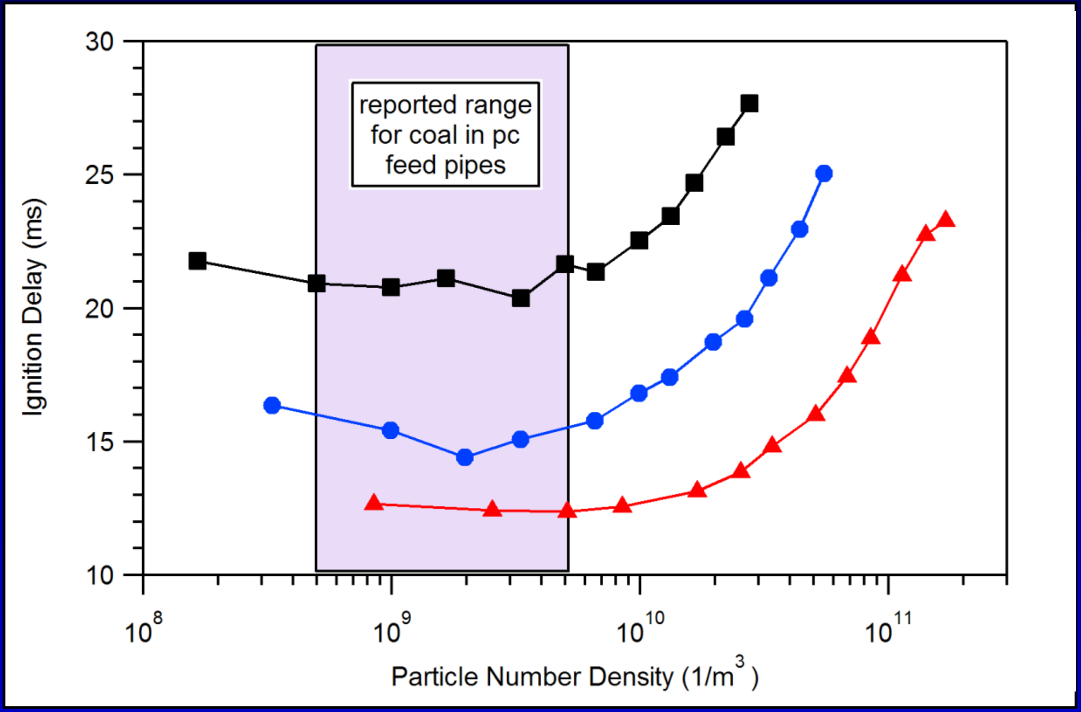
Ignition Delay Results: Influence of Particle Size

Pittsburgh coal, 12% O_2 in N_2, 1320 K



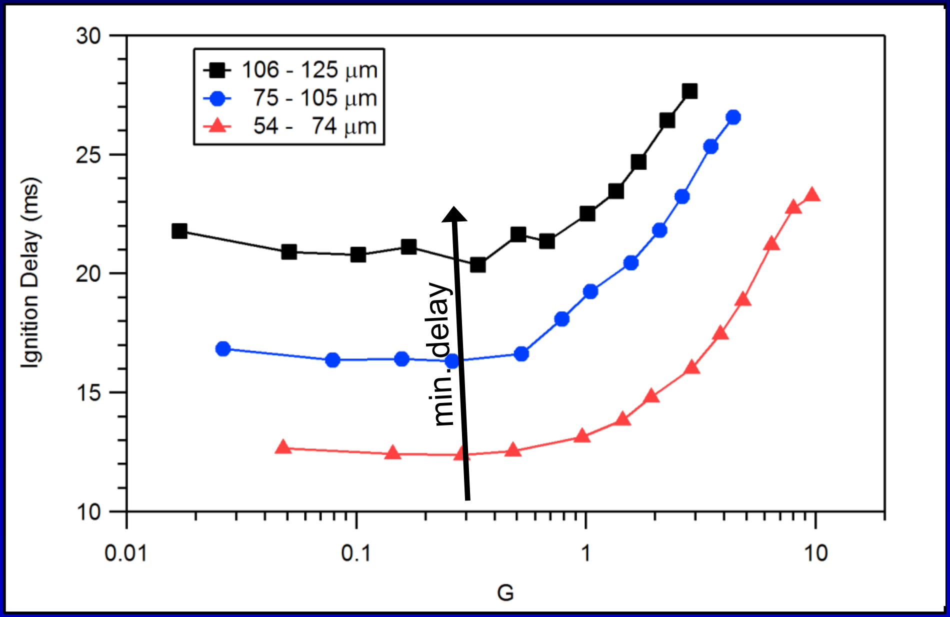
- **ignition delay is a strong function of particle size**
- **minimum ignition delay correlates better with particle number density than particle mass feed rate**

Industrial Relevance of Coal Feed Densities



Ignition Delay Results: Group Number Analysis

$$G = \frac{3\rho_g R_c^2}{a^2 \rho_p \left(\dot{m}_g / \dot{m}_p\right)} = 3\left(\frac{R_c}{a}\right)^2 f_v = 2\pi n R_c^2 d_p$$

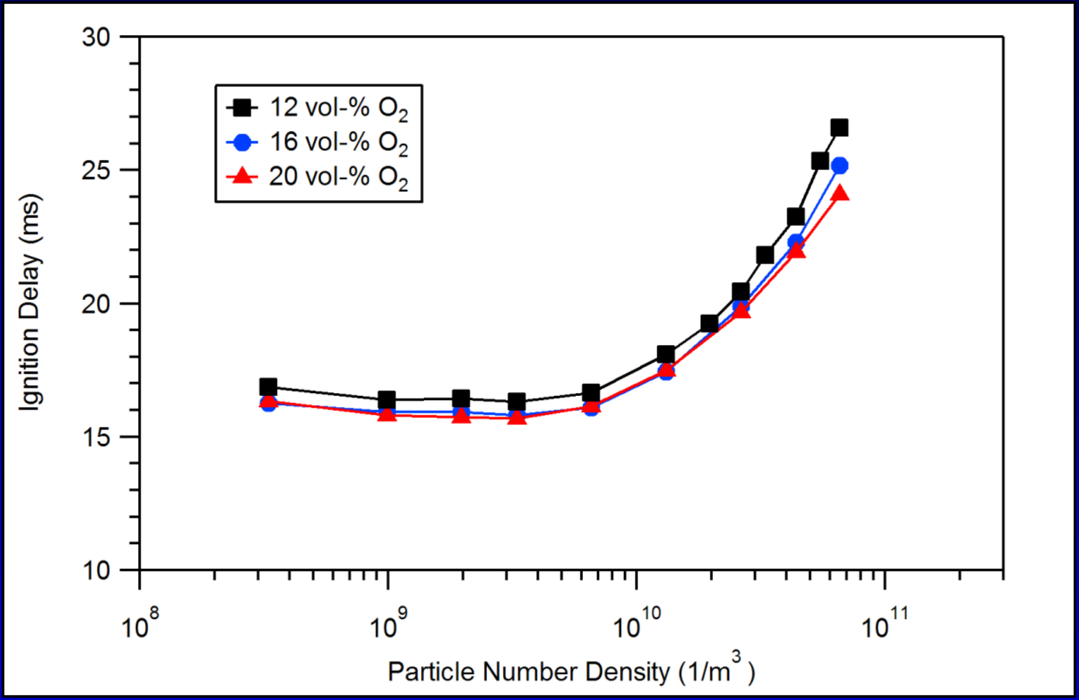


Pittsburgh coal,
12% O_2 in N_2,
1320 K

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

Ignition Delay Results: Influence of Oxygen in Bulk Gas

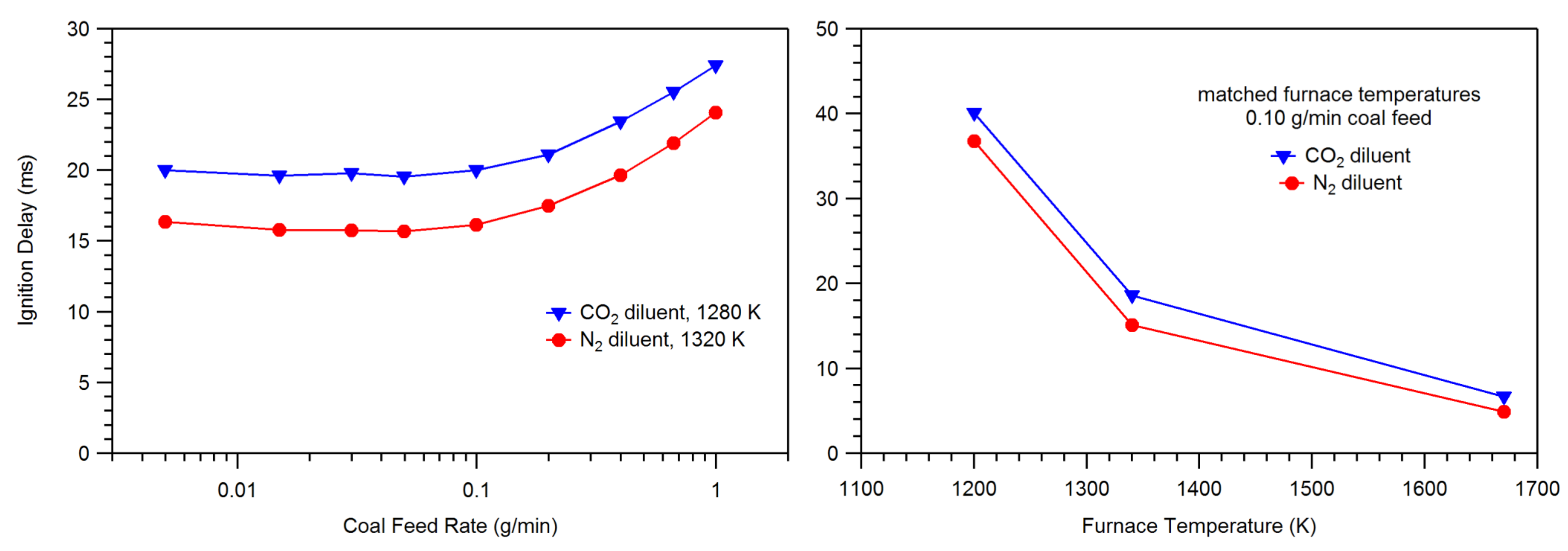
Pittsburgh coal, N_2 diluent, 1320 K



- **for T ≥ 1320 K, weak dependence of ignition delay on O_2 content (if $[O_2]$ ≥ 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 CO_2 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

Research sponsored by U.S. DOE Fossil Energy Power Systems Advanced Research program, managed by Dr. Robert Romanosky, National Energy Technology Laboratory (NETL)

End of Presentation

Questions?