Oxy-coal combustion for retrofit to existing boilers:

Issues, opportunities and challenges

Jost O.L. Wendt
Presidential Profesor
University of Utah, Utah 84112

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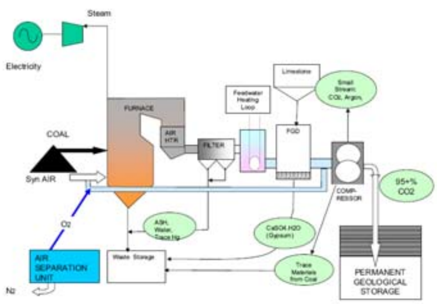
Scope of this white paper

- Identify potential role of oxy-coal combustion for coal retrofit to existing boilers
- Identify over-arching issues and problems to be resolved
- Focus on pulverized coal configurations rather than on circulating fluid bed combustors, and other systems since the former are most applicable for retrofit
- Identify critical research issues to advance enabling technology allowing oxy-coal for retrofit.
  - Need for simulations to allow extrapolation from air firing to oxy-coal firing
  - Specific technical research problems
    - Near term
    - Intermediate term
    - Long term

Oxycoal combustion: near-term application to efficient conventional boilers. (Stobbs. 2007)



SaskPower Oxyfuel Process

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Why oxy-coal?

- Has potential near term applications
- Using flue gas recycle, system can be made to look like existing conventional air fired pulverized coal boilers.
  - Reassuring to electric utility companies
  - Can be engineered to use existing boiler heat transfer surfaces, steam side system and power generating turbine.
  - Consists of components (ASU, boiler, turbine, CSS) which *individually* are *not new* technologies, although they have hitherto *not* been tested to work together as a system
    - Work in progress by Vattenfall in Germany using integrated ASU and 30MW test furnace.
- Costs are claimed to be competitive with other systems.
  - Might not require extensive air pollution control devices (APCD's) if trace contaminants are automatically removed in the condesate during compression to super-critical CO2

CCS: Comparison of COE costs

(new units)

taken from IEA CCS 2008 Summer School Plant Cost Worksheet:
Author: Michael B Burkenpass, Carnegie Mellon University, 2005

Plant Type & Technology	Total Plant Costs ($2002)						
	Capital Cost $/kW	w/o CCS $/kW	Capital Cost[5] $/MWh	Total O&M Cost[5] $/MWh	Total COE[6,7] $/MWh	w/o CCS $/MW	% increase COE rel to w/o CCS
NGCC Plant[1]	915.7	563	20.6	38.5	59.1	43.3	36
PC Plant[2]	1961.5	1229	44.1	29.3	73.4	44.9	63
IGCC Plant[3]	1831.2	1327	41.2	21.3	62.56	46.8	34
Oxyfuel Plant[4]	2417.3		54.4	24.4	78.85		76

Notes
1. NGCC plant = 432 MW (net); 517 MW (gross); two 7FA gas turbines; gas price = 4.0 $/GJ
2. PC plant = 500 MW (net); 719 MW (gross); supercritical boiler; Pittsburgh #8 coal; price = 1.0 $/GJ
3. IGCC plant = 490 MW (net); 594 MW (gross); GE gasifiers + two 7FA gas turbines; Pgh #8 coal; price = 1.0 $/GJ
4. Oxyfuel plant = 500 MW (net); 709 MW (gross); supercritical boiler; Pittsburgh #8 coal; price = 1.0 $/GJ
5. Based on levelized capacity factor of 75% for all plants
6. COE is the levelized cost of electricity
7. Based on fixed charge factor of 0.148 for all plants

Oxy-coal combustion for retrofit: Four major over-arching issues:

1. O_2 supply energy penalty
   - Current cryogenic technology can consume 15-20% of energy produced
2. Purity of CO_2 flue gas for sequestration
   - Is it a waste? Or a resource?
   - Regulatory and legal issues.
     - Directives issued for comment from EU, Japan, and US EPA (July, 2008)
   - Does it have commercial value for tertiary oil recovery?
   - What impurities are allowed?
     - Corrosion during transportation to disposal site?
     - Compression cost limitations?
   - Technology for purification, if required.
3. Ingress of air through air leakage
   - Dilutes exiting CO_2
   - Increases compression costs
4. Not suitable for *partial* CSS using a slipstream from an existing plant.

Oxygen supply

- Currently available
  - Air separation unit (ASU)
  - Modest energy improvements
  - Must be coupled to boiler as part of an integrated system (Vattenfall)
- Breakthroughs needed
  - Oxygen transport membranes
  - Unlikely to be applicable to existing systems

CO_2 purity: Technical issues

- What impurities can be removed during simple compression?
  - Moderate co-capture 100% SO_2, 15%NO_x (might require SCR)
  - Extreme co-capture (*Allam, Air Products, 2006*)
- SO_2 is converted to Sulfuric Acid, NO_2 converted to Nitric Acid:

– $NO + NO + O_2$	=	$2NO_2$	(1)	Slow
– $2\ NO_2$	=	N_2O_4	(2)	Fast
– $2\ NO_2 + H_2O$	=	$HNO_2 + HNO_3$	(3)	Slow
– $3\ HNO_2$	=	$HNO_3 + 2\ NO + H_2O$	(4)	Fast
– $NO_2 + SO_2$	=	$NO + SO_3$	(5)	Fast
– $SO_3 + H_2O$	=	H_2SO_4	(6)	Fast

- Rate of Reaction 1 increases with pressure to the 3rd power
  - only feasible at elevated pressure
- No Nitric Acid is formed until all the SO_2 is converted
- Hg, As and other trace metals dissolved in acid solution
- Pressure, reactor design and residence times, and NO concentration are important
- Can oxy-coal combustion operate with no APC technology required?
- Is high NO_x desirable for the reactions above to occur?

Oxy-coal combustion *research*.
Desired outputs as they relate to retrofit

1. Enabling technology for retrofit in conventional, but new, high efficiency, air-tight, air-fired units that have been proven for air firing (short term).
   - ✓ Application to *CSS ready* units – the most logical application, but politically not attractive.
2. Enabling technology for retrofit in conventional, older, air-fired units that have been proven for air firing (short term) and do not have excessive air leakage.
   - ✓ Application to units at slight positive pressure (forced draft).
   - ✓ Modify design of air heater and other components to minimize typical 15% air leakage.
3. Enabling technology for oxy-coal application to new units that were never planned for air firing, but "still look (somewhat) like boilers". Might have some application to retrofit. (intermediate term)
4. Research for development of new technologies which do not look at all like current boilers (long term). Probably little application to retrofit of existing boilers.

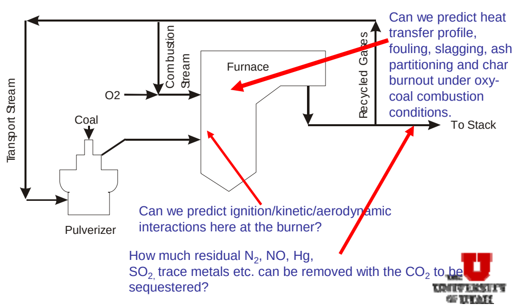
Retrofit for existing, but efficient air fired units with minimal air leakage

Short term applications: "not only looks like a boiler, but actually works like a boiler"

- Need for *simulations* which allow:
  1. Fiddle-free *validation* using comprehensive (heat transfer, temperature profile, O_2, CO_2, NO_x profiles, ash deposition, steam side properties) data from air-fired coal combustion units
  2. *Validated sub-models* for various oxy-coal combustion processes – heat transfer, ignition, burnout, ash etc.
  3. *Extrapolation* from air fired to oxy-combustion conditions

Oxy-coal combustion (short term):

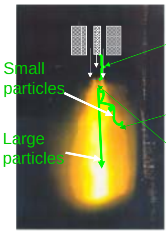
Schematic of oxygen fired PC furnace with CO_2 recycle (*Sarofim et al, 2004*)



Retrofit issues: need for *validated* sub-models to extrapolate from air to O_2

- Heat transfer sub-model
  - Radiant zone
  - Convection zone
- Coal jet ignition sub-model
  - Chemistry
  - Burner aerodynamics and heat transfer
- Char burnout sub-model
- Ash partitioning sub-model
  - Deposition
  - Trace metals
- Combustion by-products
  - NO_x, SO_x, Hg
- Integrated furnace model
  - Calculation of heat transfer, species, temperature profiles in all furnace zones as function of recycle ratio. For heat transfer see *Payne, Chen, Wolsky, and Richter Combust. Sci. Technol, 67,1,1989*

Coal jet ignition sub-model



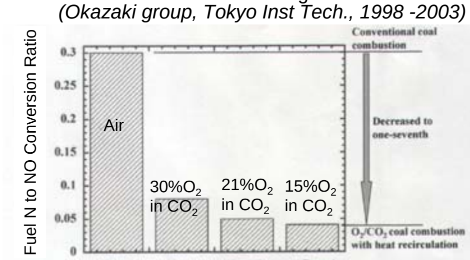
- Standoff ignition distance depends on primary jet velocities, and P_{O2}, which becomes an independent variable under oxy-coal combustion
- Sub-model should capture observations that smaller particles preferentially migrate to jet edge. *Sinclair Curtis (2003)*. Implications on effects of secondary P_{O2}, also an independent variable.
- Pyrolysis behavior. *(Naredi and Pisupati, 2007, Penn State University)*
- Particle ignition. (*Shaddix and Molina, 2005, 2006, Sandia Labs)* Influence of gas properties which vary heat transfer to coal particle.

Char burnout sub-models

- Contradictory results in the literature on effects of oxy-coal combustion, with CO_2 recycle, on char burnout times.
  - Increased burnout times (Alverez, 2005, Shaddix et al. 2006, 2007)
  - Similar burnout times (Liu et al., 2005), Borrego et al., 2007)
  - Decreased burnout times (Borrego et al. 2007)
- Need to untangle conflicting effects of
  - Residence time changes
  - Surface reaction effects of composition changes
  - Particle transport effects of composition changes
  - Coal composition and rank effects
  - Temperature profile changes.
- Need well defined, systematic, experimentation to validate existing char burnout models and identify the need for new ones.

Combustion by-products sub-model: NO_x

- NO_x produced is very much less with recycle on a mass emission basis.
- Mechanism due to reburning and is well understood *(Okazaki group, Tokyo Inst Tech., 1998 -2003)*



Taken from Okazaki, K. Plenary lecture, 13th intl. Heat Transfer Conf., Sydney, August 2006

Application to new units: Intermediate term

"Still looks like a boiler" *somewhat*.

Might have some application to retrofit.

- How to minimize (optimize, eliminate?) externally recycled CO_2 stream.
  - H_2O recycle/injection?
  - CANMET oxy-fuel R&D program (*Zangane, K., 57th Canadian Chemical Engineering Conference, Edmonton, October 28-31, 2007)*
- Draw on oxy-fuel experience for glass furnaces.
- Use internal recycle to diminish temperature peaks.
  - "Flameless combustion"?
- Identify critical barriers to implementation in boilers.
  - Materials
  - Directed O_2 injection.
- Need simulations
  - Aerodynamic/temperature predictions for internal recirculation caused by super fast jets
  - Heat transfer simulation to allow controlled cooling
  - Ash partitioning and deposition
  - Steam side system predictions
  - Validated components/modules

New technologies: long term

Unlikely to look much like a current boiler.
Probably not applicable for retrofit.

- Integrated oxygen transport membrane applications.
- Chemical looping (using oxygen carriers)
  - Iron oxide based
  - Calcium sulfate/sulfite based
- Circulating fluidized bed
- Other

Summary & conclusions

- Future use of coal requires CCS, and oxy-coal combustion is a competitive technology for this.
- Four over-arching issues as far as retrofit is concerned: O_2 supply, required CO_2 purity, air leakage and not suitable for partial CO_2 capture (and partial CO_2 credit)
- Oxy-coal combustion can play an important role for new, efficient, airtight boilers, initially built to fire air, but with the potential for future retrofit (new, CCS ready boilers)
- Oxy-coal combustion may also play a role for boilers initially built to fire air, but with minimal air leakage. May require re-design of some boiler equipment.
- In the short term *validated* simulations will be the key to allow retrofit with confidence.
  - Simulation sub-models still require some development and validation, although much is already known.
- Intermediate term should focus on optimizing (eliminating?) flue gas recycle. Needs *validated* simulations.
- In the long term there are many competing concepts, ranging from chemical looping to integrated oxygen membranes. These units will not look much like boilers and are not applicable for retrofit for the existing fleet of pulverized coal boilers.

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