Lab-Scale Studies of Oxy-fuel Combustion

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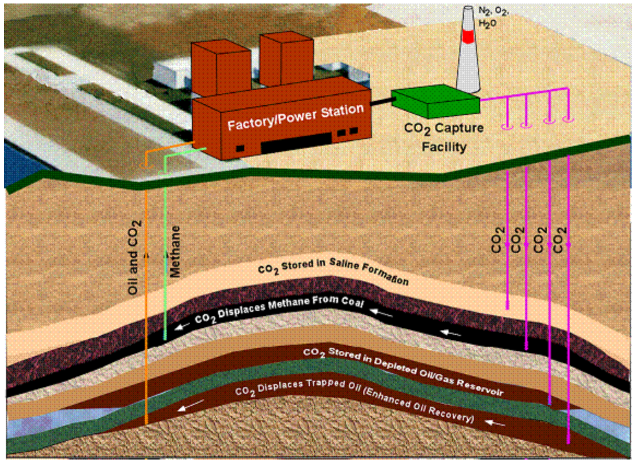
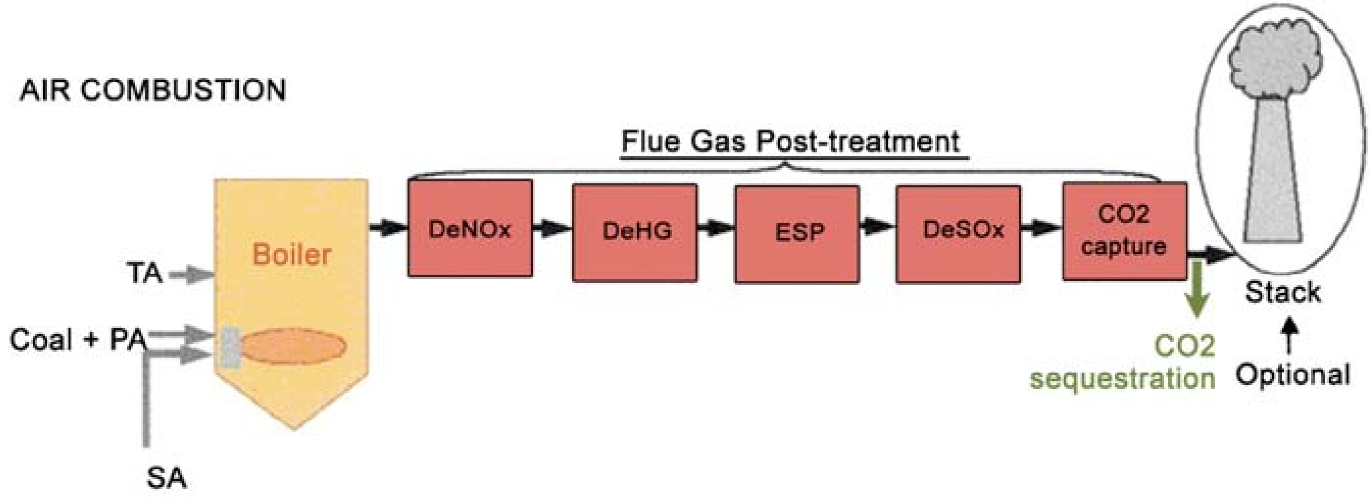
Benefits of O_2-Enriched Combustion

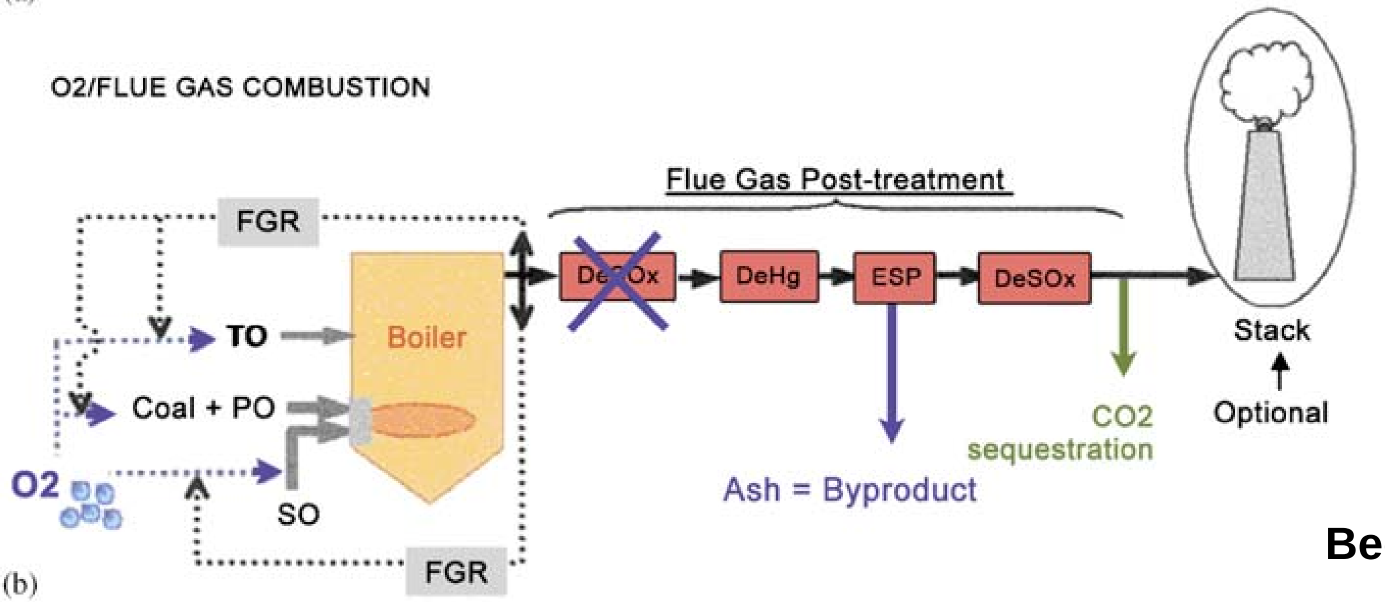
- Reduces NO_x
  - Reduces amount of nitrogen in flame
- Recirculation of flue gas
  - reduces fuel-NOx
  - Improves sorbent capture of SO_2
- Reduces flue gas volume
- Facilitates CO_2 capture and sequestration
  - high concentration of CO_2 in exhaust stream ~ 95% (Kimura, et al, 1995)



Oxy vs. Air-Fired Coal Combustion



(a)



(b)

Beer '07

Motivation

- Oxy-fuel combustion opens up the potential for a wide range of novel mixing scenarios that are not available when air is the primary oxidizer.

- The method of mixing the reactant streams can dramatically affect the local composition and temperature and this, in turn, can affect the products of combustion.

- Oxy-fuel combustion can be optimized for multi-pollutant control

Inert Exchange to Vary Z_{st}

Stoichiometric Mixture Fraction, Z_{st}

Mixture fraction where fuel and oxidizer are in stoichiometric proportions

$$Z_{st} = \left(1 + \frac{Y_{F,0} W_{Ox} \nu_{Ox}}{Y_{Ox,0} W_F \nu_F} \right)^{-1}$$

Constant amount of inert at flame fixes adiabatic flame temperature

For example:

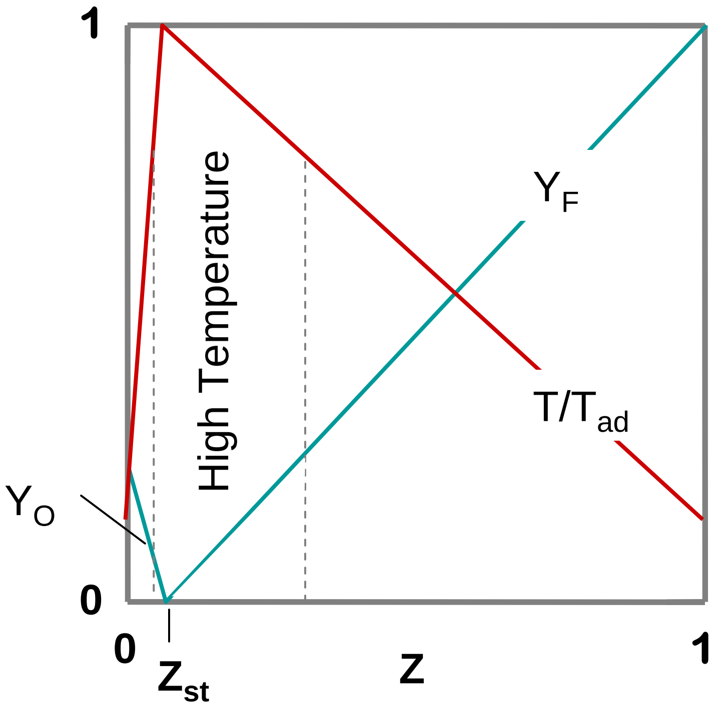
$C_2H_4 + (3O_2 + 11.3\ N_2) \rightarrow$ products $\quad Z_{st} = .064$

$(C_2H_4 + 11.3\ N_2) + 3O_2 \rightarrow$ products $\quad Z_{st} = .78$

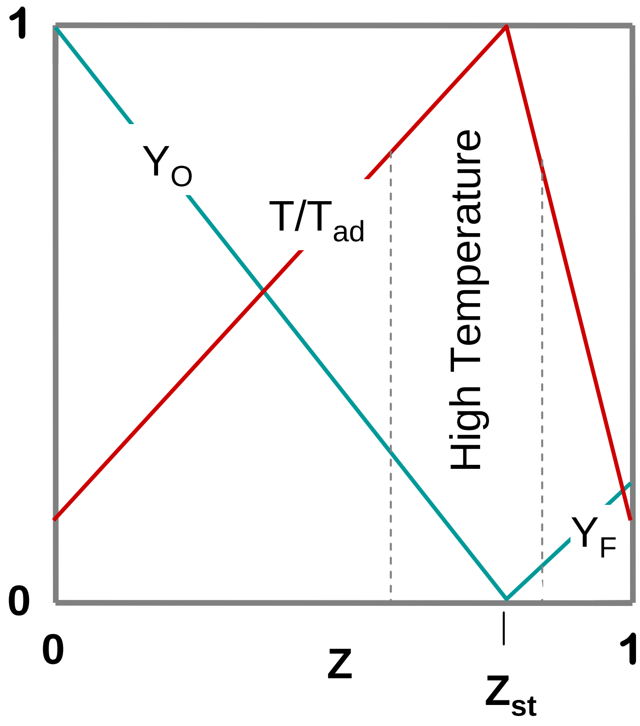
$T_{ad} = 2370K$

Global Flame Structure

“Normal” Structure: $Z_{st} = 0.064$



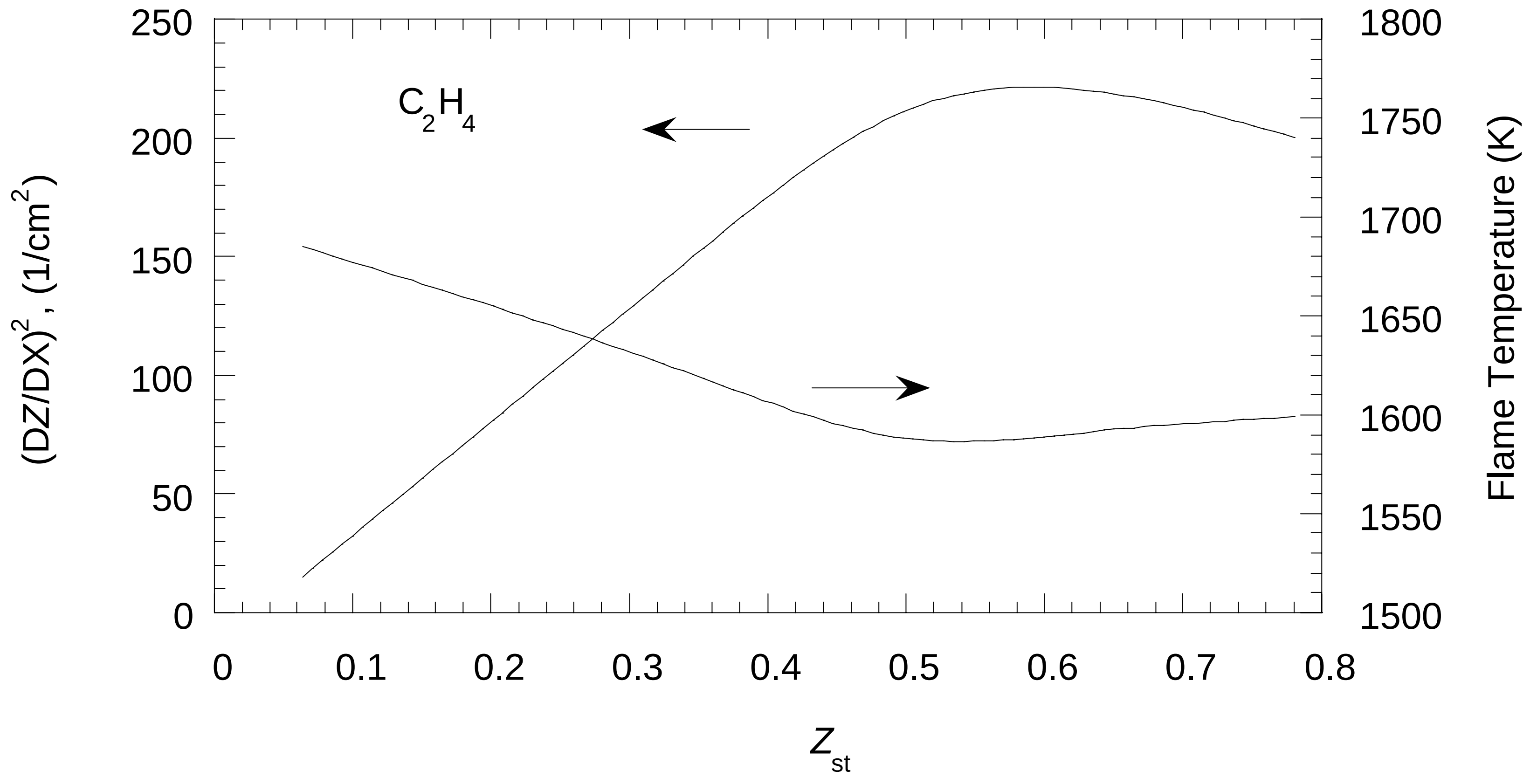
“Inverted” Structure: $Z_{st} = 0.78$



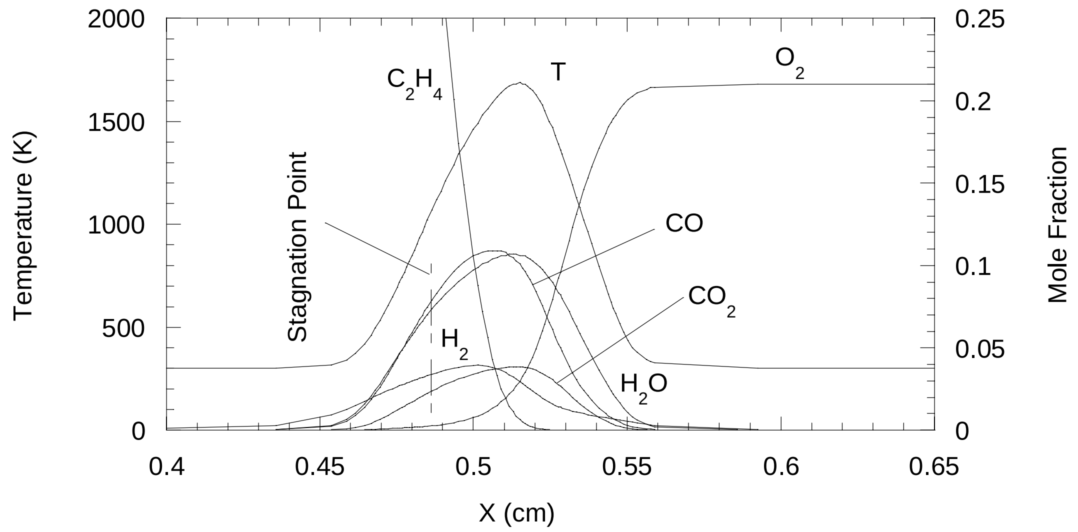
Increasing stoichiometric mixture fraction:

- **Increases the oxygen concentration in the high temperature region, thus strengthening the flame.**
- **Reduces the high-temperature region on the fuel-rich side, thus reducing soot inception.**

Effect of Z_{st} on Extinction

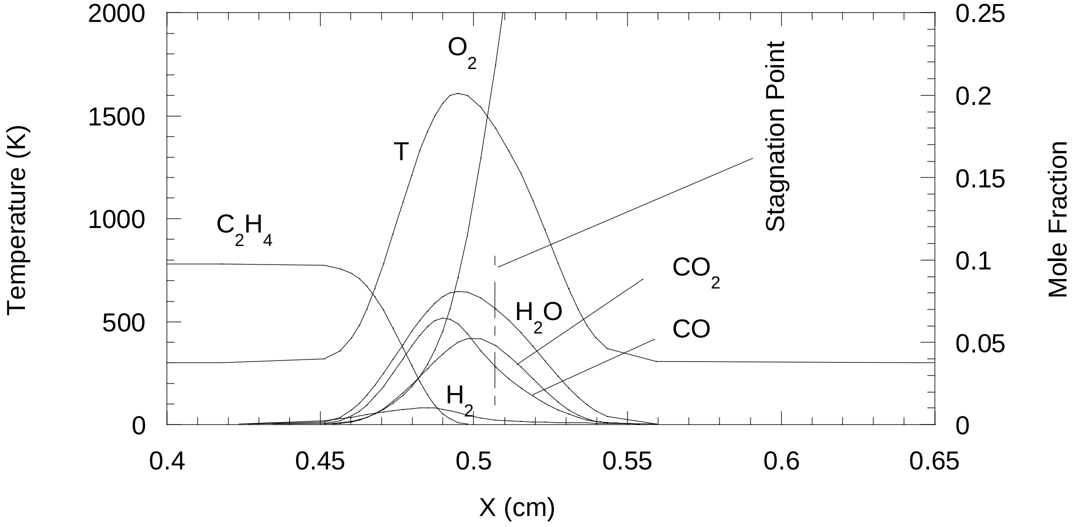


Major Species and Temperature



Flame 1:

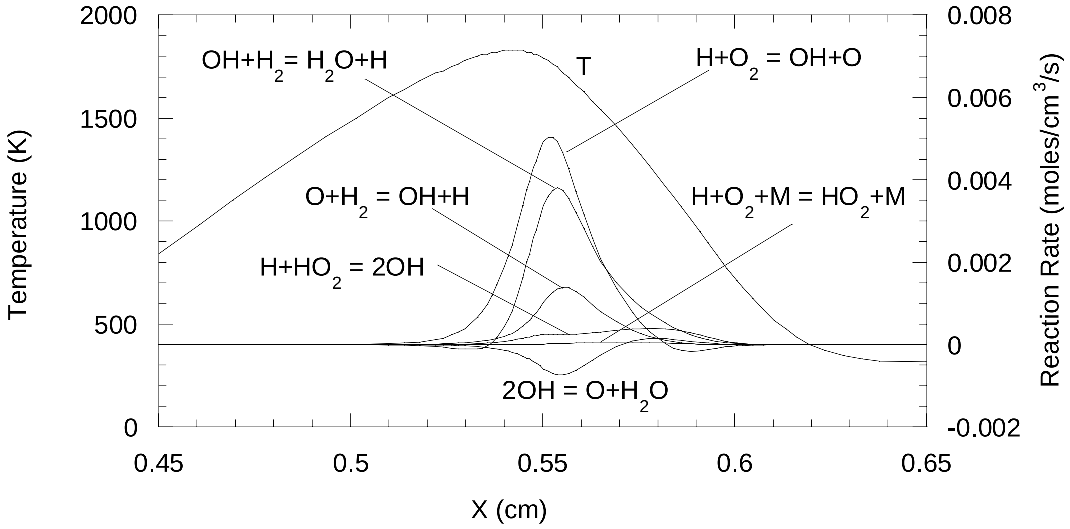
$Z_{st} = 0.064$



Flame 5:

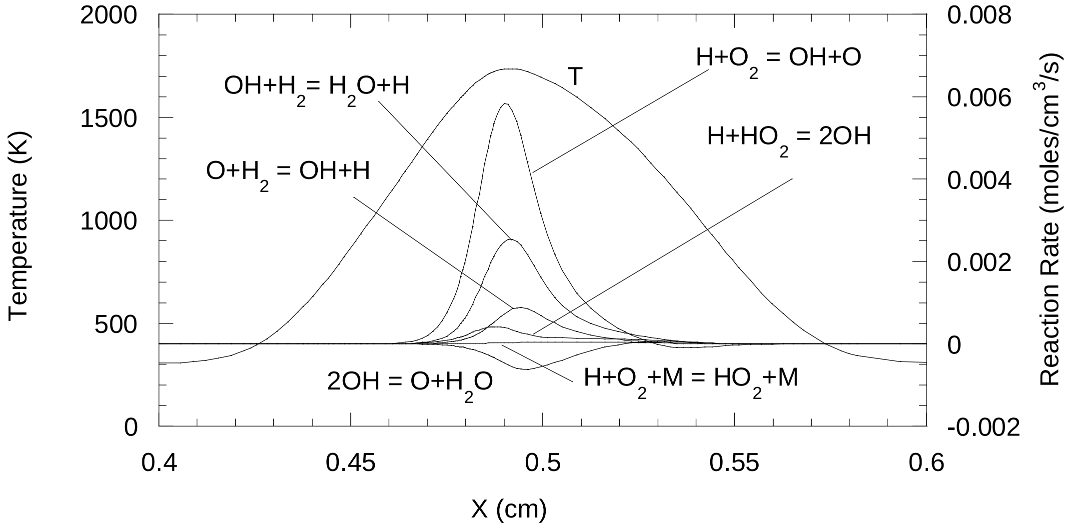
$Z_{st} = 0.78$

Reaction Rates and Temperature



Flame 1:

$Z_{st} = 0.064$



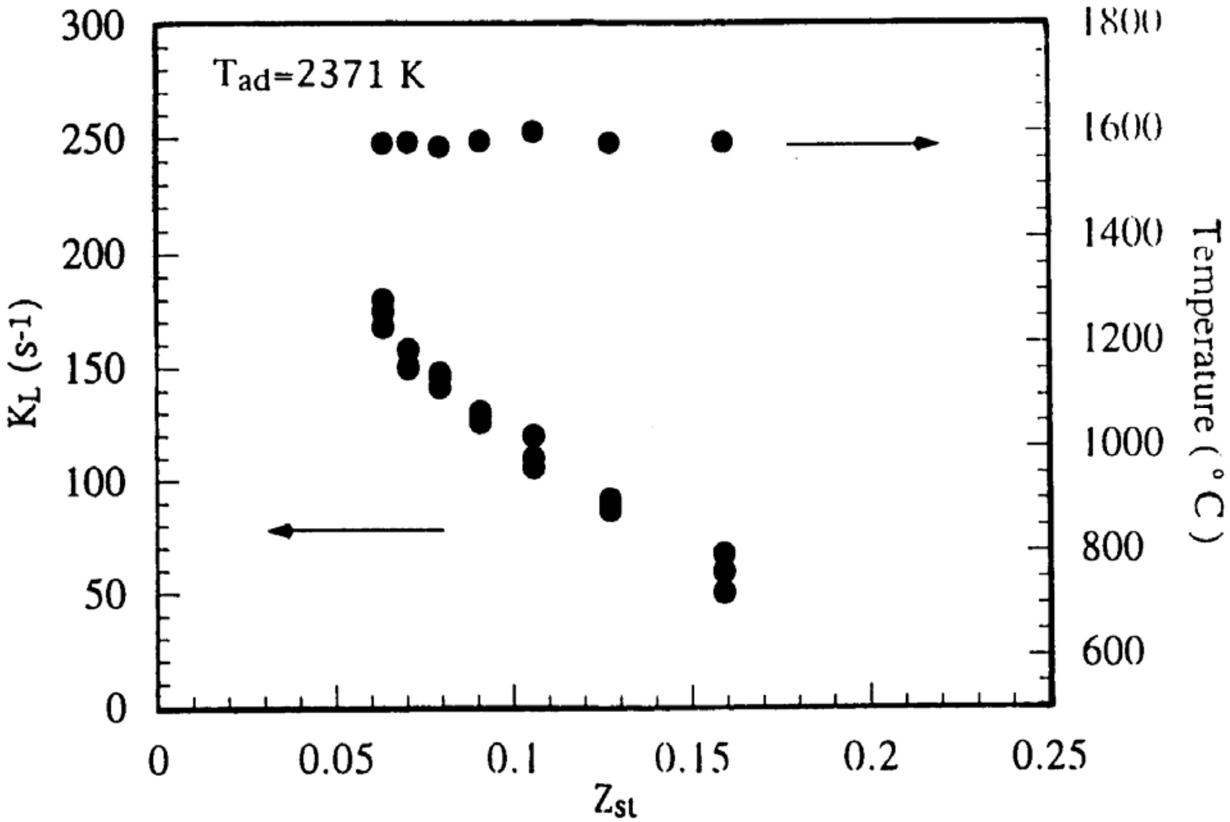
Flame 4:

$Z_{st} = 0.65$

Soot Inception Limits

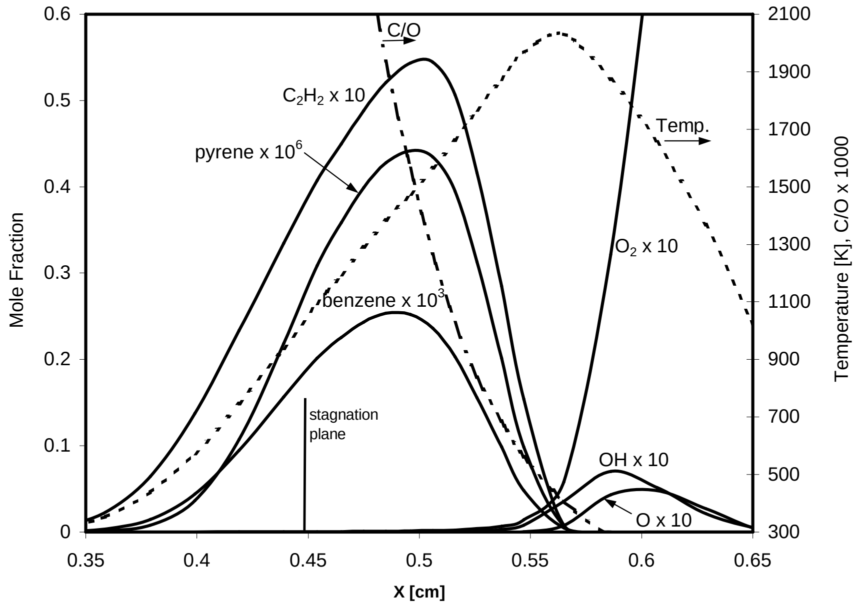
Counterflow Diffusion Flames

$C_2H_4 + 3O_2 + 11.3\ N_2 \rightarrow$ products; $(T_{ad} = 2371K)$

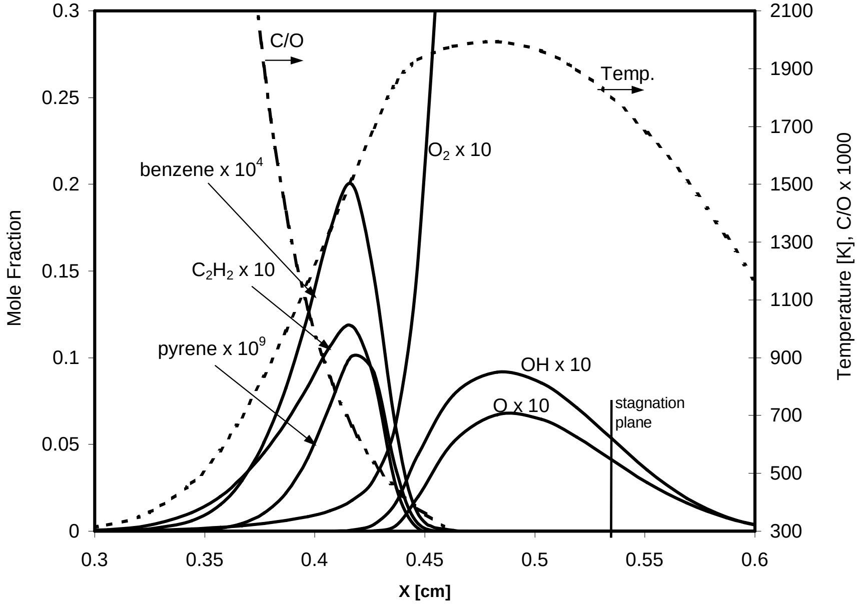


Du and Axelbaum, C&F (1995)

Structure of Low and High Z_{st} Flames



Zst =0.064



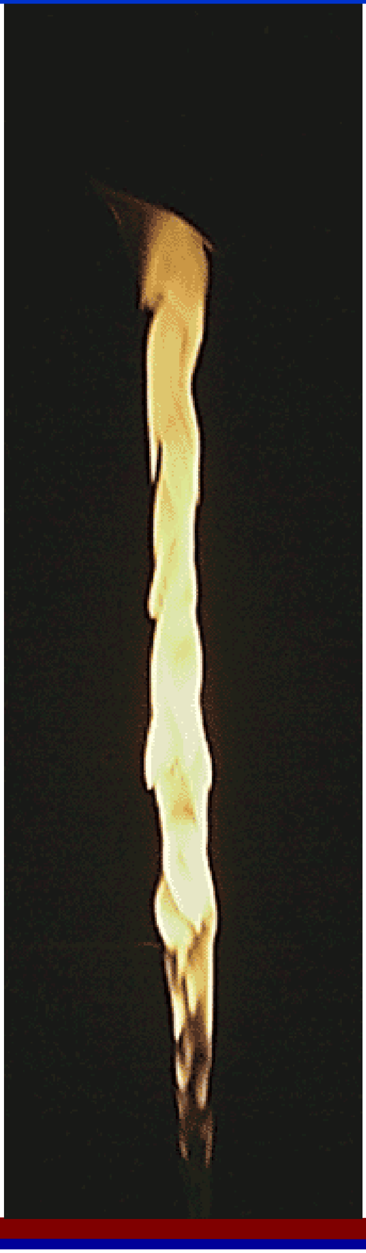
Zst =0.78

OEC in Turbulent Jet Flames

C_2H_4/Air

$Z_{st} = 0.064$

$T_{ad} = 2370$ K



$C_2H_4+CO_2/O_2$

$Z_{st} = 0.74$

$T_{ad} = 2543$ K

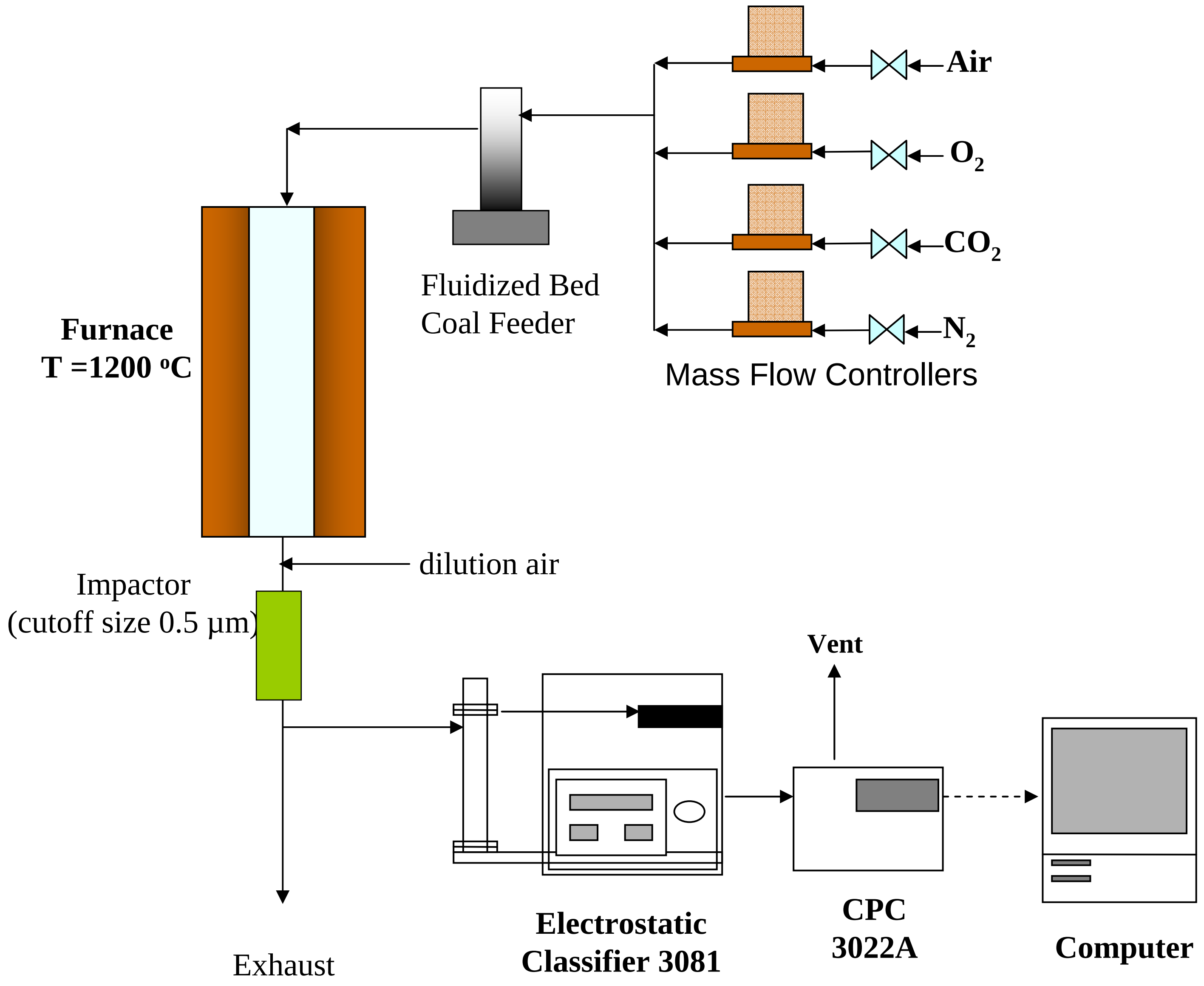
Inverted

Objectives – Part A

Employing a Drop-tube furnace determine the effects of O_2 - CO_2 coal burning on:

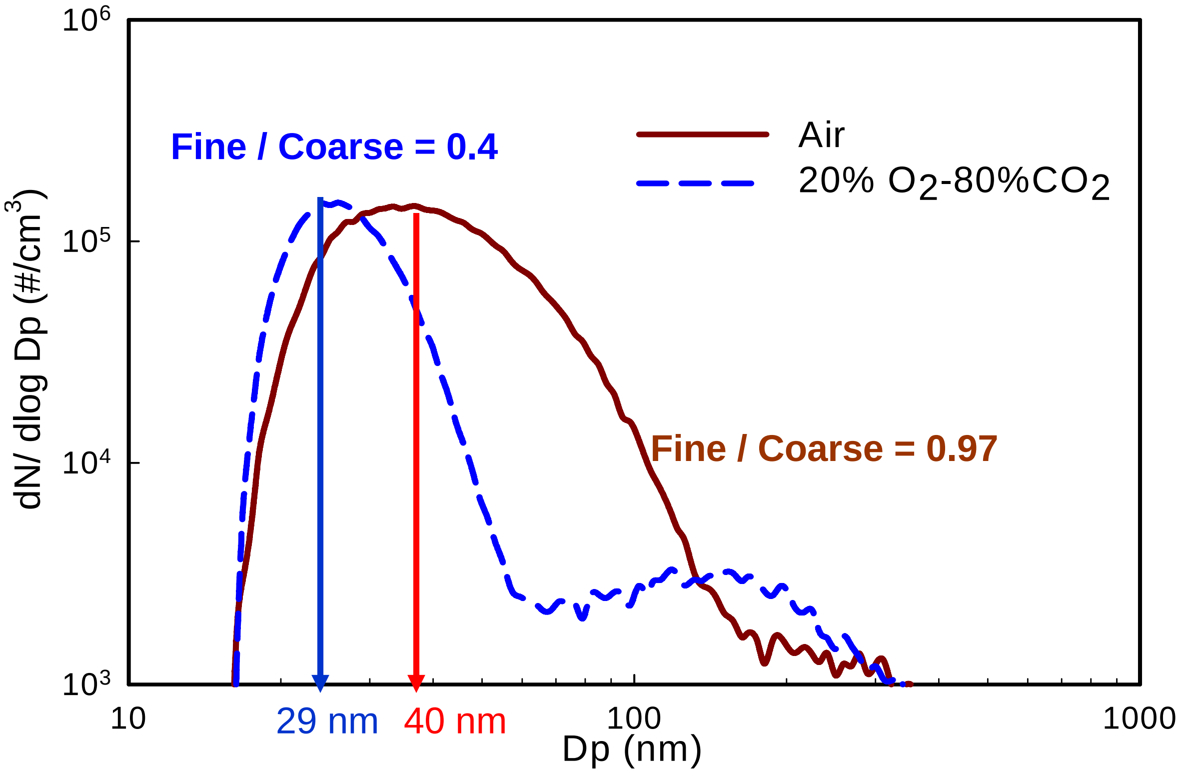
1. the aerosol characteristics of submicrometer-sized particles
2. the capture efficiency of the particles by an electrostatic precipitator (ESP)
3. Mercury speciation

Experimental Setup

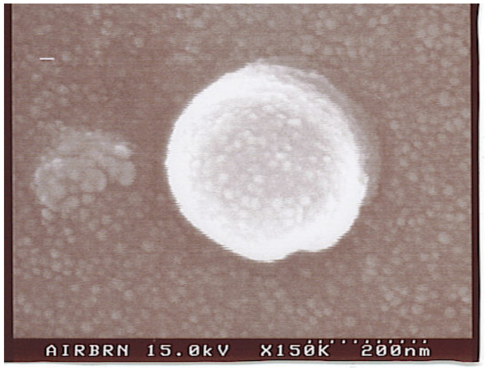


Aerosol Characteristics

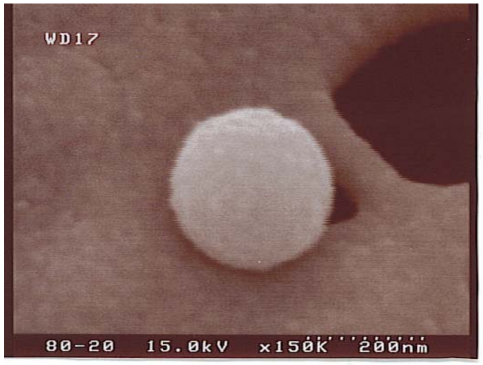
Air vs. 20%O_2+80%CO_2



Air Burn



O_2/CO_2 Burn



When AIR is replaced by 20%O_2+80%CO_2:

- Geometric mean particle size decreases from 40 nm to 29 nm
- Total number concentration decreases from 6.4 x10^4 to 3.9 x10^4
- No effects on particle shape

Suriyawong et al, *Energy&Fuels,* 2006; 20(6) pp 2357 - 2363

Effect of Carbon Dioxide

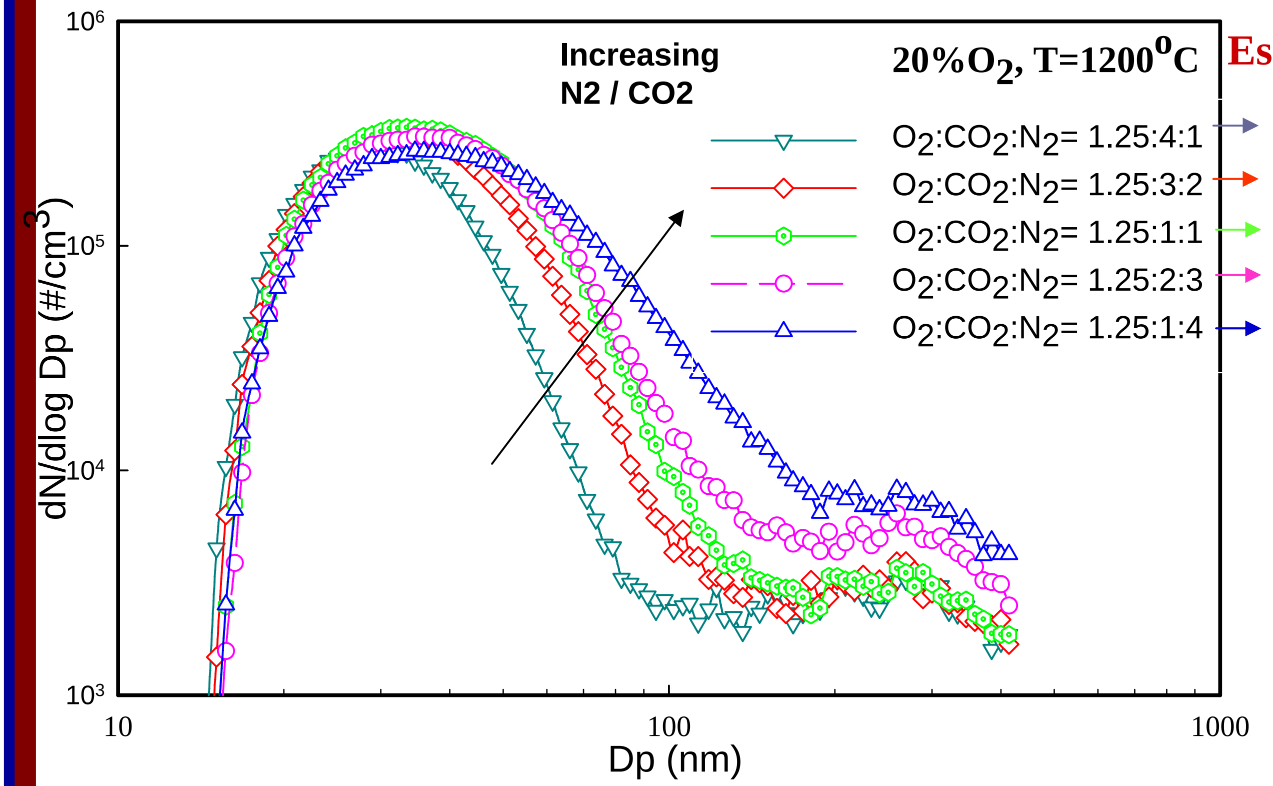
	N_2	CO_2
• Density (kg/m^3)	0.28	0.45
• Heat Capacity (kJ/kmol-ºC)	20.78	58.84
• Diffusivity(m^2/s)	1.7×10^{-4}	1.3×10^{-4}

Replacing N_2 (AIR) with CO_2, results in:

1. slower ignition time for both coal and char particles *(Molina and Shaddix, 2005)*
2. lower temperature in the vicinity of burning coal particle, leading to slower vaporization
3. slower diffusion rate of O2 to the surface of char particle *(Molina and Shaddix, 2005)*.

HENCE, SUBMICROMETER AEROSOL FORMATION IS SLOWED

Effects of N_2/CO_2 mixture

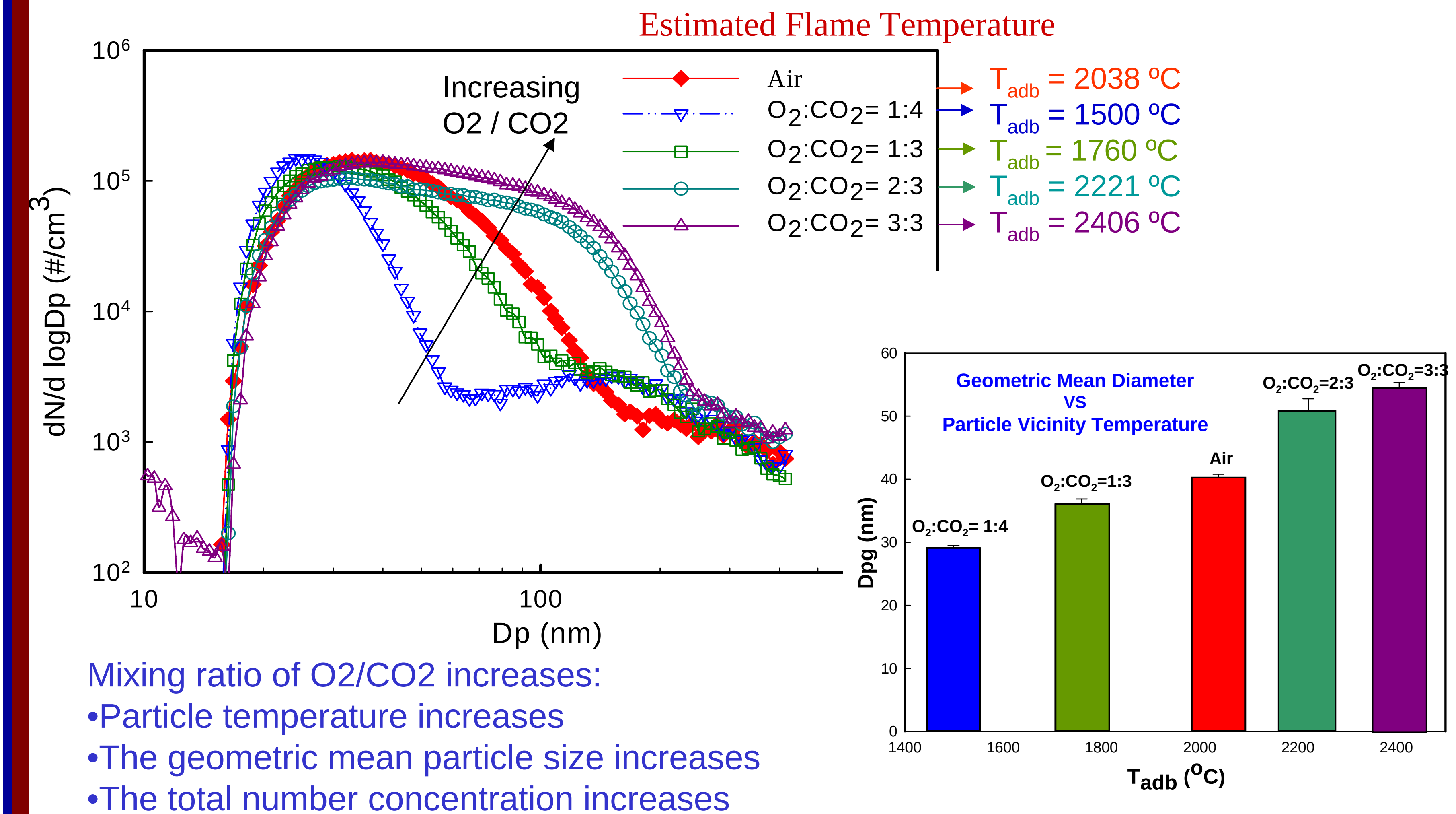


Estimated Flame Temperature

→ T_{adb} = 1576 °C
→ T_{adb} = 1660 °C
→ T_{adb} = 1704 °C
→ T_{adb} = 1752 °C
→ T_{adb} = 1856 °C

- N_2 has lower specific heat capacity than CO_2
- Particle vicinity temperature increases with increasing N_2 / CO_2 ratio
- The geometric mean particle size and the total number concentration increase with increasing N_2 / CO_2 ratio.

Effects of O_2/CO_2 mixing ratio



Mixing ratio of O2/CO2 increases:

- Particle temperature increases
- The geometric mean particle size increases
- The total number concentration increases

Composition of Submicrometer Flyash

PRB Sub-bituminous Coal

Major Element	Lab-scale Combustor	Full-scale coal-fired power plant
silicon (SiO_2)	48.0%	32.3%
aluminum (Al_2O_3)	16.0%	17.0%
magnesium (MgO)	5.0%	4.0%
iron (Fe_2O_3)	8.0%	8.0%
calcium (CaO)	21.0%	20.0%
Unreported	2.0%	18.7%

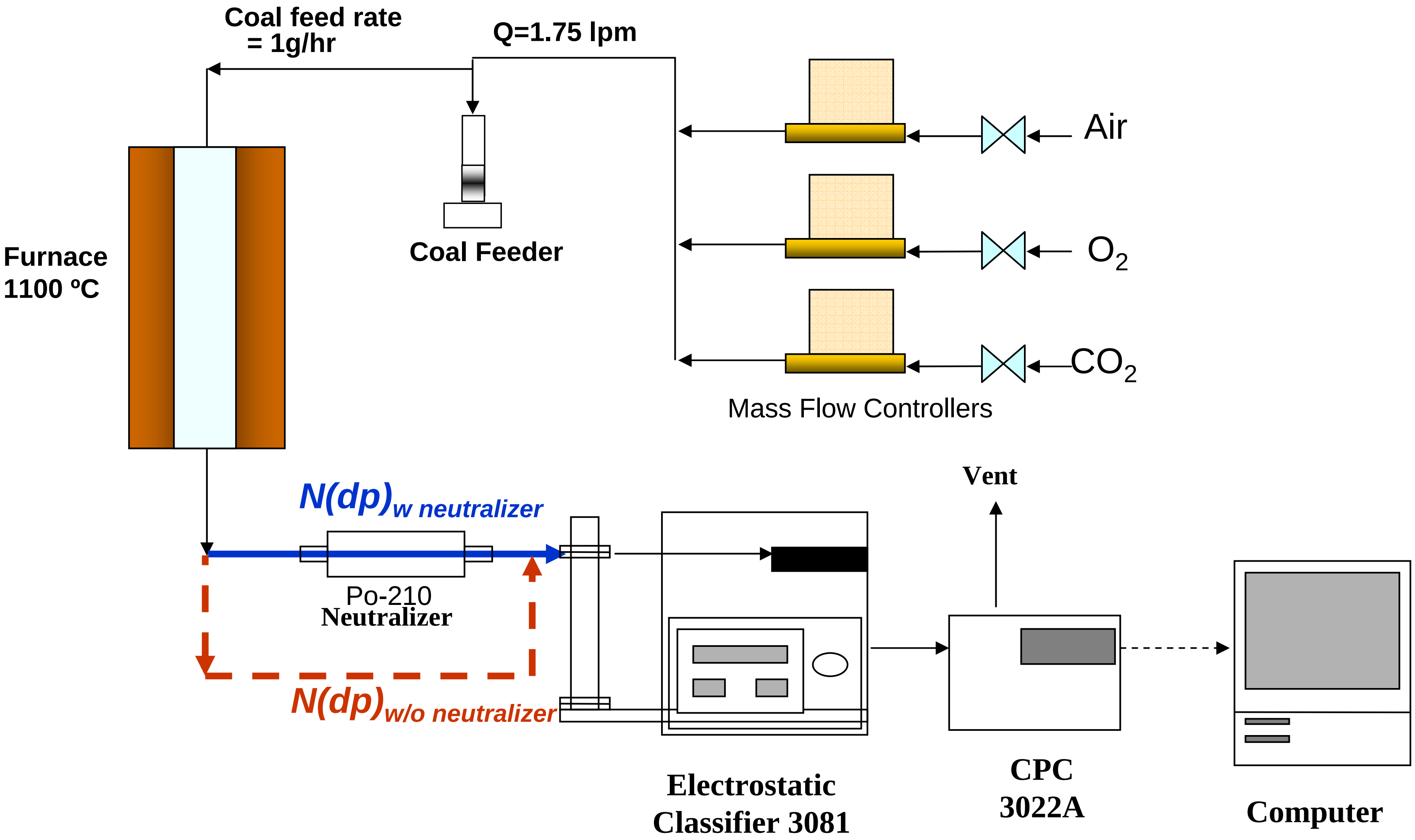
Objectives - Charging Study

Collection efficiency of an ESP can be influenced by:

- Fraction of particles that carry charge before entering the ESP
- Particle charging efficiency inside the ESP

1. Determine fraction of submicrometer particles that carry charge at different combustion gas mixture (Conventional vs. O_2-CO_2).
2. Determine penetration of submicrometer particles through an ESP at a constant corona current for different gas compositions.
3. Evaluate corona inception voltage for different gas compositions.

Charged Fraction Determination



Calculation of Charged Fraction

Assumption :

- Charged particles acquire +1 or -1 charge (Jiang et al, *J. of Electrostatics, 2006)*
- Particles after neutralizer have equilibrium charge distribution

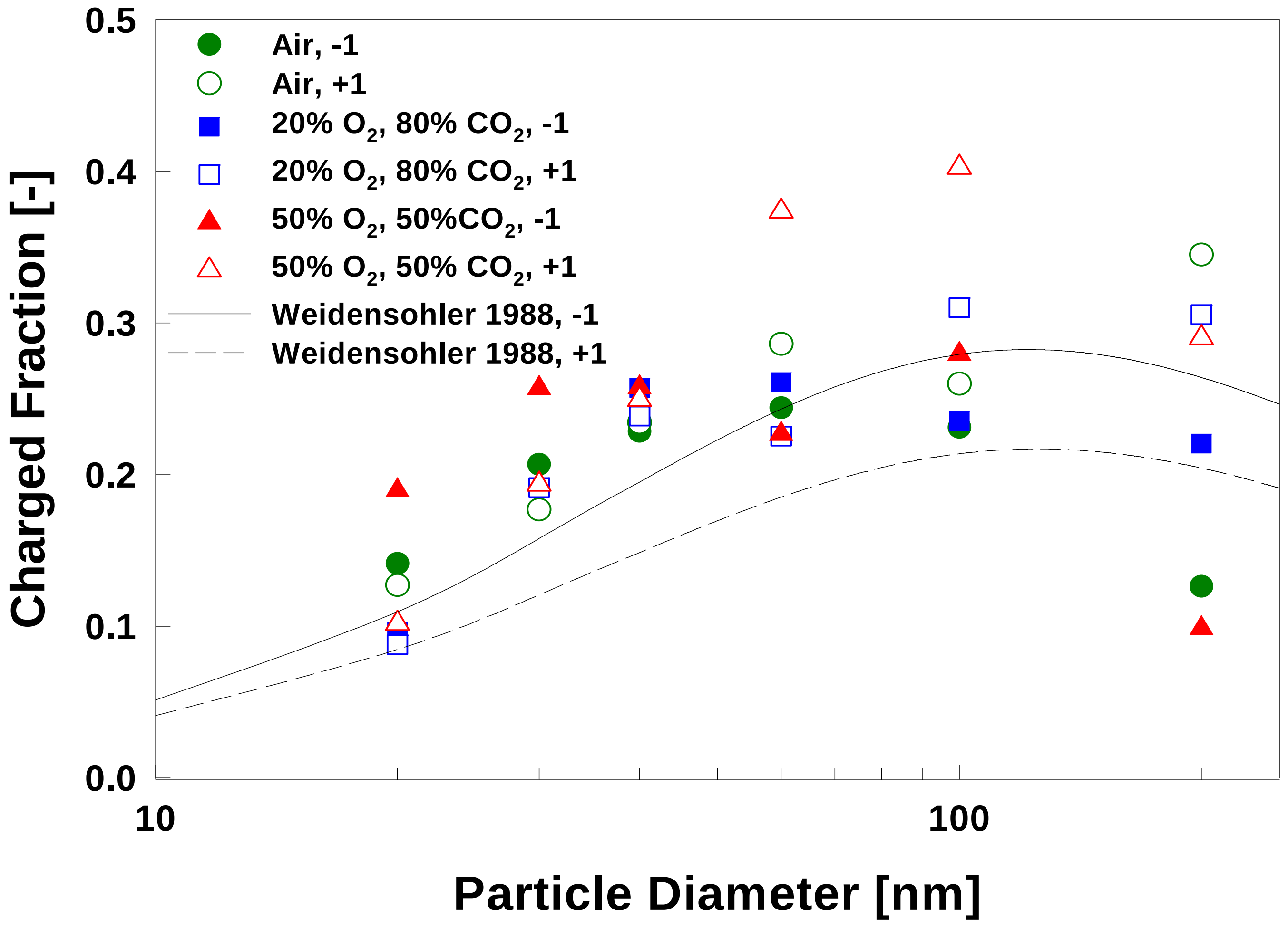
$$\text{Eq. charged fraction}(dp) = 10^{\left[\sum_{i=0}^{5} a_i (\pm 1)\left(\log \frac{dp}{nm}\right)^i\right]} = \frac{N(dp)_{w/neutralizer}}{N(dp)_{tot}}$$

(Wiedensohler A., *J. Aerosol Sci*, **1988**, 19, 387-389)

measured

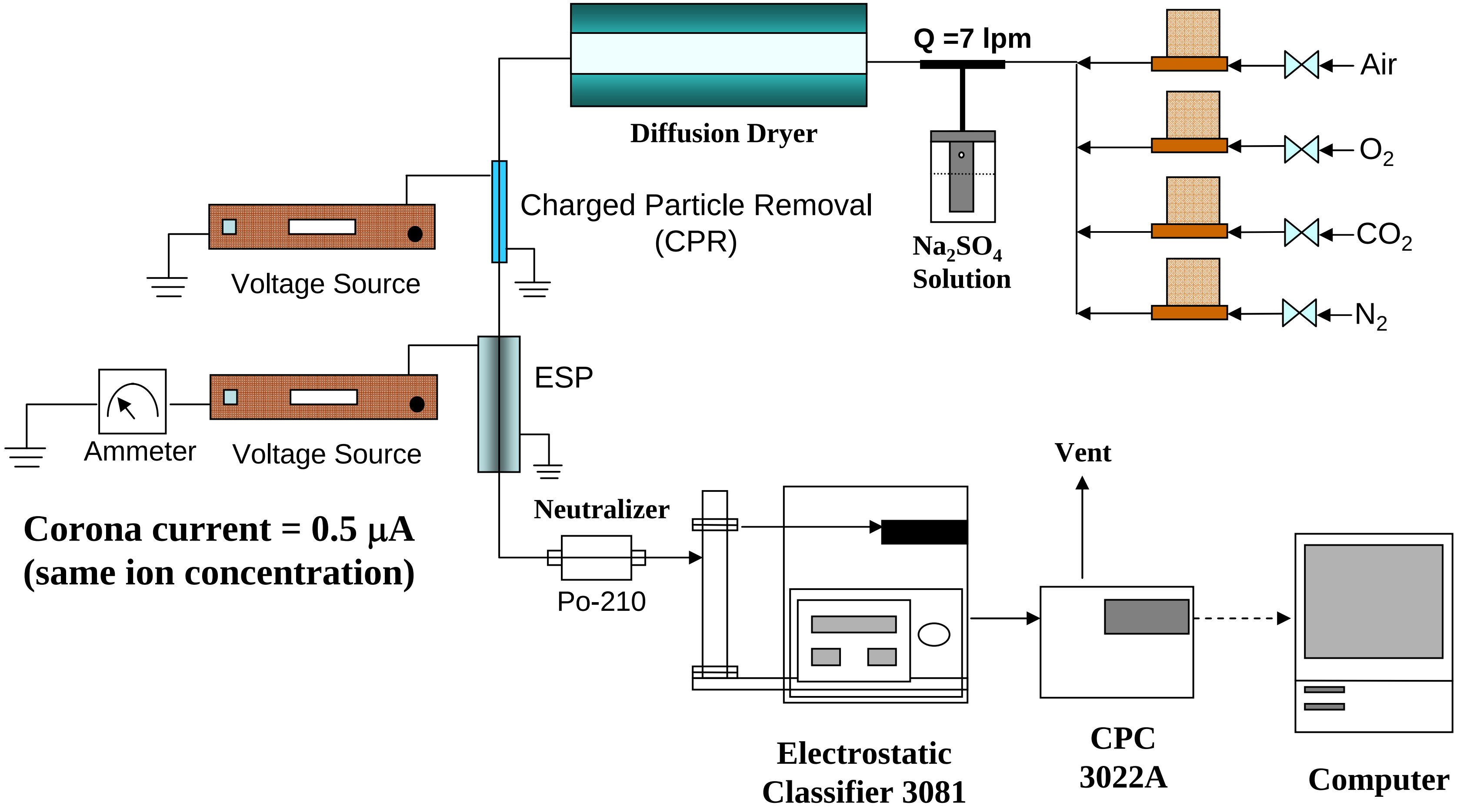
$$\text{Charged fraction}(dp)_{comb} = \frac{N(dp)_{w/o\ neutralizer}}{N(dp)_{tot}}$$

Charged fraction of submicrometer and ultrafine particles at the outlet of the combustor.



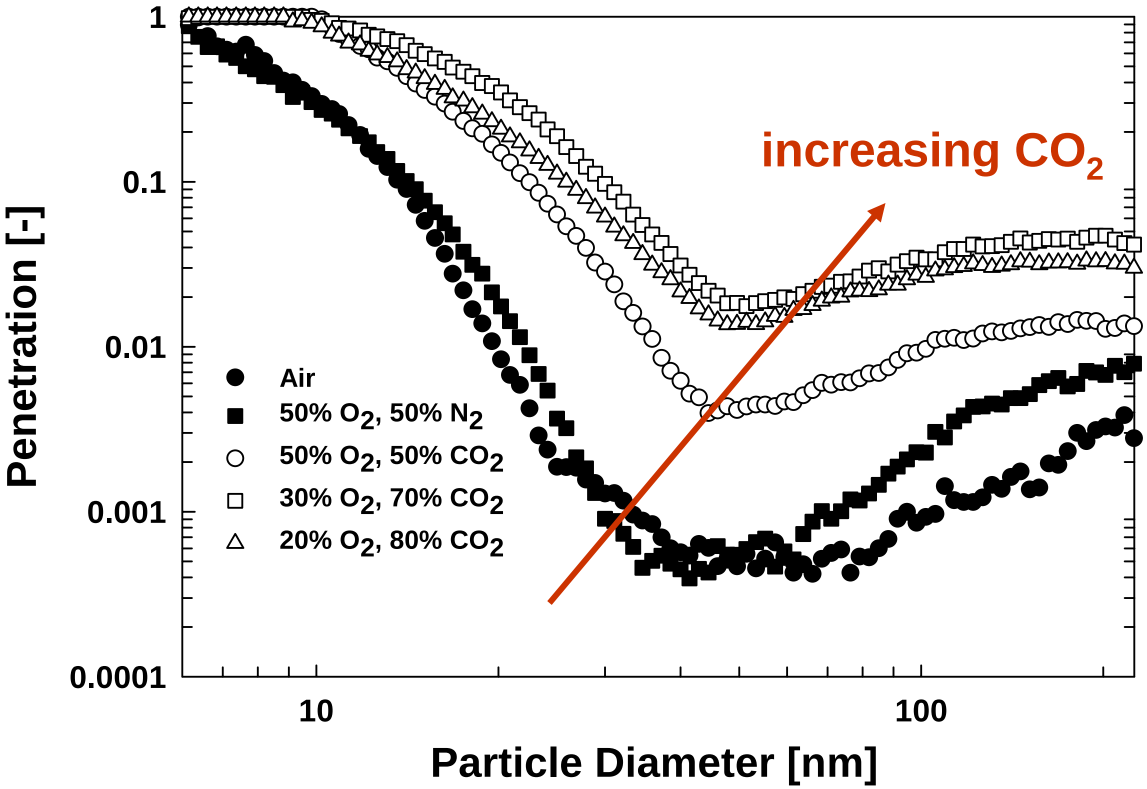
- The charged fraction for most sizes is slightly higher than equilibrium
- More positively charged particles found in larger particle sizes
- Fraction of charged particles are independent of combustion condition

Impact of Different Combustion Gases in Charging and Penetration



Corona current = 0.5 μA
(same ion concentration)

Penetration with positive ion generation with same corona current (0.5 μA)

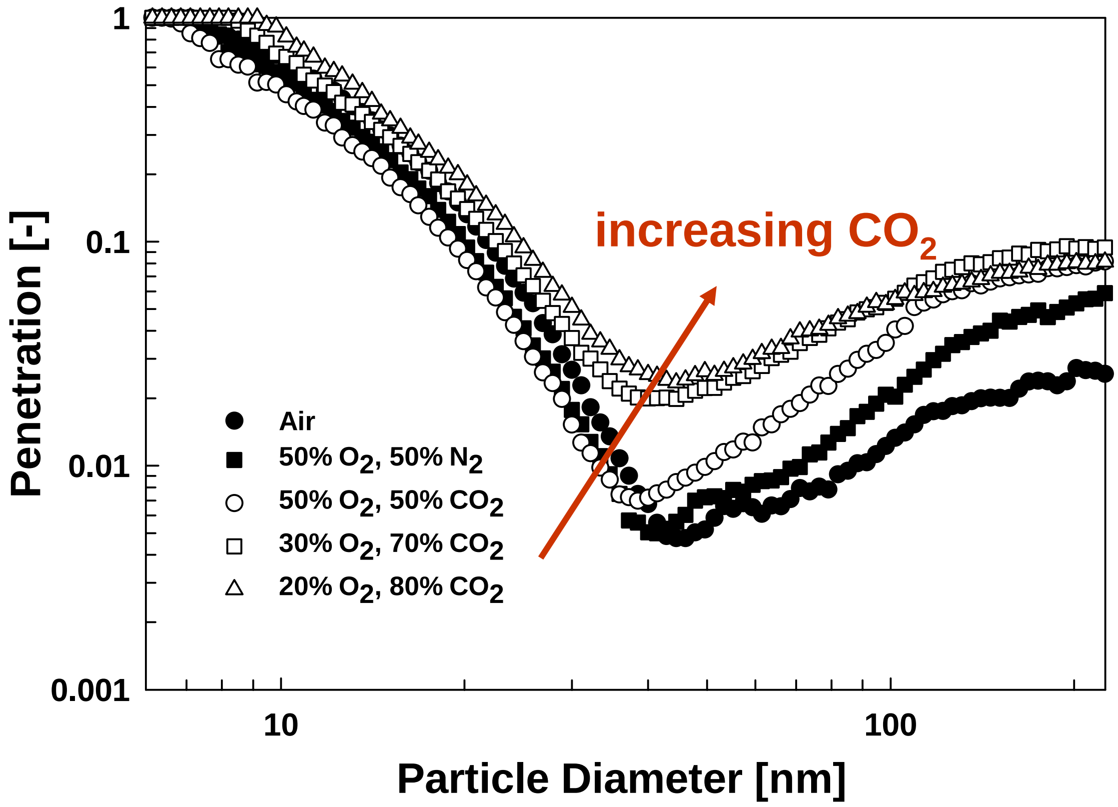


- When N_2 is replaced by CO_2, penetration of particles increased by approximately 1-2 orders of magnitude.

- In O_2-CO_2 gas mixture, positive ions were generated in a much lower concentration compared to that generated in O_2-N_2 gas mixture, resulting in higher particle penetration in O_2-CO_2 carrier gas

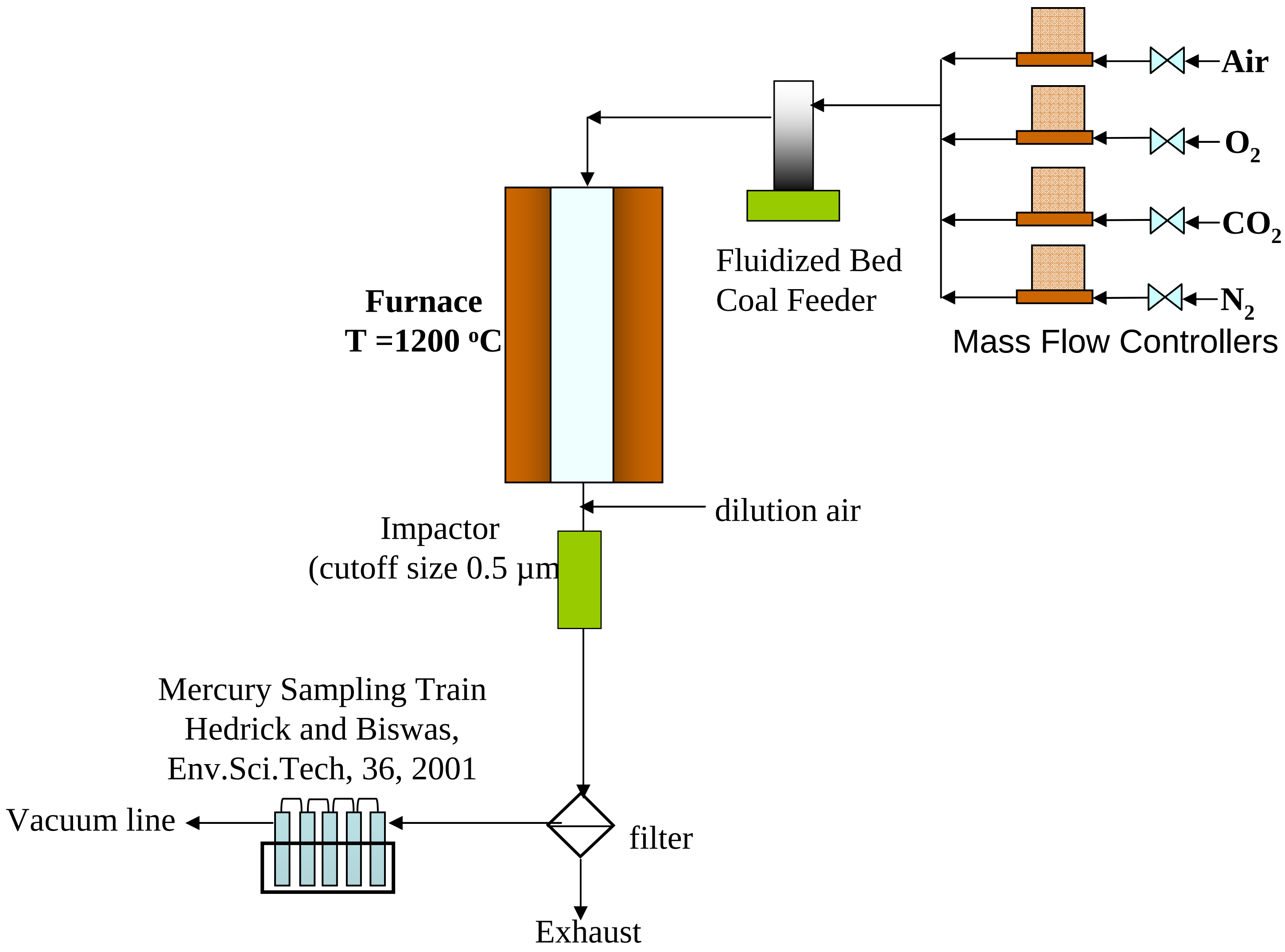
Ref: Suriyawong et al,*Fuel*, *Charged Fraction and Electrostatic Collection of Ultrafine and Submicrometer Particles Formed during O2-CO2 Coal Combustion,* (submitted)

Penetration with negative ion generation with same corona current (0.5 μA)



- Penetration of particles in O_2-N_2 gas mixture is lower than O_2-CO_2 gas mixture
- Ions in O_2-N_2 and O_2-CO_2 formed in negative corona have similar mobility.
- Negative ion generation depend primarily on the presence of O_2, presumably due to the formation of O_2^-

Mercury Speciation - Experimental Setup



Air

O_2

CO_2

N_2

Mass Flow Controllers

Fluidized Bed
Coal Feeder

Furnace
T =1200 ^oC

dilution air

Impactor
(cutoff size 0.5 μm

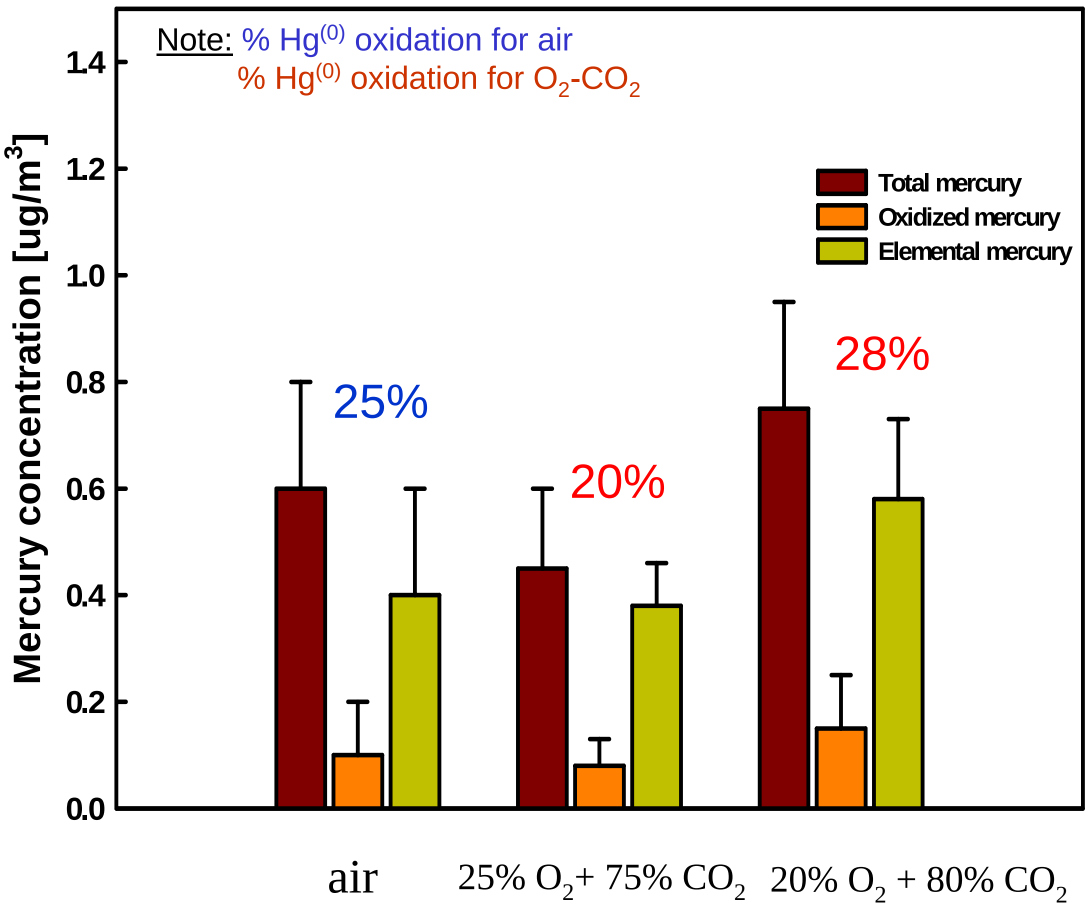
Mercury Sampling Train
Hedrick and Biswas,
Env.Sci.Tech, 36, 2001

Vacuum line

filter

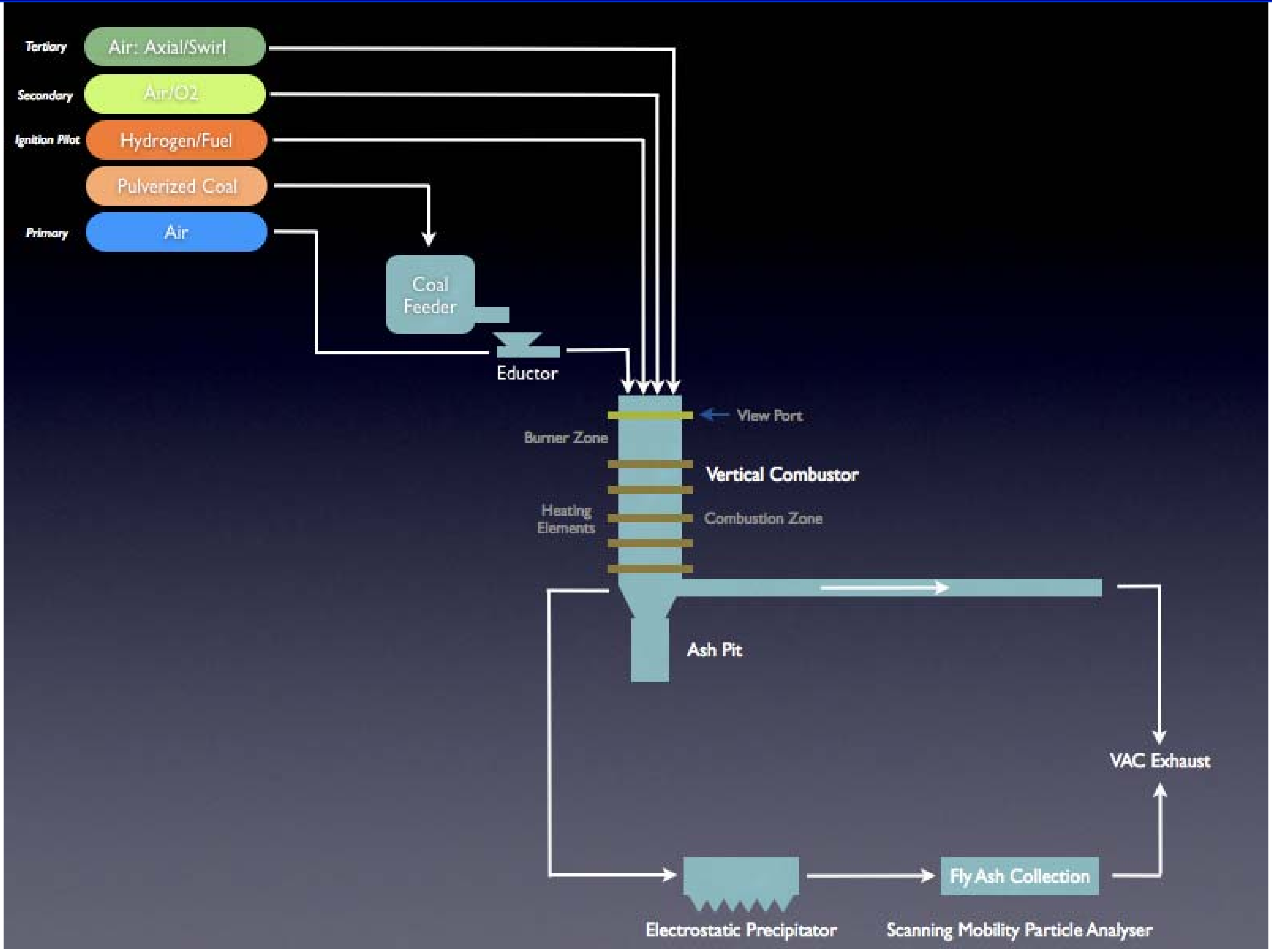
Exhaust

Mercury concentration measured at the exit of the combustor

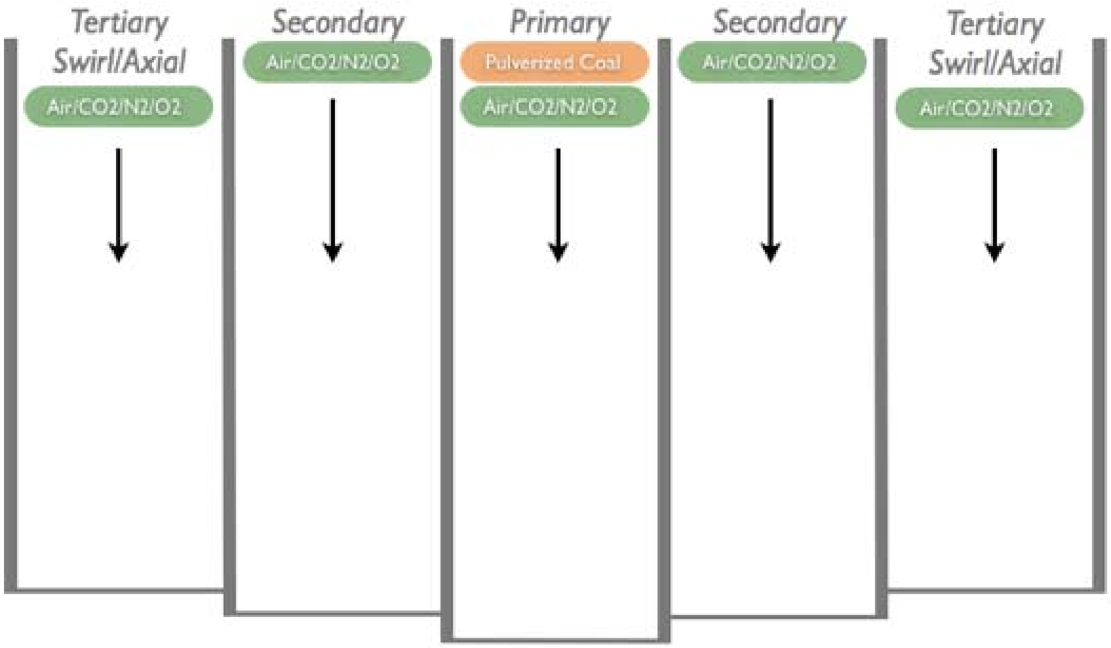


No significant difference in speciation of mercury in O_2-CO_2 coal combustion versus air coal combustion

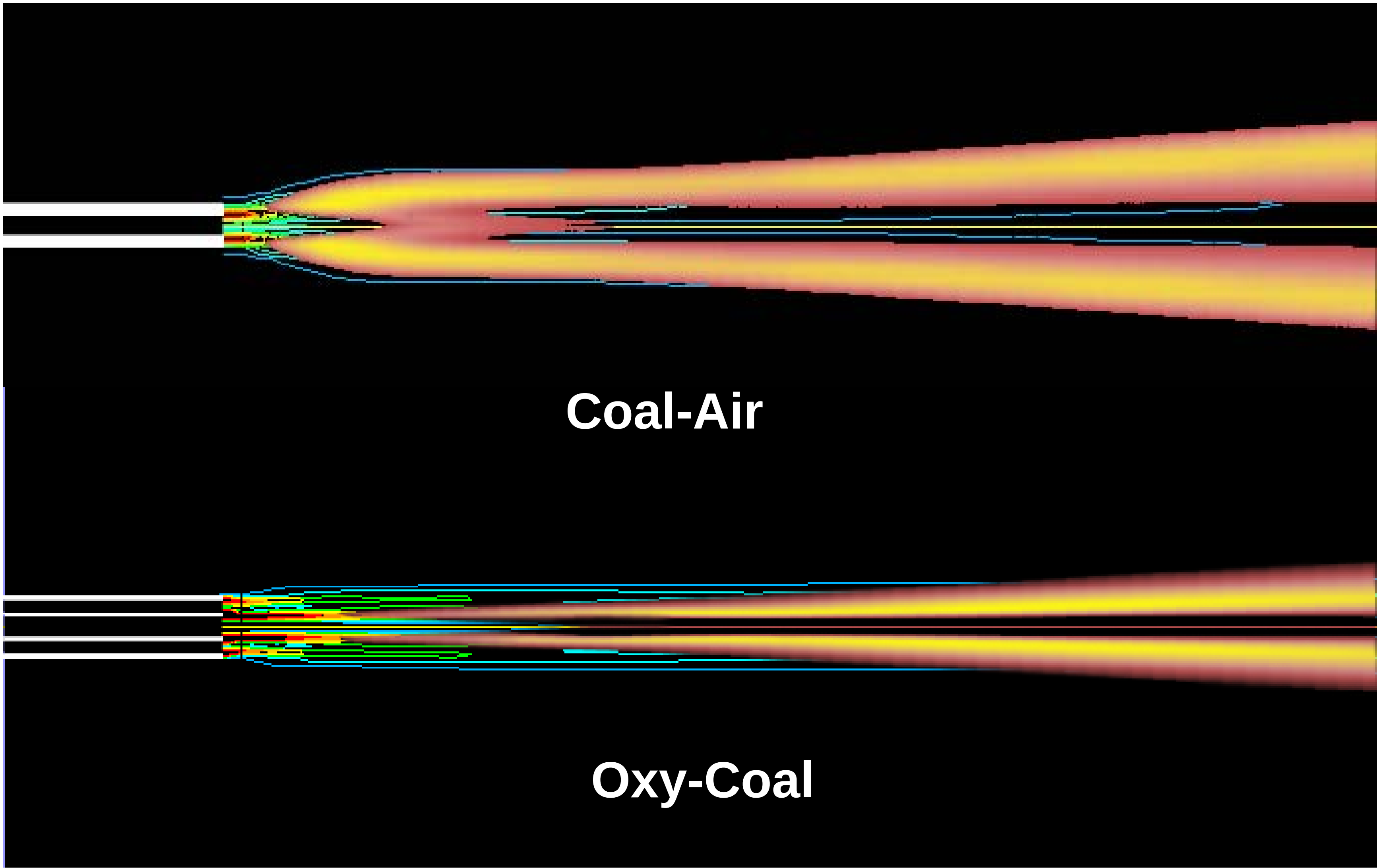
Lab-Scale Oxy-Coal Combustor



Burner Flow Capabilities



FLUENT Modeling of Iso-Strain Rates and Isotherms

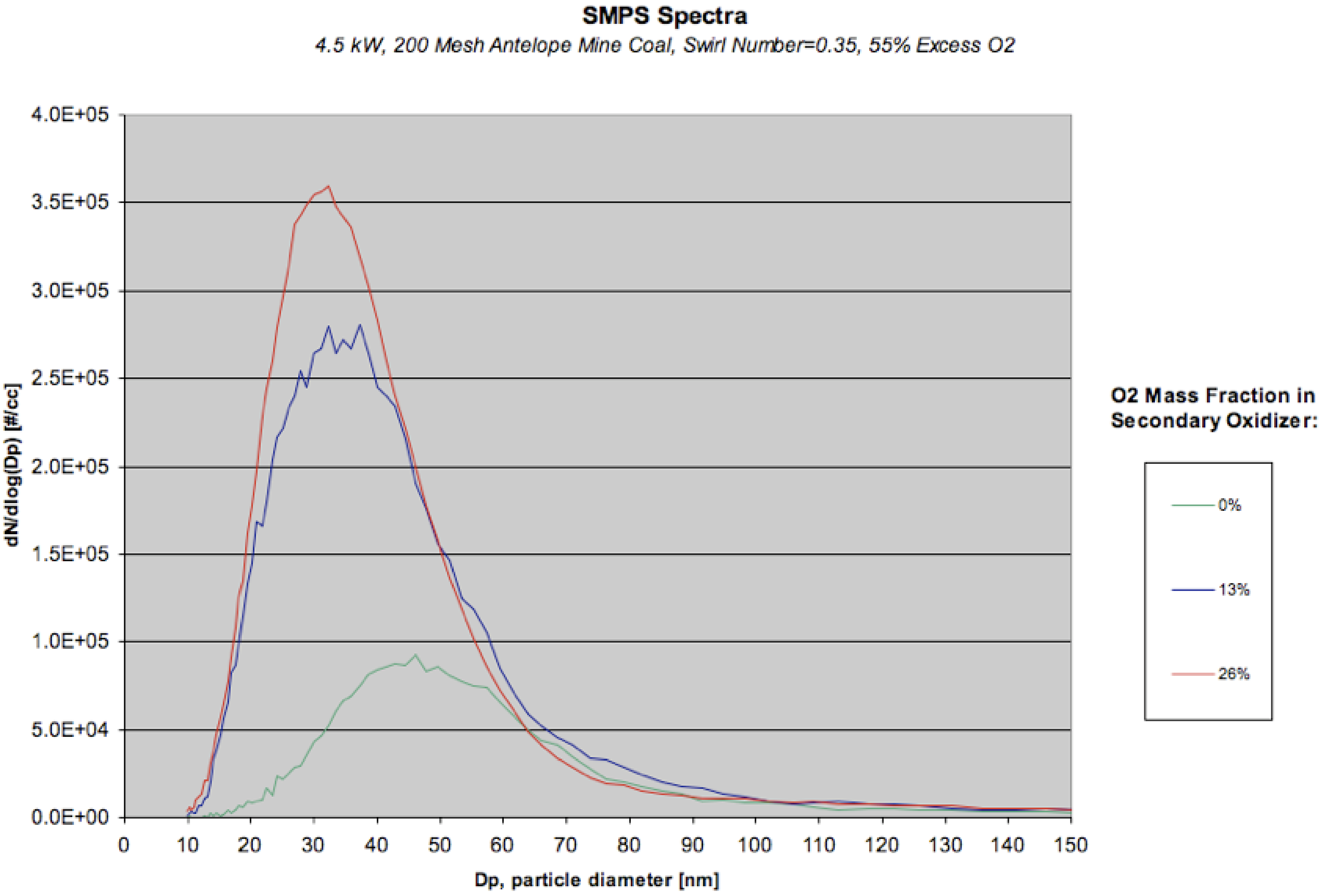


Photographs of Coal Combustor

Axial

Swirl

Effect of O_2-Enrichment on Ultrafines



Conclusions

- O_2 – CO_2 combustion results in delayed volatilization – hence, mean size of submicrometer mode is smaller with less associated mass (more mass in coarse mode)
- No significant differences in mercury speciation
- Submicrometer and ultrafine particles produced by coal combustion carry charge (thermal ionization as a primary mechanism).
- The fraction of particles carrying charge is not dependent on combustion gas composition.

Conclusions, cont.

- With positive applied voltage, penetration of submicrometer and ultrafine particles are orders of magnitude higher in O_2-CO_2 gas mixtures as compared to O_2-N_2 gas mixtures.

- With negative applied voltage, relatively little difference on penetration when replacing N_2 with CO_2.

- ESP with positive applied voltage requires higher energy input for O_2-CO_2 gas mixtures to produce the same corona current as O_2-N_2 gas mixtures.

Conclusions, cont.

- Flame extinction and sooting-limit studies indicate that stronger, less sooty flames can be obtained by increasing Z_{st} (i.e., in oxy-fuel flames).

- The extinction temperature can be minimized by matching radical production zone with peak temperature.

- Oxygen-enrichment provides a flexible tool for design of combustion systems in ways that heretofore may not have been realized.

Acknowledgements

- Department of Energy DOE-UCR under the technical direction of Kamal Das
- Ameren UE., St.Louis, MO