Clean Energy Research Center

Advanced Coal Technologies Consortium

Annual Report 2013

Cooperative Agreement DE-PI0000017

West Virginia University Research Corporation

US-China Clean Energy Research Center

Advanced Coal Technology Collaboration

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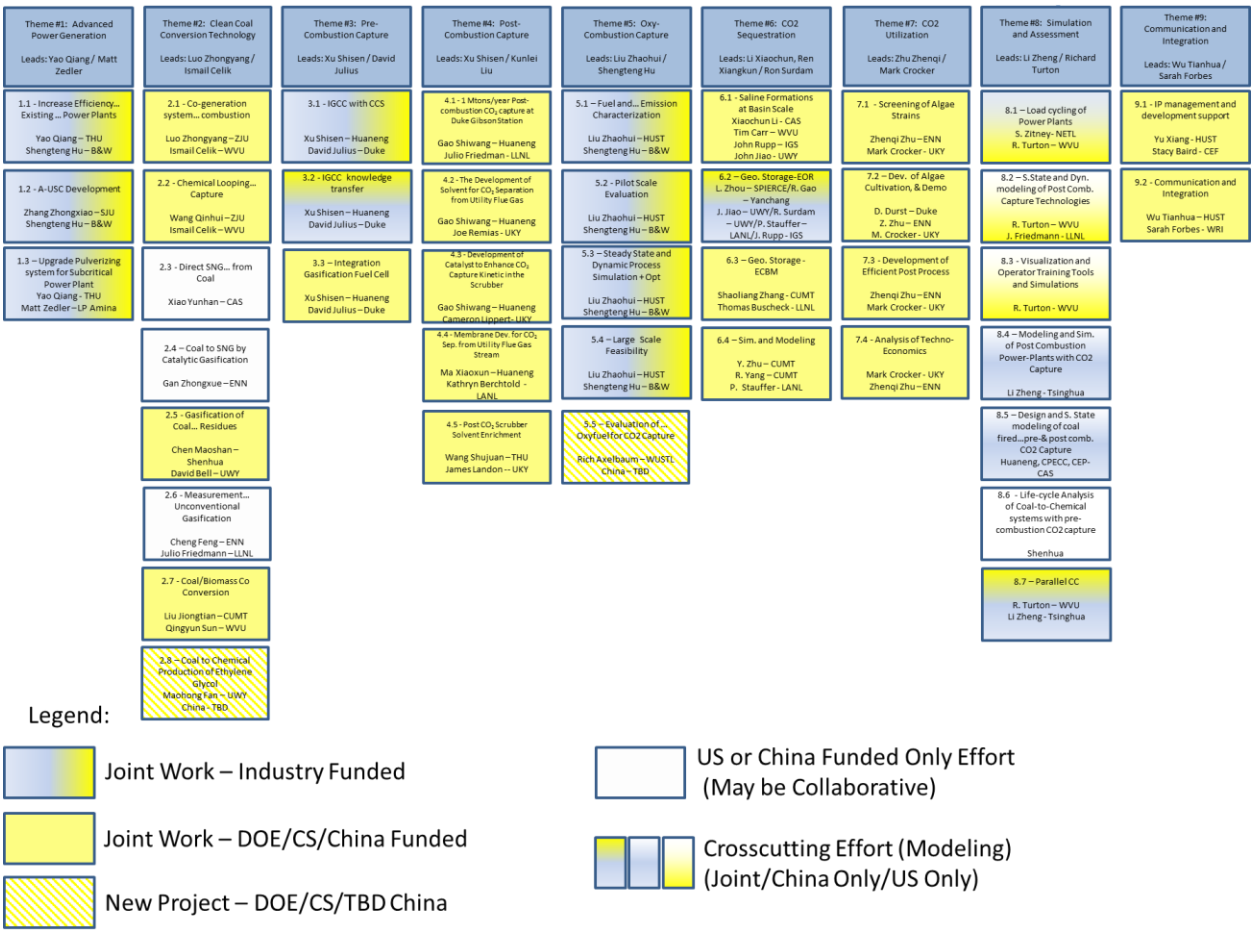
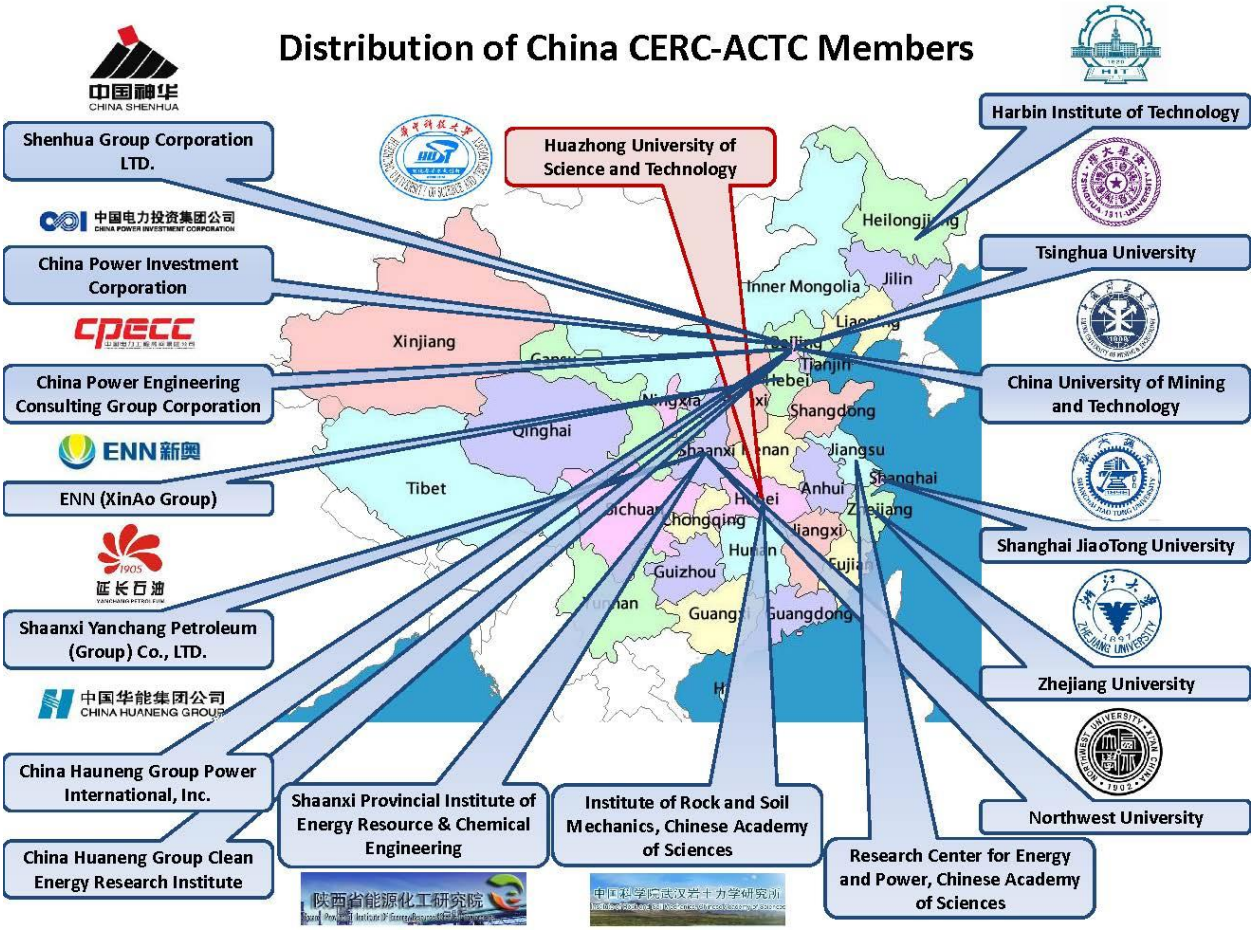
Introduction



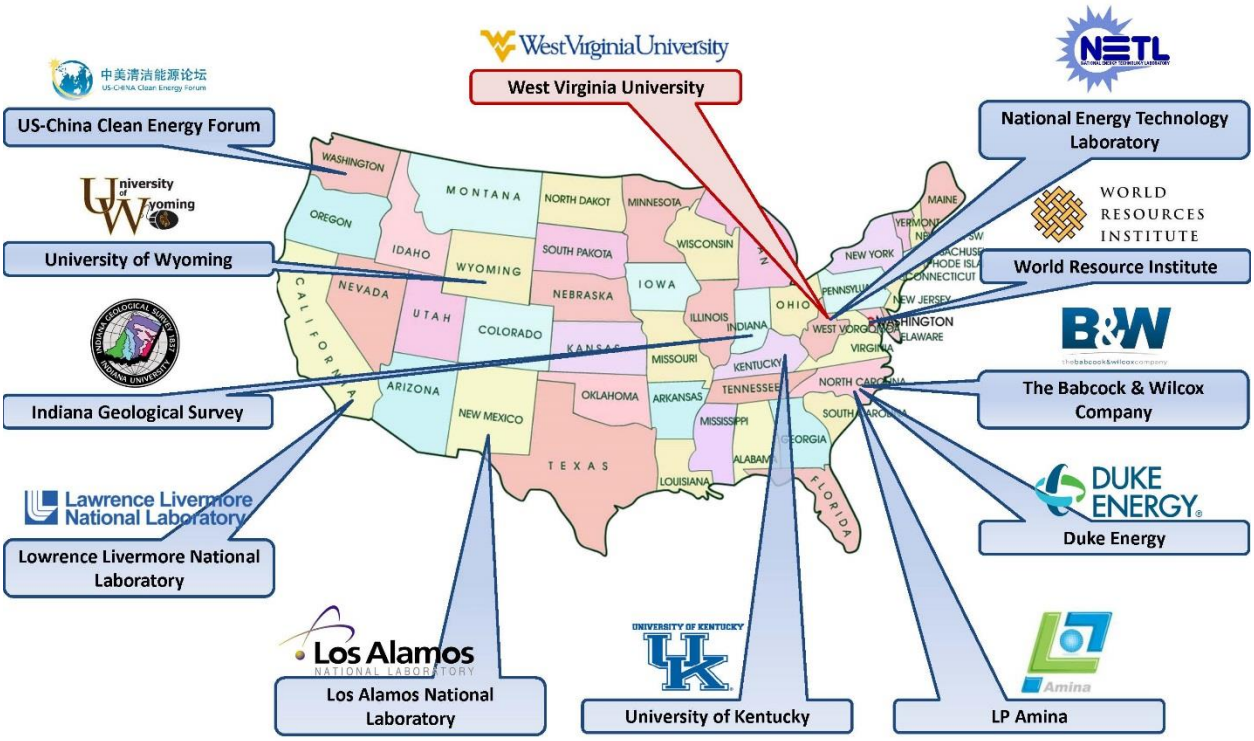
ACTC Tasks and Cooperation Partners

No	Tasks	China/US Leaders	China Participants	US Participants
1	Advanced Power Generation	YAO Qiang/ Will Latta	THU, SJTU, HIT, , CHNG-CERI, CPIC, CPECC, Shenhua	LP Amina, WVU
2	Clean Coal Conversion Technology	LUO Zhongyang/ Ismail Celik	ZJU, Shenhua, ENN, CEP-CAS, CUMT	WVU, LP Amina
3	Pre-combustion Capture	XU Shisen/ David Julius	CHNG-CERI, THU, CPIC, CEP-CAS	Duke Energy, LLNL, West Virginia University
4	Post-combustion Capture	GAO Shiwang/ Kunlei Liu	CHNG-CERI, THU, NWU, CPECC, CPIC, ZJU, CUMT	University of Wyoming, LANL, LLNL
5	Oxy-CombustionCapture	LIU Zhaohui/ Kevin McCauley	HUST, THU, CPECC, HIT	B&W, WVU, LLNL, NETL
6	CO_2 Sequestration	LI Xiaochun, Ren Xiangkun/ Tim carr, Ron Surdam, Phil Stauffer	Shenhua, IRSM-CAS, THU, CUMT, NWU, Yanchang Petroleum	WVU, University of Wyoming, LANL, LLNL, Indiana geological Survey, WRI
7	CO_2 Utilization	ZHU Zhenqi/ Mark Crocker	ENN, ZJU	University of Kentucky, Duke Energy, PNNL
8	Simulation and Assessment	LI Zheng/ Richard Turton	THU, Shenhua, CPECC, CUMT, NWU, CHNG-CERI, HUST, CEP-CAS, ENN	WVU, NETL, LLNL, Duke Energy
9	International Coordination & Integration	WU Tianhua/ Sarah Forbes	HUST, THU, CHNG-CERI	WRI, WVU, CEF

Distribution of China CERC-ACTC Members



Distribution of U.S. CERC-ACTC Members



Research Activities

Theme 1 - Advanced Power Generation

Research Objectives

During the reporting year, the research team has continued working toward the original goal – to improve the performance of existing Chinese and US coal-fired power plants (CFPPs). The theme contains three subtasks. Most of the original objectives have been completed. At the end of the reporting period, the team intends to generate a new plan for future work (see Future Work Plans). Subtask 1.1 was the pilot research of the subtask 1.3, and tend to development potential cooperation in the future; and the subtask 1.3 remains as joint effort.

Subtask 1.1 Increase efficiency & availability of existing CFPPs

- Survey, identify specific units, investigate needs, evaluate opportunities, develop final toolbox, conduct a workshop, implement at chosen plant
- Suspended as of summer 2013, a technical roadmap was finished this year
- Performing the online monitoring based on the operation data;
- Reduce power consumption of the balanced draft system for the ultra low pollutant emission for Chinese coal power plant

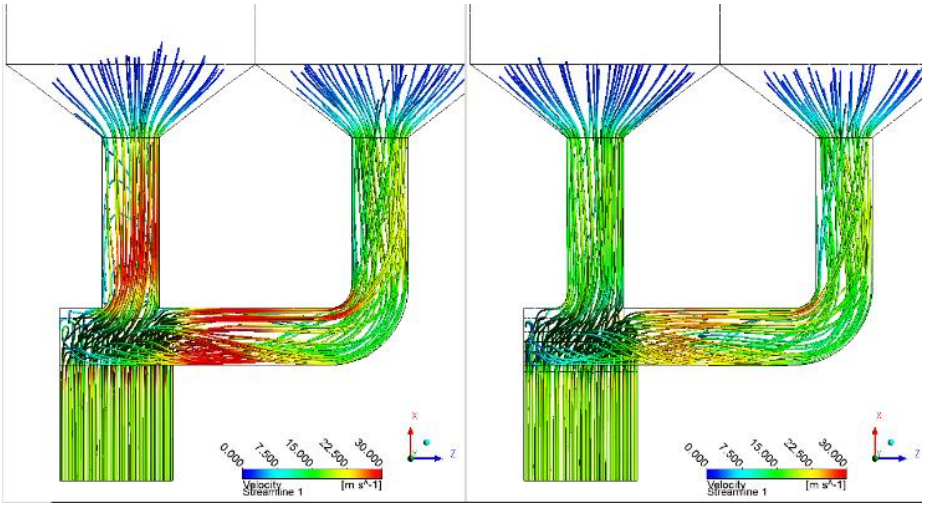
Subtask 1.2 Upgrade pulverizing system for subcritical power plants

- Evaluate current state of pulverizers / mills in US & China, identify target projects which could benefit from LP Amina's new static classifier
- Develop validated models for prediction of particle segregation / separation in cyclone separators, aimed to characterizing dense two-phase flow using experimental and analytical tools
- Model effect of staged fineness on NOx reduction, soot formation, ash fouling, slag, etc. (incl. China Zhundong coal)

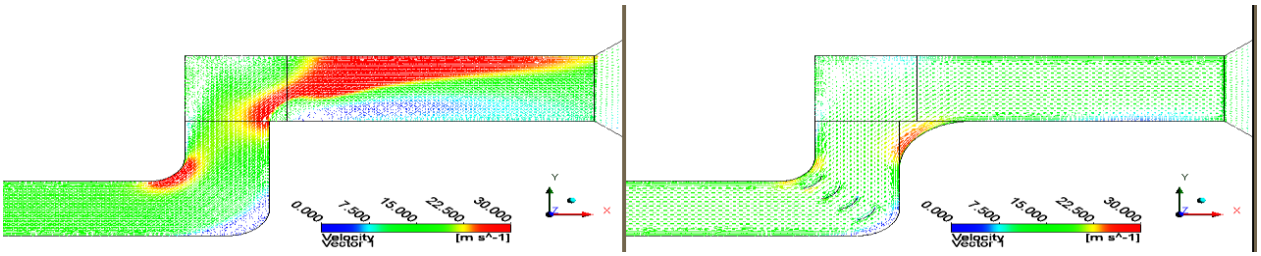
Research Outcomes

- New research and demonstration on the ultra low pollutant emission on the thermal power plant, such as the particulate matter limits is 4.5 mg/Nm^3, SO_2 is 20mg/Nm^3. NOx is 30mg/Nm^3, which lead a new challenge for the draf system for safety and power consumption, aimed to develop high fidelity modeling for multiscale two phase flow system, using experimental and analytical tools.
- Fan power consumption modeling: adaptive diversion and flow. It will improve the flow and speed distribution, remove vortices, lower pressure drop, and avoid high speed erosion with balanced speed.

Scheme	Improved	Original
Deviation of flow	**1.82%**	**24.02%**
Deviation of sectional flow	**13%**	**29.66%**
Pressure drop	**199 Pa**	**342 Pa**



Before After



Before After

- Results: experimental

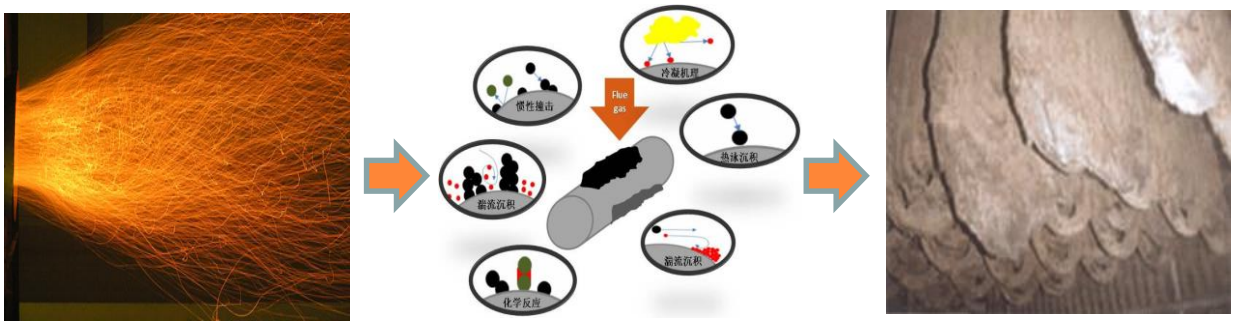
600 MW ESP & flue gas duct combined model

Fan flow rate: 42,000 m^3/hr *

600 MW SCR reactor & flue gas duct model

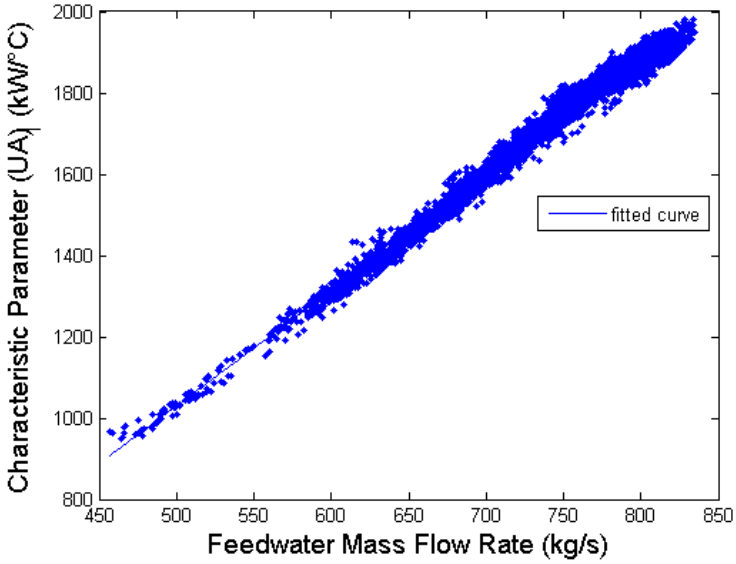
Tracer visualization experiment

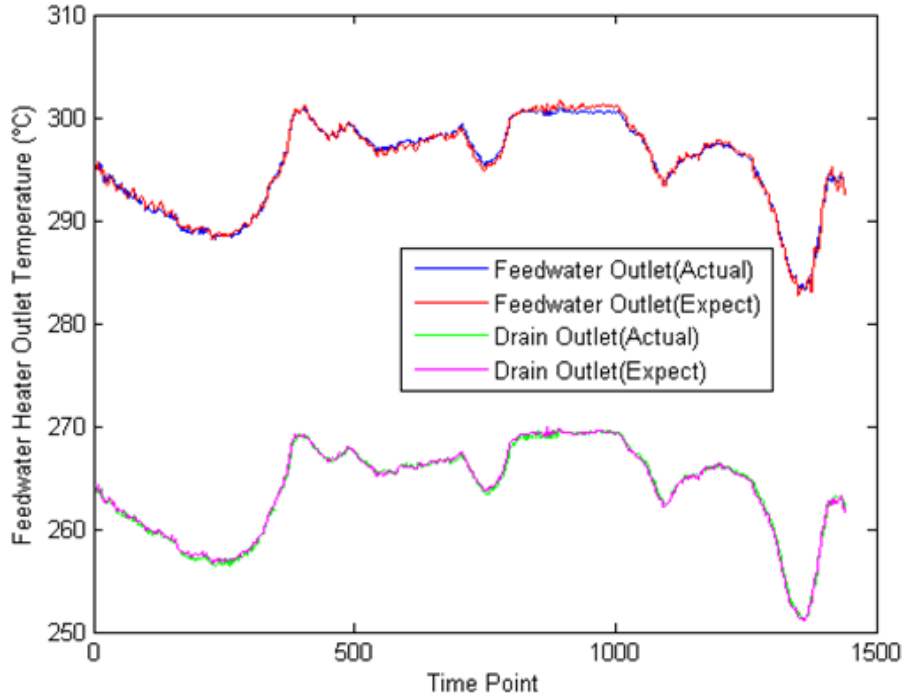
- Research on fouling and slagging issue related to super 700℃ USC boiler (task 1.1)

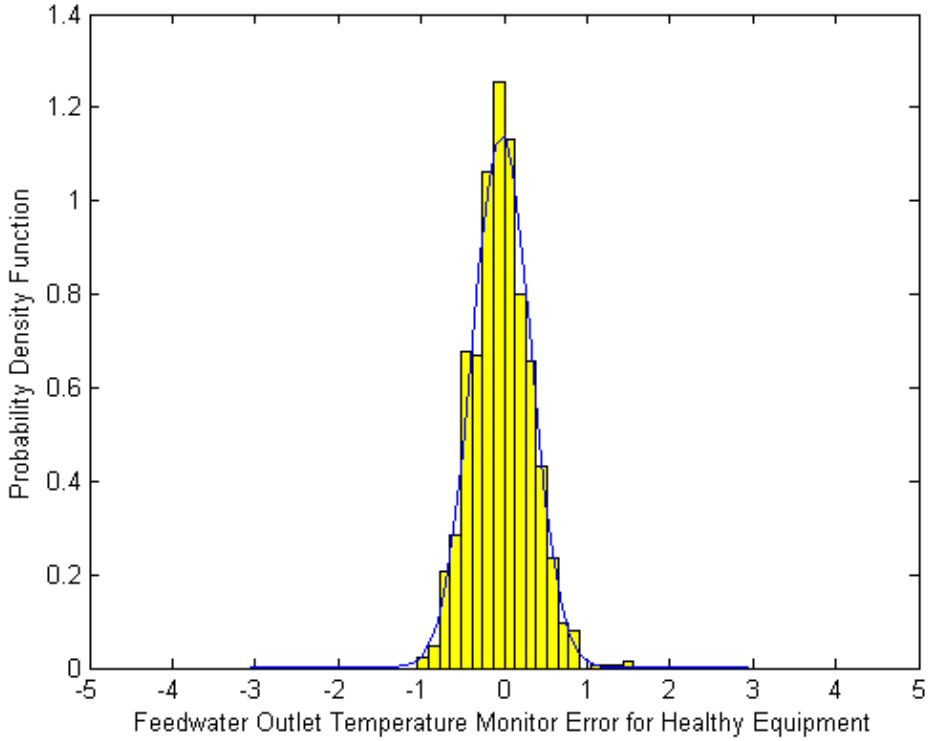


Prediction model and prevention methods of slagging and fouling

- Performing on-line monitoring based on the operation data (task 1.1)

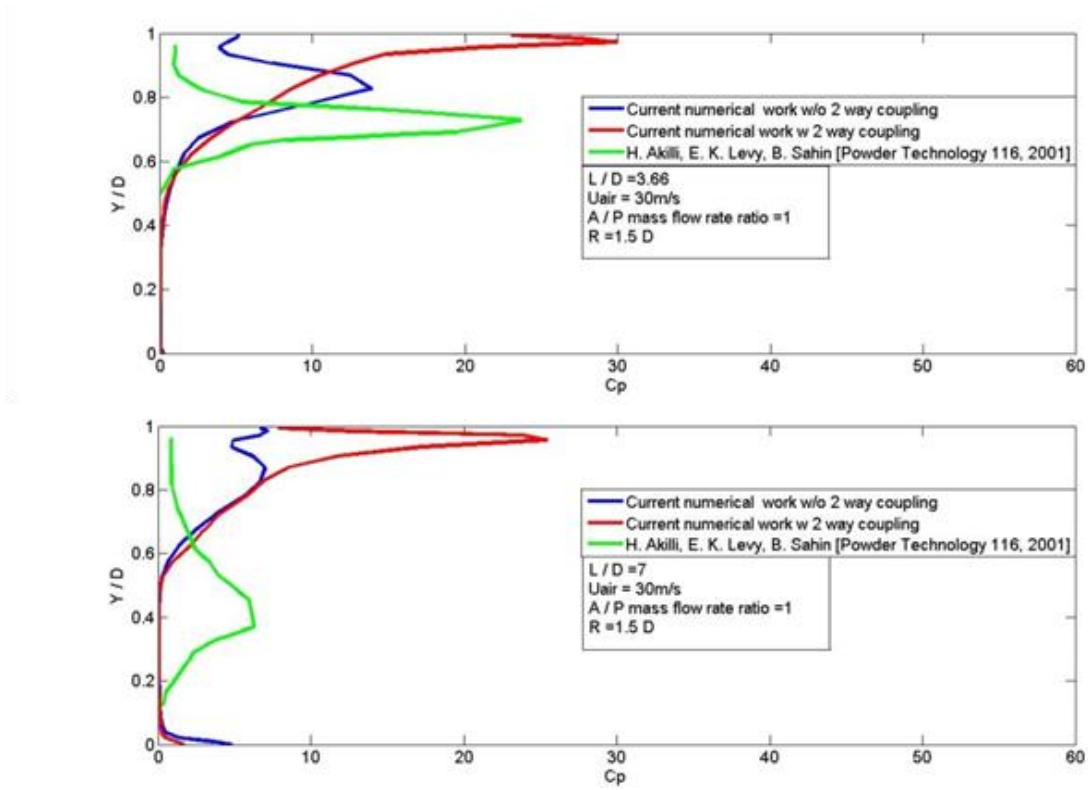






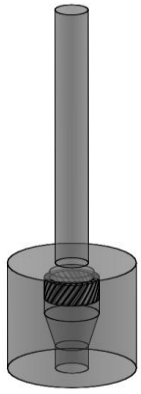
- Gas – Solid Flows: A Validation Study for CFD Models (Participants: WVU – NETL – LP Amina)

1) Developed validated models for prediction of particle segregation / separation in cyclone separators.
2) Laboratory experiments utilizing high speed, high definition cameras to track particle behaviors is being conducted by NETL researchers.
3) CFD simulations are currently being validated using data from literature.
4) A laboratory-scale experimental setup has been constructed, testing will begin shortly for further validation

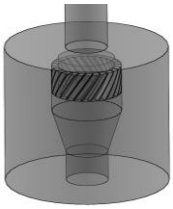


Sample of preliminary CFD simulation result

- Axial Cyclone Simulations: geometry



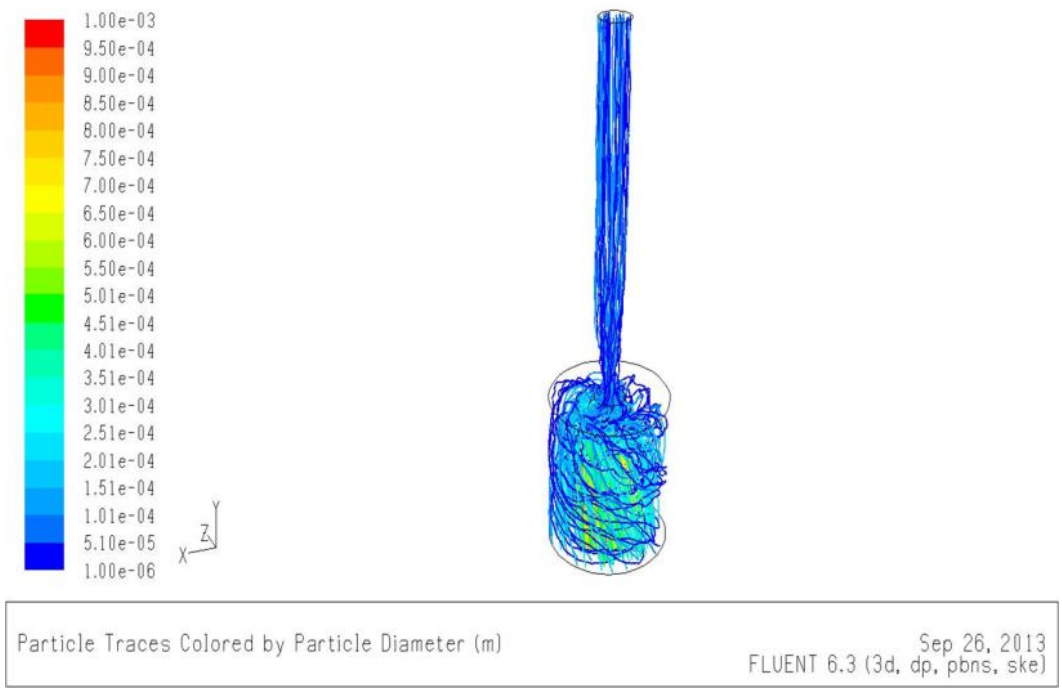
Cyclone Geometry



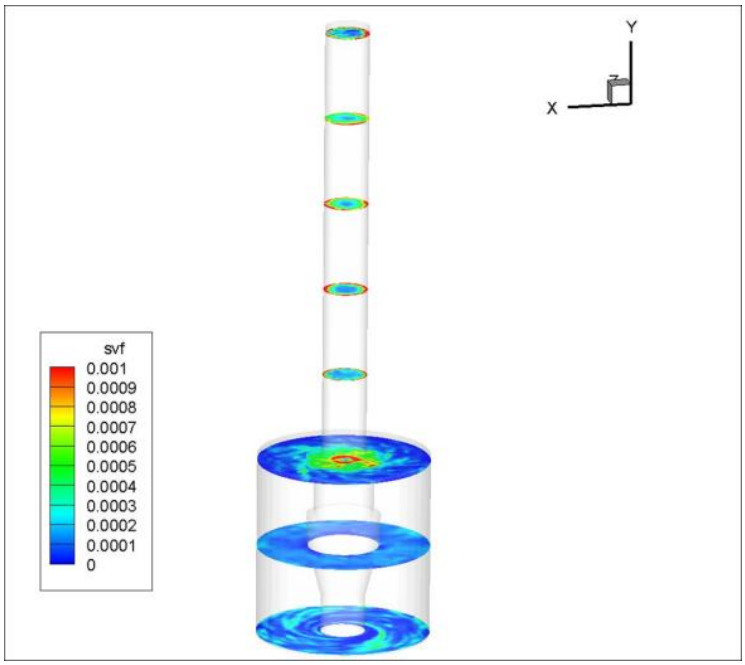
Close up view of drum and vanes

Axial cyclone separator simulations results:

- Inlet BC is a velocity inlet BC given in cylindrical coordinates which are 1.8 m/s axial and 1 m/s tangential.
- Outlet 1 (where fine particles and gas flow through) is a pressure outlet BC with 0 gauge pressure.
- Outlet 2 (where coarse particles are collected) is a wall BC which is set to trap particles.
- Coal (lignite) at the inlet is defined by a Rosin-Rammler distribution.
- Solids loading is 50%.



Particle trajectories (colored by particle diameter)



Solids volume fraction

Accomplishment of Current Year

- Data reconciliation-based modeling and diagnosis is launched
- Construction of experimental system completed on gas-solid flow for fan power consumption
- Preliminary CFD simulations complete
- Two major deliverables
  1) Installation of high speed / high definition camera system and Laser Doppler Anemometer. LPA has installed A-type classifiers on all mills on two boilers in China (600 MW supercritical, 300 MW subcritical)
  2) Experiments and additional CFD validation simulations will be conducted to explore particle roping behavior as a function of solids loading. WVU has installed experimental test rig, is using literature-based results to evaluate CFD simulations.

Future Work Plans

Bilateral Plans for next two years have been developed at the joint technical meeting on October1-3, Wyoming. The research leads from both China and US sites agree to focus on improving the performance of existing Chinese and US coal-fired power plants (CFPPs) as the team's continued goal.

<u>Subtask1.1 Increase efficiency, availability of CFPPs</u>

2014 - Fundamental research on flow pattern

2014 - Experimental work through demonstration projects

2014 – Development of data reconciliation-based modeling for the water-steam system in an ultra-supercritical power plant

2015 – Complete international design standard for ducts, pipes, etc.

2015 – Demonstration of the technology of on-line monitoring in a real-life power plant

<u>Subtask 1.3 Optimize pulverizer performance</u>

2014Q1 – Compare results to boiler performance to determine kinetics

2014Q2 - Determine particle size distribution at classifier outlet based on fundamental research results
2014 - Installation of high speed / high definition camera system and Laser Doppler Anemometer (LDA)
2014 - Experiments and additional CFD validation simulations
2015 – Power plant demonstration
2015 – Publish joint report including fundamental and empirical work

Theme 2 - Clean Coal Conversion Technology

Research Objectives

Clean coal conversion will be one of the main coal utilization technologies. Based on the research of the Chinese and US teams, the partners will complete the research and development of new co-generation systems with combined pyrolysis, gasification, and combustion, advanced coal gasification processes (Chemical Looping gasification with CO_2 capture, Direct SNG production from coal, Gasification properties of the Coal liquefaction residue), coal/biomass co-conversion process and new syngas to chemicals or fuel technology. In addition, conversion of coal or coal gas to high valued chemicals will be investigated. This project will pursue high conversion efficiencies with low cost, reduced carbon footprints, low carbon emissions, and pollution control at large coal conversion plants. Selected developed technologies will be demonstrated successfully at industrial scale for development and installation in both countries.

Theme 2 has more than 7 subtasks under the general theme of Coal Conversion involving more than 10 institutions including universities, research centers and industrial companies. A short summary of the research topics is given below:

- Subtask 2.1 Co-generation System with Combined Pyrolysis, Gasification, Combustion and Poly-generation;
- Subtask 2.2 Chemical Looping Gasification with CO2 Capture
- Subtask 2.3 Direct SNG Production From Coal
- Subtask 2.4 Development of new syngas to chemicals technology
- Subtask 2.5 Gasification Properties Of Coal DTL Residue
- Subtask 2.6 Measurement, Modeling And Environmental Technologies for Unconventional Coal Gasification
- Subtask 2.7 Coal/Biomass Co-conversion Processes

Research Outcomes

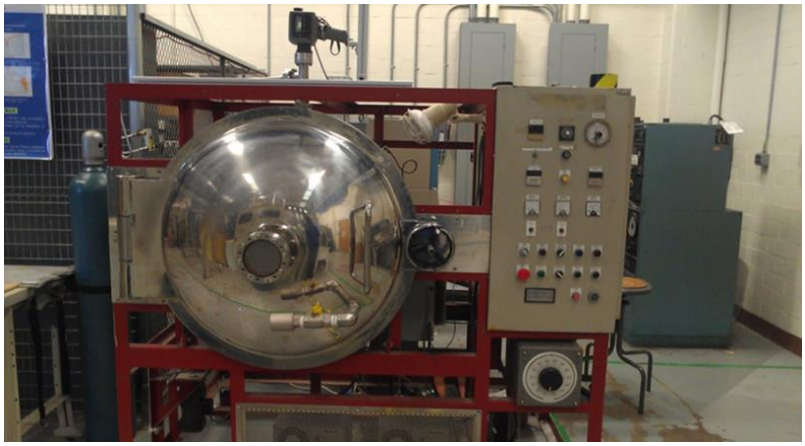
According to the original research plan of theme 2 , all research partners of subtasks from the Chinese and US teams have carried the related research and development projects smoothly and achieved good progress. Meanwhile, all participants have collaborated on research work and academic exchanges. More than 25 papers have been published and 12 patents have been applied for or have been granted. Some of the primary accomplishments of the sub-tasks are as follows:

<u>Subtask 2.1 Co-generation system combined pyrolysis, gasification and combustion</u>

The primary research efforts conducted by Zhejiang University and West Virginia University are:

- Experiments on typical coal pyrolysis process by Thermo-Gravimetric Analysis (TGA), Pyrolysis Gas Chromatography (Py-GC) and fluidized bed pyrolysis reactor to investigate the effect of temperature, mineral, reaction gas atmosphere and coal properties.
- Char properties and combustion behaviors including pollutant emissions and control in a circulating fluidized bed reactor.
- Tests on the retrofitted 1MWt coal co-generation pilot plant combined pyrolysis, gasification and combustion.
- Efficiency, economic, environmental analysis on a constructed 300mW lignite co-generation system
- ZJU and WVU collaborates to simulate the gas solid flow behaviors in the dual fluidized bed reactor system and PhD student from ZJU (Wang Hao) has performed this work in WVU for six months from March to Sep. in 2013.
- 2-D and 3-D simulations of Very High Temperature Entrained Reactor (VHTER) have been completed.

- Reduced order model for quick design analysis of combined power and carbide production in entrained reactors is completed at WVU.
- An enhanced slag flow model is under development.
- The WVU-VHTER design has been refined.
- Reaction kinetics modeling for carbo-themic reactions is validated. This model will be used in simulation of Carbide production process.
- Experiments on reaction kinetics have been carried on the microwave reactor (Temp. ~ 1000 - 1500°C) and the tube furnace reactor (Temp. ~ 1500-1800°C).



WVU Microwave Furnace

1MWt coal stage conversion pilot plant

Feedstock processing ***Operator training*** ***Reactor and auxiliary equipment***

LP Amina's 50 MW demonstration facility designed to Co-produce 100,000 barrels/year in Shanxi, China. Groundbreaking design will allow the power plant to co-produce electric power and high value bi-products, increasing revenues and cutting emissions.

<u>Subtask 2.2 Chemical Looping Gasification with CO_2 Capture</u>

The following research efforts of this sub-task were carried out based on the research plan by Zhejiang University and West Virginia University:

- Experiments on Char combustion in pressurized O_2/CO_2 atmosphere.
- Pressurized steam gasification of coal char under various *T* and *P*
- Effects of pressure, temperature, CO_2 concentration and heating rate on the carbonation of Ca-based sorbent under pressurized atmosphere
- Experiments on the characteristics of Ca-based CO_2 sorbent cyclic carbonation/calcination under various reaction conditions based on PTGA.
- Model establishment of coal chemical looping gasification process based on AspenPlus® software and model optimization
- Primary experiments were performed on the 15kg/h chemical looping gasification facility.
- Workshop on Chemical Looping technology organized by ZJU, WVU and NETL was held in Sep. 30, 2013 in Morgantown.

Construction of laboratory scale ~15Kg/h coal chemical looping gasification system and primary experiments

Subtask 2.3 Direct SNG Production from coal (China Only)

- A bench scale high-pressure constant volume reactor has been built. Coal gas with high-concentration CH4 was obtained, which validated the possibility of direct SNG production from coal
- A circulated high-pressure constant pressure reaction system is constructed for coal-to-SNG

Subtask 2.4 Development of new syngas to chemicals technology (China Only)

The main research works have been carried in WVU and ZJU are:

- Construction of experimental system for synthesis of ethylene glycol from dimethyl oxalate is completed;
- Calculations of molecular dimensions and polarizations completed for Zeolite Y.
- Thermo-gravimetric analysis (TGA) used to determine thermal stability characteristics for palladium nitrate hydrate and zeolite

Subtask 2.5 Gasification properties of the Coal direct liquefaction residue

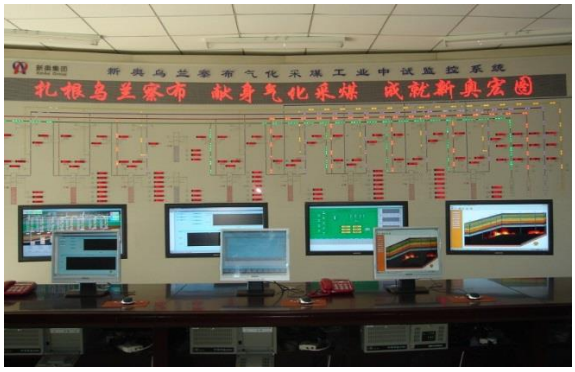
China Shenhua Group, together with WVU have completed the following:

- Coal quality analysis and evaluation analysis of raw material coal in Bu lian Ta coal mine.
- Basic analysis of liquefaction residue.
- Liquefaction residue and coal mixture sample analysis.
- Coal liquefaction residue slurry analysis and developing suitable additives for coal liquefaction residue and coal mixture slurry;
- Validate the liquefaction residue for coal gasification feasibility;
- Construction of gasification kinetics reactor is completed and carried the preliminary coal pyrolysis experiments;
- Major components of coal extraction apparatus purchased
- Preliminary coal pyrolysis experiments carried out in the gasification kinetics reactor at the University of Wyoming.

Subtask 2.6 Measurement\ Modeling\ Environmental Technologies for Unconventional Coal Gasification (China Only)

The primary research accomplishments of 2013 achieved by ENN together with LLNL are:

- According to the characteristics of underground coal gasification, a model test reactor was designed with the ratio of 1:12.5 to model an underground coal seam, inlet pipes, outlet pipes and four peep holes for closed circuit industrial television (CCTV) monitoring were installed in the reactor, thermocouples and water pipes were set in the coal seam.
- The concentration field and temperature field, combined with the experimental cavity data was drawn by the process software and the expansion law of cavity were studied simultaneously.
- Apply the developed measurement technologies, model, and environment analysis methods and emission control technologies to the data acquisition and analysis, and evaluation of the demonstration plant.



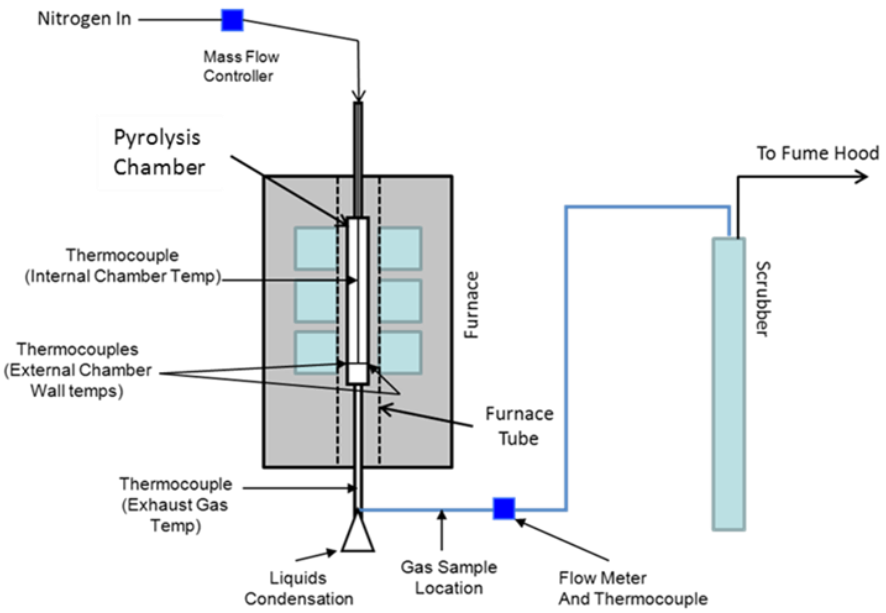
Wulancabu UGG demonstration plant Data acquisition and analysis of the demonstration plant

Subtask 2.7 Coal/biomass co-conversion process

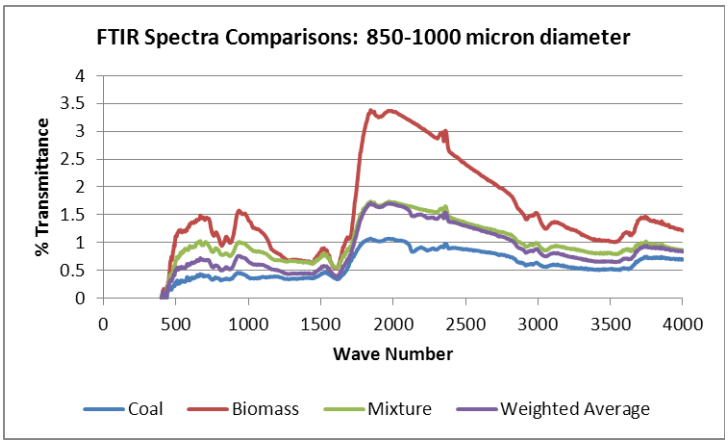
The main research efforts carried by China University of Mining Technology in cooperation with West Virginia University are as follows:

- The smoothing progress of experimental study: the pretreatment and modification methods of biomass have been completed, the forming process and pyrolysis characteristics of bio-coal briquette have been studied. The synergistic effect and interactive mechanism of co-pyrolysis of coal and biomass have been researched.
- The catalyst used to coal/biomass-catalyzed gasification have been researched.
- Developed an experimental platform of co-gasification of coal and biomass, where the gas calorific value is higher than 3000kJ/Nm^3 in the conditions of air-steam as being the gasification agent.
- Study the key processes and the efficient catalyst on co-transformation of biomass and coal.
- At WVU, a vertically-mounted tube furnace capable of temperatures of 900°C was used for co-pyrolysis of coal and hardwood biomass, and tests with pure coal, pure biomass, and a 50/50 mixture were completed.
- The effects of particle size on char and tar production, and the chemical structure of the char, was studied. Tar yield from coal-biomass mixture is found to be less than that tar yield from col pyrolysis alone. .

Co-gasification of coal and biomass experiment system



Schematic of WVU pyrolysis furnace



- At WVU, a vertically-mounted tube furnace capable of temperatures of 900°C was used for co-pyrolysis of coal and hardwood biomass.
- Tests with pure coal, pure biomass, and a 50/50 mixture were completed.
- In addition, the effects of particle size on char and tar production, and the chemical structure of the char, was studied.

Accomplishments of Current Year

- Coal stage conversion poly-generation technology using combined pyrolysis, gasification and combustion is verified on 1MWt pilot plant and may now be demonstrated in industry.
- Coal to intermediates technology developed by LP Amina in cooperation with WVU will allow the power plant to co-produce electric power and high value bi-products (such as calcium carbide), increasing revenues and cutting emissions and a demonstration facility is under construction in Shanxi, China cooperated with Gemeng Int.
- Applied the developed measurement technologies, model, and environment analysis methods and emission control technologies to the data acquisition and analysis, and evaluation of the Wulanchabu

demonstration plant of underground coal gasification in China.

- Published more than 25 papers, and applied for or authorized 12 Chinese patents.

Future Work Plans

Research work will proceed according to the 10 point research plan. Collaboration and academic exchanges between Chinese and US partners will be enhanced over the next 2 FYs:

- Each sub-tasks will be executed according to the schedules of the 10 point plans
- Efforts will be focused on publications and tech-transfer to industry
- New projects and avenues for closer collaboration among US and Chinese research teams will be sought.

Theme 3- Pre-Combustion CO_2 Capture

Research Objectives

This project has one primary goal: development of techniques to aid in the design and optimization of commercial-scale IGCC systems.

Combining advanced gasification with CCS in the power sector remains a critical pathway towards low-carbon power generation. Industrial, research, and academic leaders from both countries will work with the major demonstration projects and best in class technologies to provide the world with robust, transparent cost and performance estimates for this class of power plant. Pilot testing platform will be constructed via this research work, based on which the technology of CO_2 capture, utilization and storage based on IGCC will be developed and demonstrated.

<u>Subtask 3.1 IGCC with CCS</u>

- Assess the economic feasibility and operability of existing capture technologies in conjunction with the removal of criteria pollutants.
- Assess the technical/economic feasibility and potential economic benefit and operability of new, novel carbon capture technologies.
- Optimize the economics of different carbon capture technologies.

<u>Subtask 3.2 IGCC Knowledge Exchange</u>

- Start-up, operation and maintenance experience exchange.
- Establish guidelines/protocols/criteria for system optimization and evaluation, as well as techno-economic analysis and comparison at commercial-scale application.

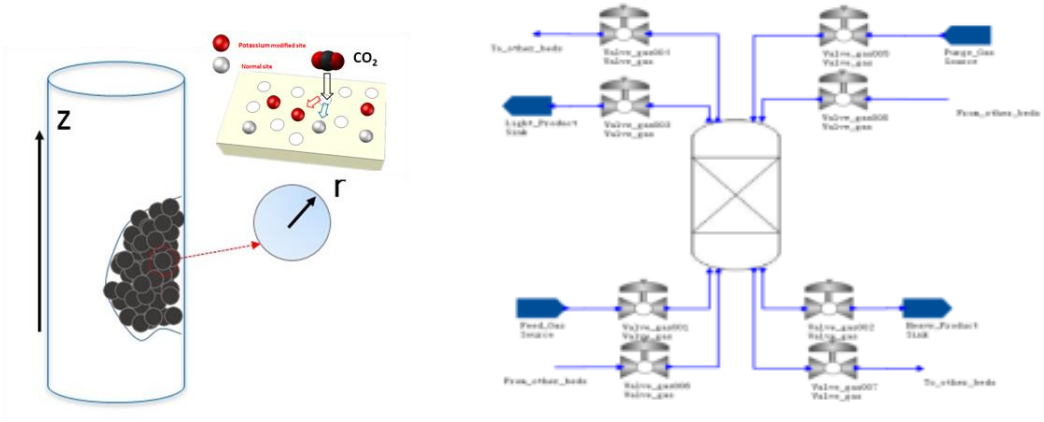
Research Outcomes

- Completed the progresses comparison and selection, and unit modeling of $30MW_{th}$ pre-combustion CO_2 capture system
- Completed the Process Flow Diagram (PFD), gives the equipment layout, process equipment tables, major static equipment diagrams, and system

- Completed the key equipment design of $30MW_{th}$ CO_2 capture system based on IGCC.
- Completed the large key equipment bidding of $30MW_{th}$ CO_2 capture system based on IGCC.
- Completed design of the 200m3/h palladium membrane H2/CO2 separation system
- Development of multi-scale multi-physical field coupling model for the adsorption column. Developed an adsorption model based on gPROMS simulation platform:

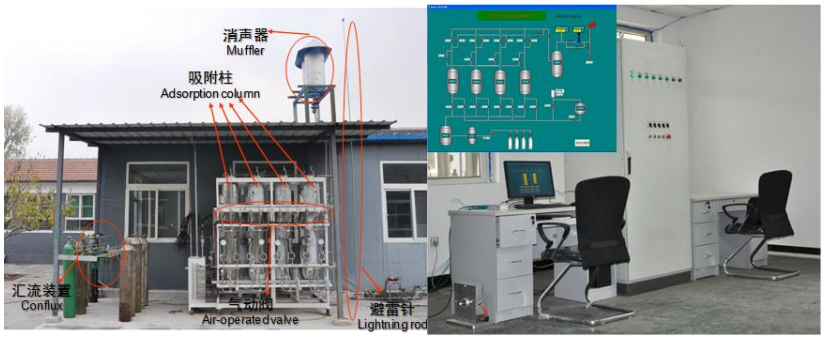
1) Micro stage: Taking particle micro structure adsorbents, adsorption /desorption elementary reactions and mass transfer into account
2) Macro stage: Taking porous diffusion and related fluid characteristics and heat transfer into account
3) Advantages: reflecting a highly convinced scale-up process, including modeling of adsorption, pressure equalization pressurization/depressurization, purge, blow down etc.

多尺度多物理场耦合准二维模型



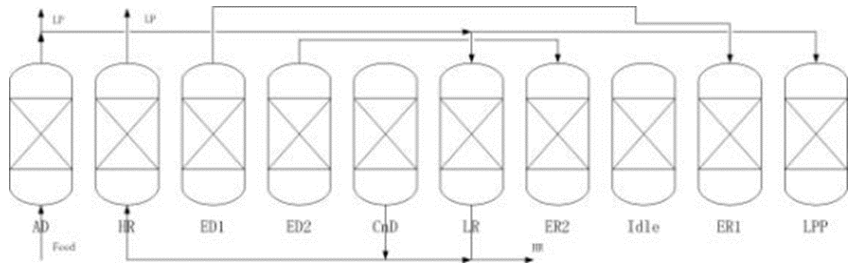
Quasi-2D multi-scale multi-physical field coupling model

- Tsinghua set up of a PSA pilot rig、a test rig and a shaping line. As a multi-functional apparatus, the functions include: production of kilograms of adsorbents, cyclic tests of adsorbents, breakthrough curve tests and PSA tests.



PSA pilot rig control unit

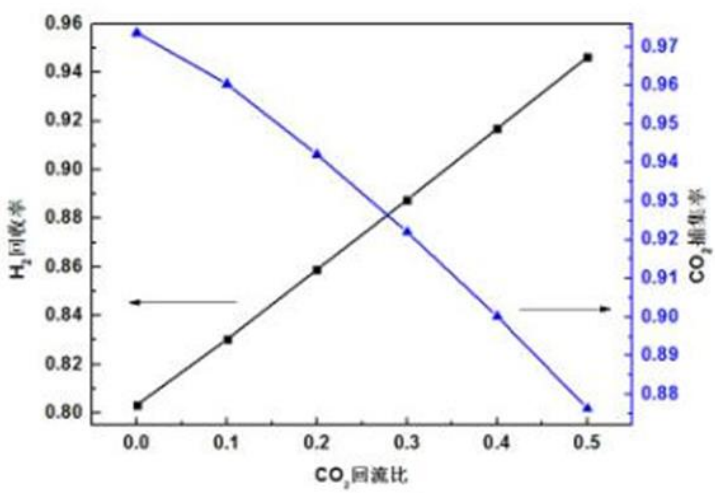
- To realize both high H_2 recovery and CO_2 capture rate by introducing reflux process



Reflux of CO_2: introduce of product CO_2 into adsorption column after adsorption process instead of raw gas

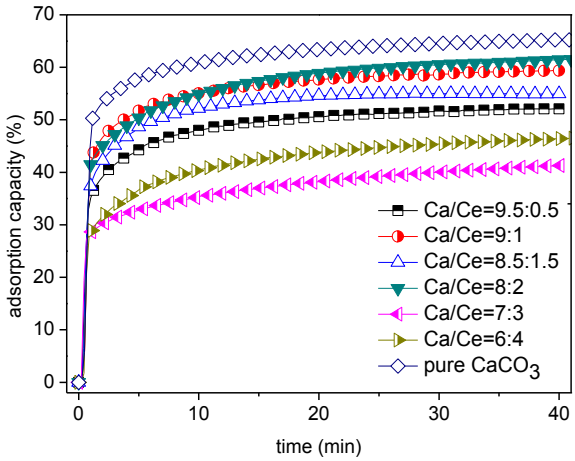
	H_2 recovery rate	CO_2 capture rate
Original 4-2-1 processes	80.38%	97.37%
After adding CO_2 reflux	91.70%	94.21%

A comparison of H_2 recovery and CO_2 capture rate between original 4-2-1 processes and new processes adding CO2 reflux



The effect of CO_2 reflux ratio on H_2 recovery rate and CO_2 capture rate

- According to the screening of the experiments, we get the doping element, Ce, and investigated the doping ratio and carbonation/calcination condition of the sorbents. The stability and working life had been improved. The single adsorption capacity and cycle stability of $CaCO_3$-CaC_2O_4 doped Mg, Ce and La had been studied.



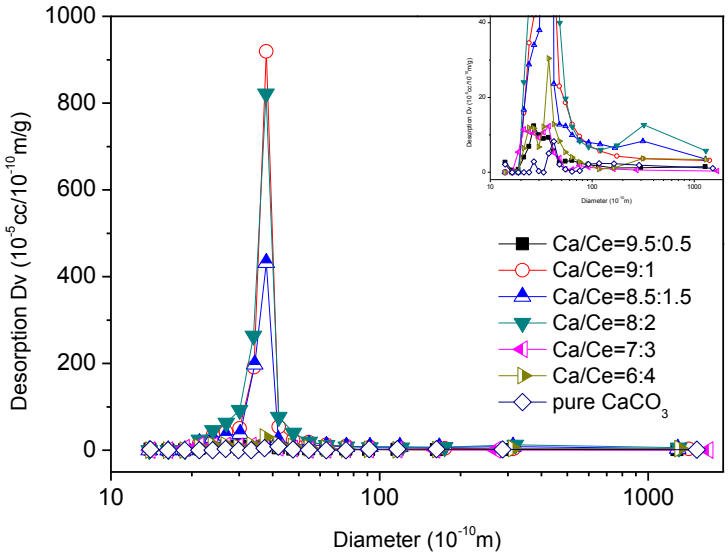
Adsorption capacity curves for CaO doped CeO_2 with different mole ratios and pure $CaCO_3$

BET analyses of sorbents doped CeO_2 with different mole ratios

doping ratio	surface area m^2/g	pore volume cm^3/g	average pore size nm
9.5:0.5	5.469	0.03418	25.00
9:1	42.08	0.1226	11.65
8.5:1.5	29.84	0.1159	15.54
8:2	**50.90**	0.1886	**14.82**
7:3	2.858	0.01402	19.62
6:4	7.655	0.07437	38.86
pure $CaCO_3$	3.710	0.03256	35.20

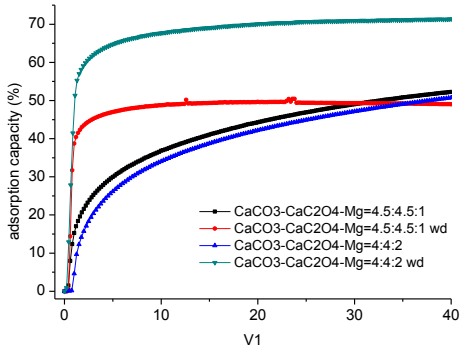
An important reason of different adsorption capacity of $CaCO_3$-Ce – pore diameter distribution is that the adsorption capacity was not only affected by surface area but also related to the diameter of pore:

- Smaller meso-porous → easily blocked by the $CaCO_3$, CO_2 hardly pass through
- bigger pore → CO_2 could easily diffuse into the core
- Conversion: Ca/Ce(8:2) > Ca/Ce(9:1)

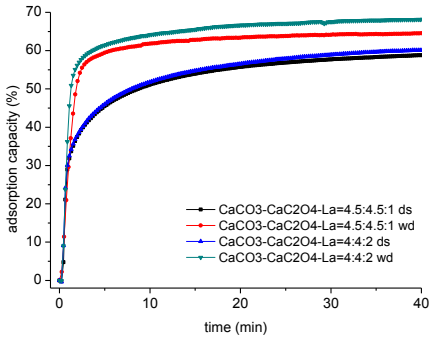


The pore diameter distribution of sorbents doped CeO_2 with different mole ratios and pure $CaCO_3$

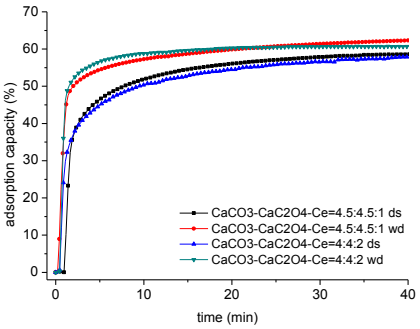
$CaCO_3$-CaC_2O_4 as precursor



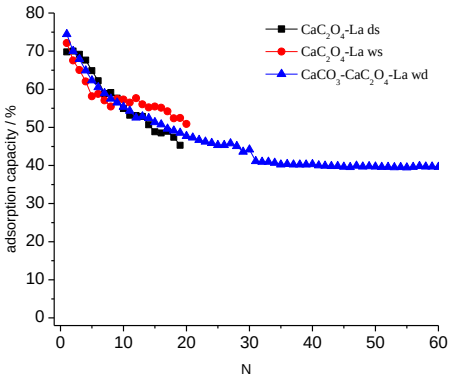
Adsorption of $CaCO_3$-CaC_2O_4-Mg



Adsorption of $CaCO_3$-CaC_2O_4-La

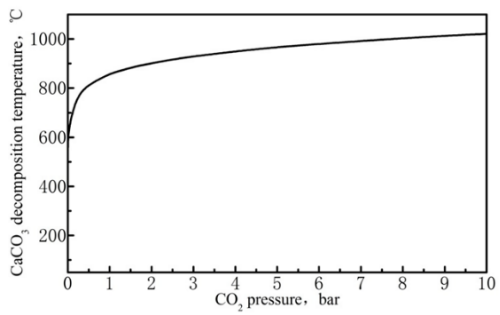


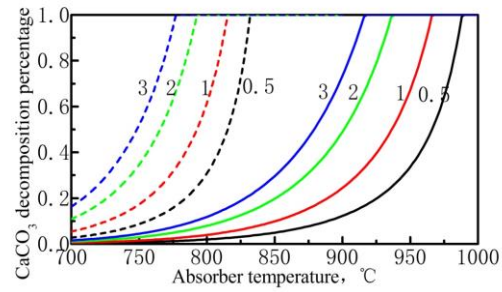
Adsorption of $CaCO_3$-CaC_2O_4-Ce



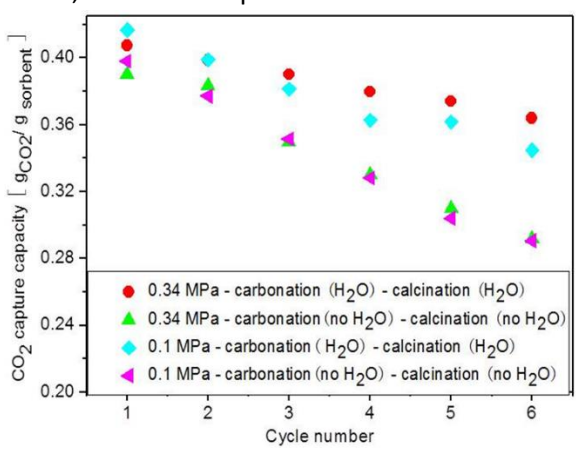
Adsorption of CaC_2O_4-La and $CaCO_3$-CaC_2O_4-La

- Tested the relationship between the decomposition extent of $CaCO_3$ and the decomposition pressure and temperature: $CaCO_3$ decomposition temperature changes with CO_2 partial pressure, $CaCO_3$ decomposition extent with the reactor temperature and the H_2O/ carbon ratio

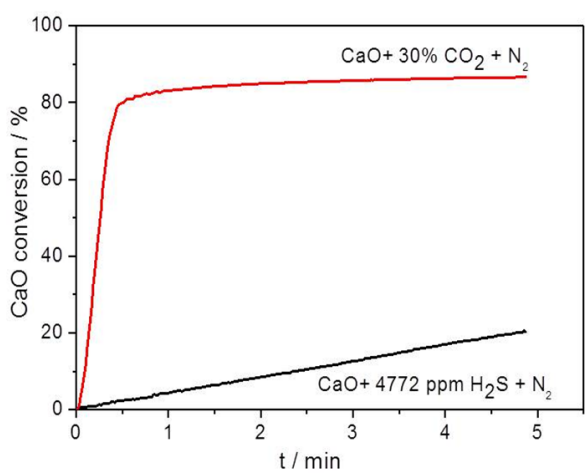




The effect of pressure on the cyclic activity of CaO-MgO sorbent: the increase of pressure benefits the CO_2 absorption of the sorbent; the effect of pressure is more obvious with H_2O present.



The effect of H_2S on the cyclic activity of CaO-MgO sorbent: the CaO conversion rate during the carbonation process is faster than the rate during the sulfidation process.



The carbonation curve and sulfidation curve of CaO at 650°C

Achievements of Current Year

Subtask 3.1 IGCC with CCS

- Completed the design of IGCC 30 MW_{th} CO_2 capture facility.
  1) Completed the comparison, selection, and unit modeling of a 30 megawatt thermal (MW_{th}) pre-combustion CO_2 capture system; 60,000 – 100,000 tpy CO_2.
  2) Completed the process flow diagram, which includes the equipment layout, process equipment tables, major static equipment diagrams, and system control program. Completed the key equipment design of a 30 MW_{th} CO_2 capture system based on IGCC.
  3) Completed the key equipment design of 30MWth CO2 capture system based on IGCC.
  4) Completed the large key equipment bidding of 30MWth CO2 capture system based on IGCC.
  5) Completed design of the 200m3/h palladium membrane H2/CO2 separation system.
- New solvent and sorbent development.
  1) Completed the capture reagent and process development evaluation. Confirmed the best adsorption temperature and the fittest CO_2 concentration of $CaCO_3$ and CaC_2O_4 as precursors.
  2) The high-temperature, solid-state method is used to modify the adsorbent by doping magnesium, aluminum, cerium, zirconium, and lanthanum. The team found that the adsorption capacity was dependent on different conditions.
  3) Development of K_2CO_3 promoted, stearate intercalated hydrotalcite (China task only)
  4) Development of multi-scale multi-physical field coupling model for the adsorption columnments
- Development of adsorption model based on gPROMS simulation platform
  1) Micro stage: Taking particle micro structure adsorbents, adsorption /desorption elementary reactions and mass transfer into account
  2) Macro stage: Taking porous diffusion and related fluid characteristics and heat transfer into account
  3) Advantages: reflecting a highly convinced scale-up process, including modeling of adsorption, pressure equalization pressurization/depressurization, purge, blow down etc.

Subtask 3.2 IGCC Knowledge Exchange

1) Critical data and lessons learned, and knowledge shared through operational experience with demonstration projects as systems are optimized and the cost of pre-combustion CO_2 capture is lowered. Such knowledge sharing contributes to accelerating the development of IGCC with CCS, a critical pathway toward low-carbon power generation with coal.

Future Work Plans

Subtask 3.1 IGCC with CCS

- Assess the economic feasibility and operability of existing capture technologies in conjunction with the removal of criteria pollutants; study the operational impact with various water-gas shift technologies and CO_2 separation process on IGCC system performance.
- Assess the technical/economic feasibility and potential economic benefit and operability of new, novel carbon capture technologies; dynamic modeling of solvents; development of Techniques for Integration and Optimization of IGCC system.
- Screen existing chemicals and develop new formula for capture reagent that will have high working capacity and less energy consumption; optimize the economics of different carbon capture technologies.
- Pre-feasibility study of pre-combustion CO_2 capture system for Edwardsport IGCC will be finished by Q4 2014.

Subtask 3.2 IGCC Knowledge Exchange

- Continue to conduct informal information exchange between Duke Energy and Tianjin IGGC Co. / Huaneng CERI. Duke Energy and Tianjin IGCC Co. (GreenGen) / Huaneng CERI will share information on an on-going basis related to their respective IGCC programs, including but not limited to the construction and operation of new IGCC power plant facilities, IGCC design improvements, or efficiency enhancements. Also, reasonable access to observe the operation of IGCC power generating facilities.
- Develop draft reports for Tianjin IGCC and Edwardsport IGCC per agreed template by Q2 2014.
- Develop final reports for Tianjin IGCC and Edwardsport IGCC per agreed template by Q4 2014.

<u>Subtask 3.3 IGFC (Integrated Gasification Fuel Cell)</u>

- Development of improved solid oxide fuel cell anodes for long-term stability; resistance to sulfur contamination from the syngas by Q2 2015.

Theme 4 - Post-Combustion CO2 Capture

Research Objectives

The ACTC team is directly addressing the need for steep emissions reductions from the existing coal fleet by analyzing, testing, and demonstrating technologies for post-combustion capture integrated with sequestration at real power plants. The goal of this theme is to mitigate CO_2 emissions with breakthroughs in process integration and significant cost reduction through:

- Advanced membrane separation
- Solvent enrichment
- New solvent development and reaction rate enhancement
- Scale-up engineering and process integration

<u>Subtask 4.1 Demonstrate a reasonable match between experimental prediction and simulation output</u>

- Evaluate 1M tons/year post combustion CO_2 capture projects at Duke Gibson station based on the Huaneng experience
- Optimize ASPEN models from Gibson-3 with mixed adsorption solvents for better prediction of the system performance
- Further study of energy savings plans, including the use of let-down turbine for energy recovery, or the use of an additional boiler to provide steam
- Optimization of the system integration

<u>Subtask 4.2 Develop solvent that reduces overall CO_2 capture cost at pilot scale (0.1 MWth)</u>

- The development of new solvent for CO_2 separation from utility flue gas
- Evaluation of the novel absorption solvents
- Conduct corrosion and degradation testing of the solvent.
- Evaluate solvent for mass transfer rate using a wetted wall column

<u>Subtask 4.3 Develop a catalyzed amine solvent showing increased mass transfer at mini-scale scrubber</u>

- To test CO_2 hydration catalysts to increase scrubber kinetics
- Develop cost effective catalysts that are soluble and stable in carbon capture solvents
- Integrate catalyst process enhancements to increase overall mass transfer in the scrubber

<u>Subtask 4.4 Produce a hybrid membrane that reduces overall CO_2 capture cost</u>

- Develop high permeability and ultra-thin barrier materials enabling high membrane permeance with improved separation efficiency and decreased separation costs
- Realize high performance hybrid polymer/additive membrane materials for post-combustion carbon capture from coal derived flue gas (materials development & optimization)
- Develop commercially attractive methodologies for hybrid composite membrane fabrication with ultra-thin (≤200 nm) thick selective layers (Membrane Fabrication)
- Minimize membrane support costs, maximize membrane flux, demonstrate gas perm-selectivity & thermo-chemical stability characteristics in simulated process environments (Membrane Demonstration)

<u>Subtask 4.5 Demonstrate an asymmetric capacitive deionization (CDI) for amine solvent CO_2 enrichment</u>

- To efficiently mitigate CO_2 emissions through integration of capacitive deionization-based solvent enrichment which can be used to reversibly concentrate ionic species in the carbon capture process
- Develop cost effective, highly porous carbon for adsorption of carbon-loaded amines
- Integrate process enhancements to lower device sizes and energy costs
- Use surface techniques to modify the driving force for adsorption thereby enhancing device performance

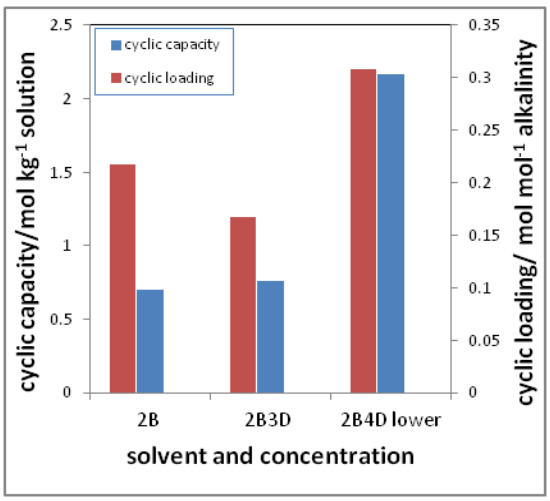
Research Outcomes

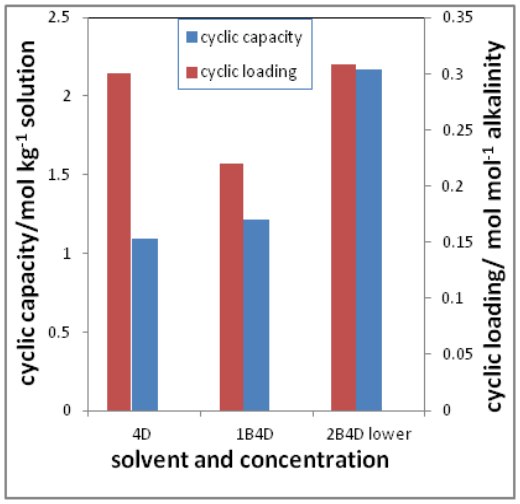
Subtask 4.1

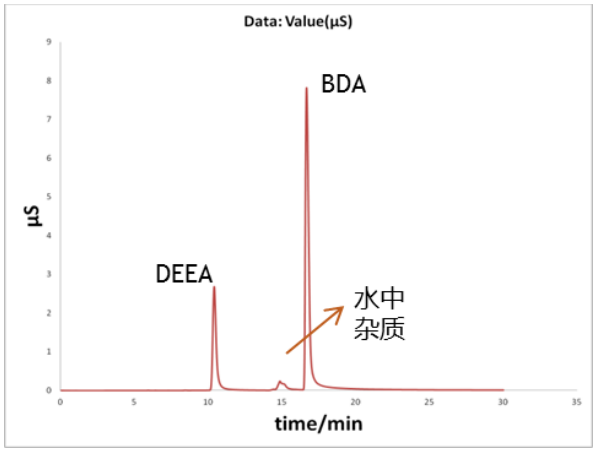
- CERI visited Duke Gibson power plant, LLNL delegate visited CERI and the 120,000 t/a PCC unit in Shanghai Shidongkou Power Plant. The visitors discussed with the engineers and operators in the power plants on system design and lesson learned from the operations.
- LLNL built ASPEN model based on CERI's technology to evaluate the technical and economic feasibility of this project.
- Based on the modeling and information exchange, LLNL has finished the evaluation draft report in August 2013. The report, Technoeconomic Evaluation of MEA versus Mixed Amines for CO_2 Removal at Near-Commercial Scale at Duke Energy Gibson 3 Plant, contains engineering analysis, process economics, uncertainties and opportunities analysis.
    - In case of 30wt% MEA, the added cost is estimated to be $68.7/MW.
    - In case of 30wt% blended amine, the added cost is estimated to be $61.8/MW.

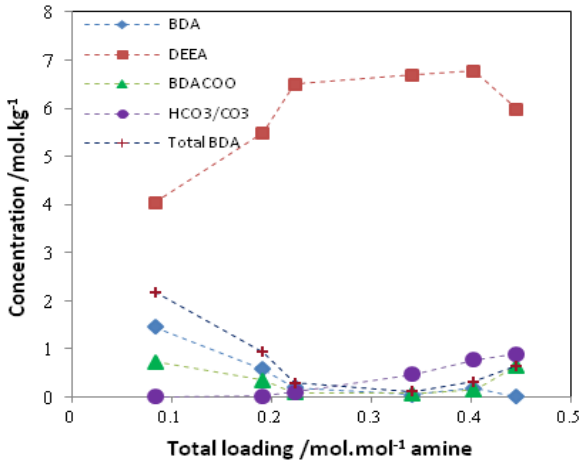
Subtask 4.2

- A 2-phase solvent has been developed to reduce the process energy cost. Screening the two phase solvent, two phase mechanism analysis, and product analysis were accomplished.
- Tests have been completed on the CO_2 absorption rate, CO_2 desorption rate in different selected absorbent candidate

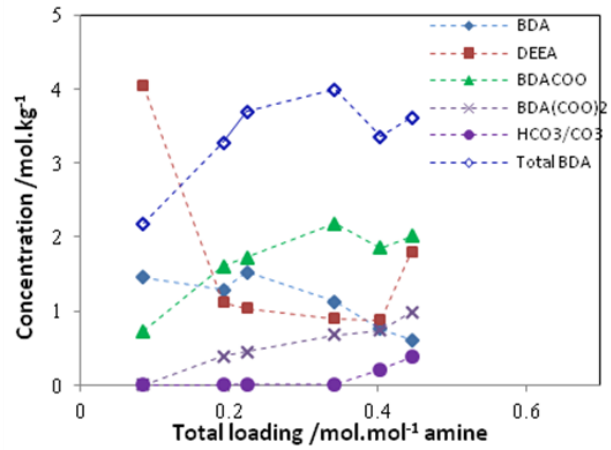








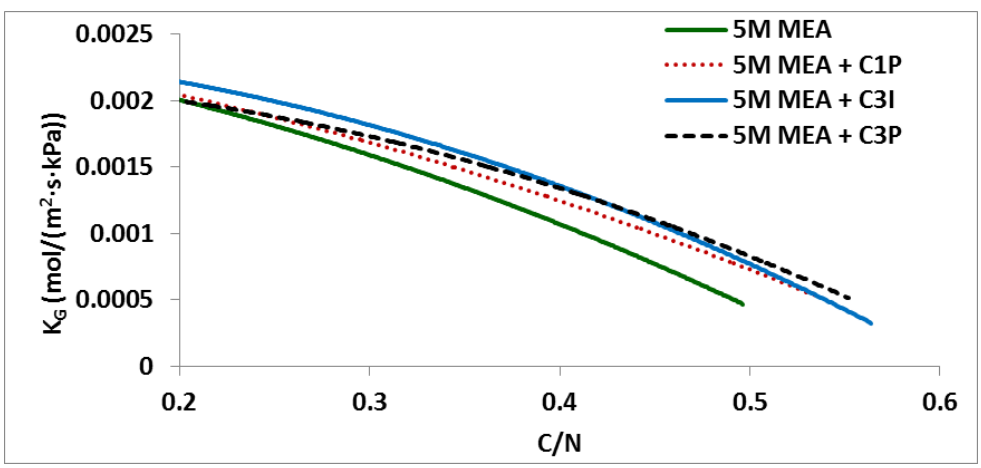
Species in the upper phase



Species in the lower phase

Subtask 4.3

- Development of Zinc and Cobalt derived catalyst, increased solubility of catalyst in amine solutions, demonstrated repeatable performance with cycling of catalyst
- Active in concentrated primary amines (5M MEA) via WWC at 40 °C
- Enhanced mass transfer over entire operational window. Up to 34% increase in overall mass transfer in 5M MEA

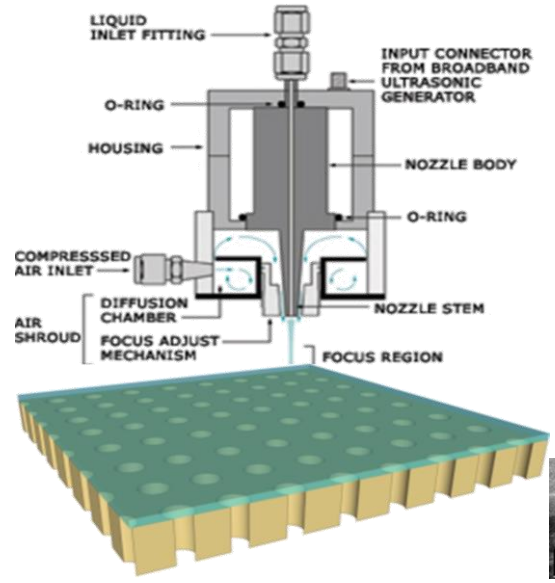


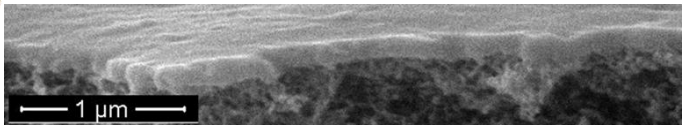
This is the first catalyst to be active in concentrated primary amines (5M MEA) at 40 °C. Up to a 34% increase in overall mass transfer in 5M MEA was found which is a two orders of magnitude increase in the rate constant vs. the current state-of-the-art.

Subtask 4.4

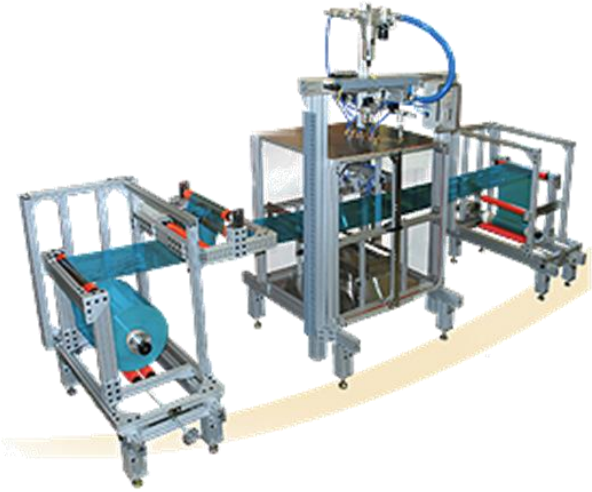
- Developed novel polymer/ionic liquid(IL) hybrid membrane designs to achieve high permeability in a mechanically robust platform
- Demonstrated that the employed polymer matrix microstructural characteristics impart the required mechanical robustness

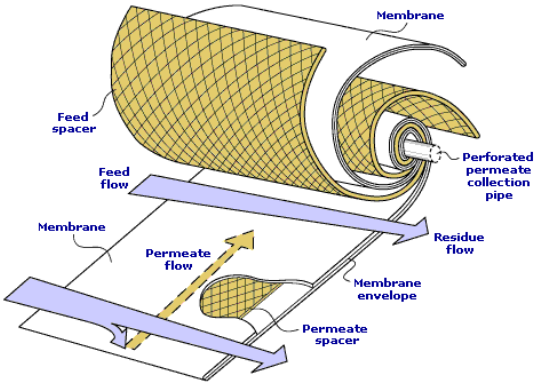
- Demonstrated that the incorporation of IL additives imparts the desired liquid like gas transport properties on the hybrid membrane by enhancing both membrane diffusivity and solubility. The permeability of the developed hybrid membranes was 100-2000X that of the neat polymer.
- Identified relationships between polymer crystallinity and membrane performance and utilized those relationships to realize improved hybrid membrane performance. In general, a lower crystallinity matrix results in higher overall permeability





An ultra-thin composite membrane fabrication method is under continuous development and optimization with a 107 nm thick CO_2 selective layer on a commercially attractive support having already been fabricated using LANL's Ultrasonic Spray Coating Technique (USCT)

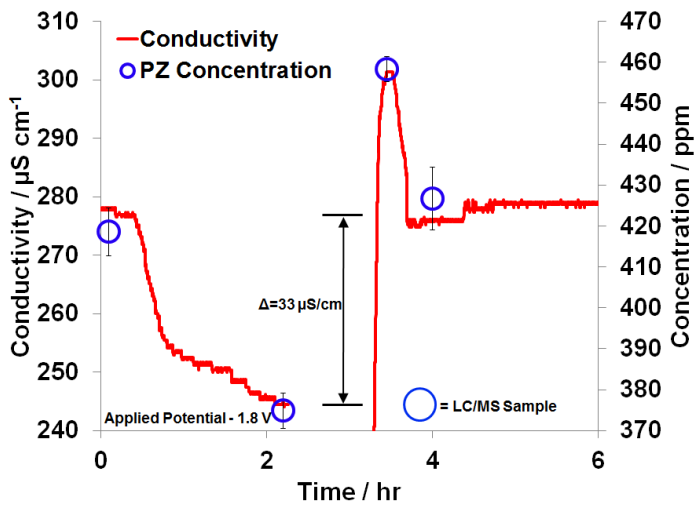




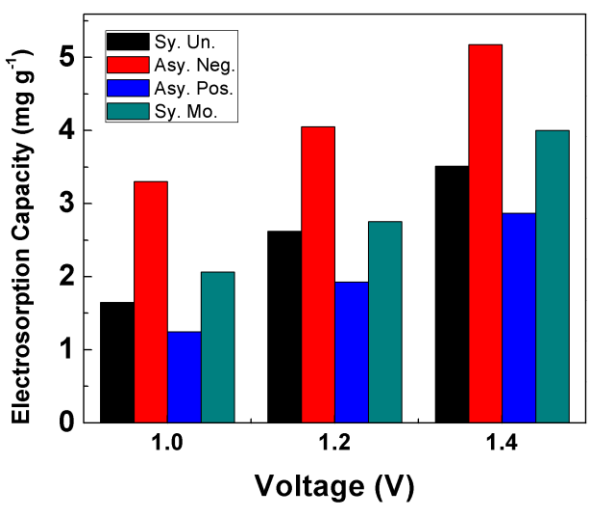
Large scale membrane fabrication is readily achievable for this technology.

Subtask 4.5

- For the first time, enrichment of a carbon-loaded amine solvent has been shown with the CDI process. Enrichment of ~10% was achieved.
- Surface studies centered on modifying the point of zero charge (PZC) led to increases in the electrosorption capacity of up to 50%. Carbon cathodes were modified through oxidation treatments and silica nanoparticle deposition. Asymmetric configuration led to the highest salt capacity.
- Construction of a new flow-through type CDI cell has taken place which will result in higher enrichments over flow-by type cells



Conductivity profiles for 1.8 V of applied potential along with liquid samples circled in blue analyzed using LC/MS. This result marks the first time enrichment of a carbon-loaded amine solvent has been shown with the CDI process. Enrichment of ~10% was achieved.



The electrosorption capacity of the carbon xerogel increased by up to 50% when treated cathodes were used. This increase is due to decreases in the co-ion expulsion effect.

Future Work Plans

Subtask 4.1

- Prefeasibility study report of the Gibson CO_2 capture by the end of 2014

- Further optimization and energy saving plans of the capture system,
- Improved mass transfer of MEA based amine
- Performance evaluation of potential CERC technologies for large scale CO_2 capture

Subtask 4.2

- Establish the absorption and desorption equilibrium model for new solvents, test of physicochemical properties of new solvents
- Energy saving desorption methods
- Comparison between two phase and single phase sorbents
- Degradation studies of new absorbents

Subtask 4.3

- Active catalyst candidates will be delivered to LLNL for computational analysis using DFT.
- Continued catalyst improvements for both activity and solubility.
- Thermal cycling experiments conducted to demonstrate potential for long term catalyst lifetime.
- Determination of effects of flue gas contaminants (NOx, SOx) on catalyst activity.
- Scale up methodology established for a catalyst to allow testing using the 0.1 MW pilot plant or equivalent sized scrubber tower.
- Collaborate on evaluating mass transfer increases with simulations to determine scrubber sizes in collaboration with Huaneng and LLNL

Subtask 4.4

- Continued development of advanced materials and process strategies for realizing improved selectivity and process efficiencies at process conditions
- Further apply developed fabrication methods for ultra-thin, defect-free membrane fabrication to newly optimized hybrid SL materials
- Demonstrate membranes with unprecedented permeance characteristics via combining newly developed hybrid materials with developed fabrication methodologies
- Materials and membrane demonstration in simulated flue gas environments

Subtask 4.5

- Scale up new flow-through CDI cell for larger enrichment studies
- Develop and implement DC/DC converter for more efficient energy recovery in integrated CDI system.
- Evaluation of precipitating solvent towards solvent enrichment using bench scale analyses

Collaboration Works

- Subtask 4.1: Work between US-China themes on modeling components
- Subtask 4.2: Work between UK and Huaneng to test advanced carbon capture solvents
- Subtask 4.3/4.4: Work to develop US-China joint modeling components with Theme 4.1 for absorber tower costs and membrane separations related to more efficient CO_2 separation
- Subtask 4.5: Collaborate on precipitating solvents to determine enrichment possibilities

Theme 5 - Oxy-Combustion Research, Development, and Demonstration

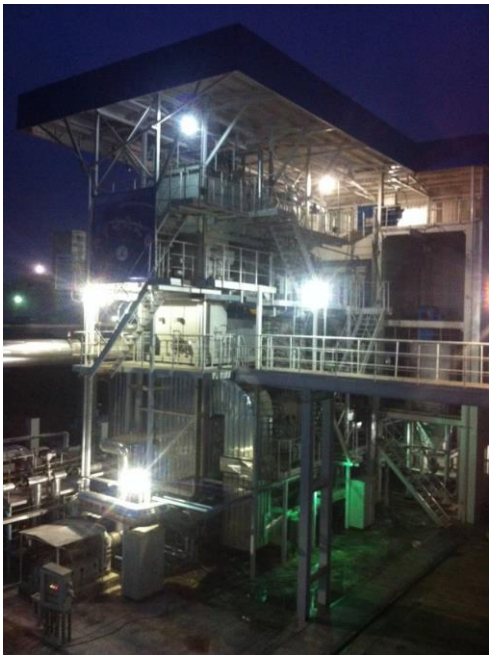
Research Objectives

Researchers from US-China ACTC (led by HUST in China and by B&W in US) will collect fundamental and pilot-scale data associated with various oxy-combustion conditions and conduct feasibility and economic analysis on the commercial-scale deployment of the technology for CO_2 capture. The oxy-combustion technology is now ready to demonstrate at commercial scale. It's suitable for both retrofit and green field plants. The goals for theme 5 are:

- Accelerate the development of oxy-coal combustion technologies for both Chinese and US coals
- Search for oxy-coal combustion demonstration opportunities

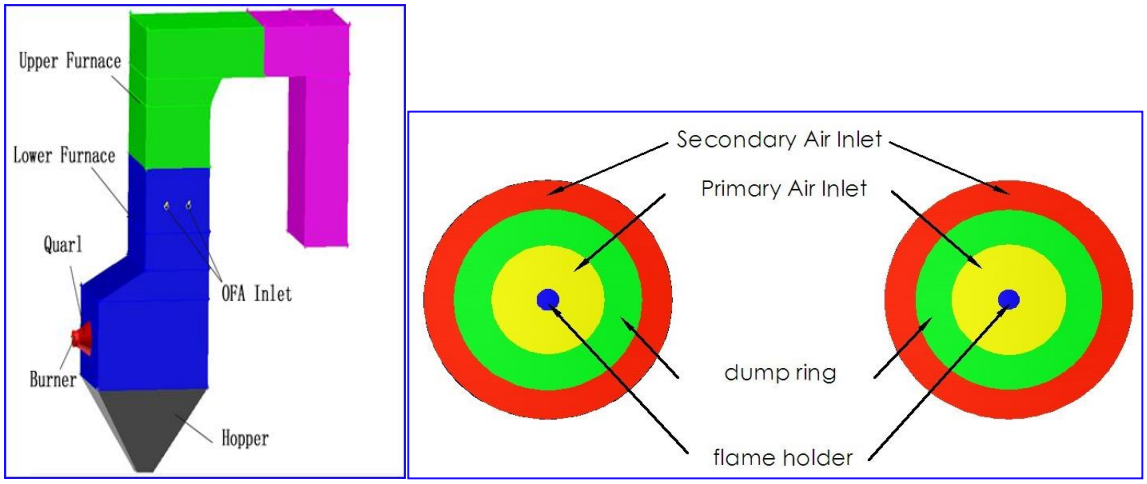
Research Outcomes

- Coal Analysis – HUST and B&W finished database on char oxidation kinetics.
- Commission and Benchmark plan on 3MW Oxyfuel FCS:
  1) Stage I: air combustion commission (2012.1~2012.2)
  - Burner worked well
  - Heat transfer design
  - PA, SA > 250C
  2) Stage II: oxy-combustion commission (2012.3~2012.10)
  - Switch from air to oxy-fuel
  - Oxygen injection safe at 300C
  - CO_2 ~80%dry,vol
  - Burner worked well
  3) Stage III: benchmark of air combustion (2012.11)
  - Burnout ratio > 95%
  - Develop detailed data of air combustion
  4) Stage IV: benchmark of oxy-combustion (2012.12-2013.6)
  - Demonstrate long-term , stable operation
  - Develop operating characteristics and control methods of heat transfer and emission

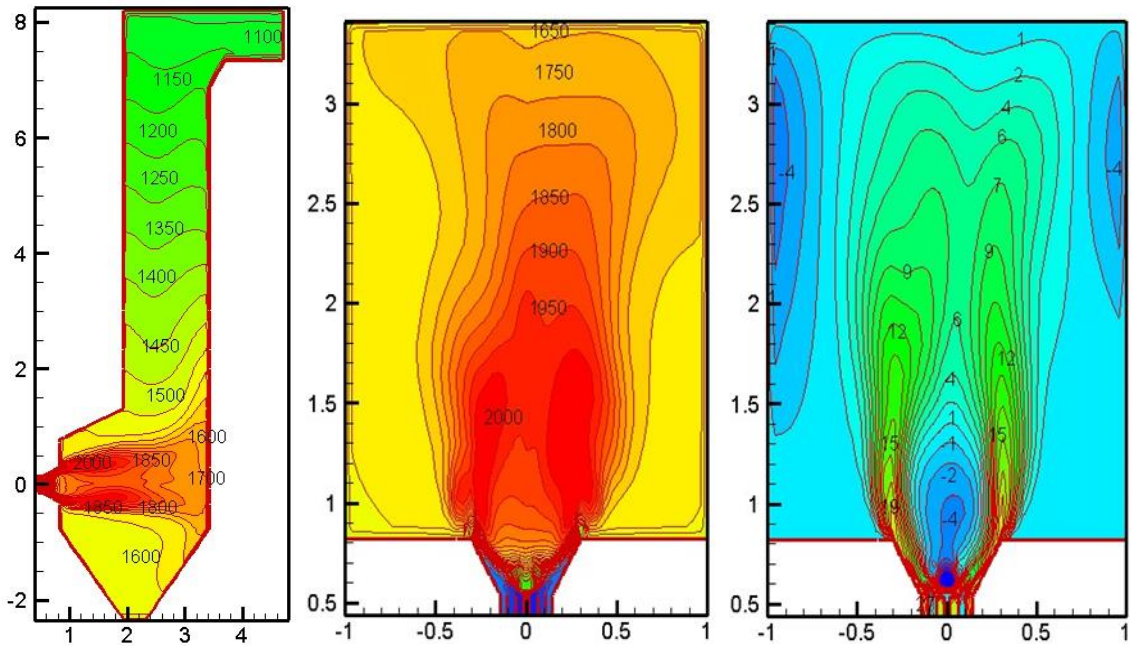


- Operation Experience and results from 3MW FCS
  - CO2 enriched as 82%vol, dry in flue gas;
  - Full chain operation to get liquid CO2;
  - Burn-out rate of can be more than 95%;
  - Design of boiler, burner, injector etc. validated;
  - Experiences on air-oxy, oxy-air Transition, air leakage monitoring and avoid etc.
- Pilot-Scale CFD Modeling

  1) HUST: descriptions on 3MW FCS Boiler geometry, operating conditions and modeling results.

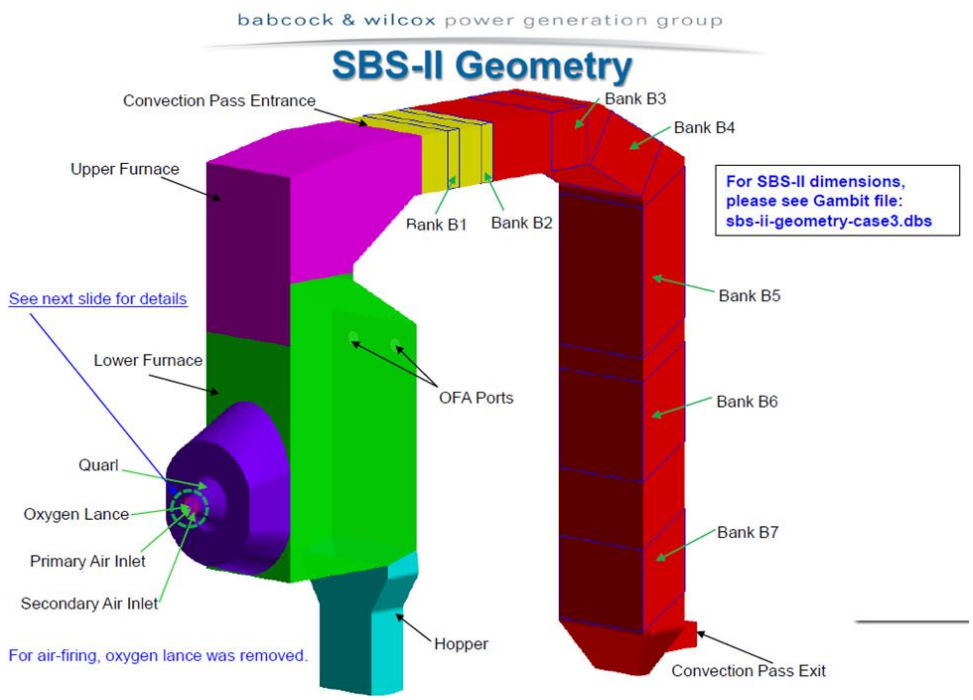


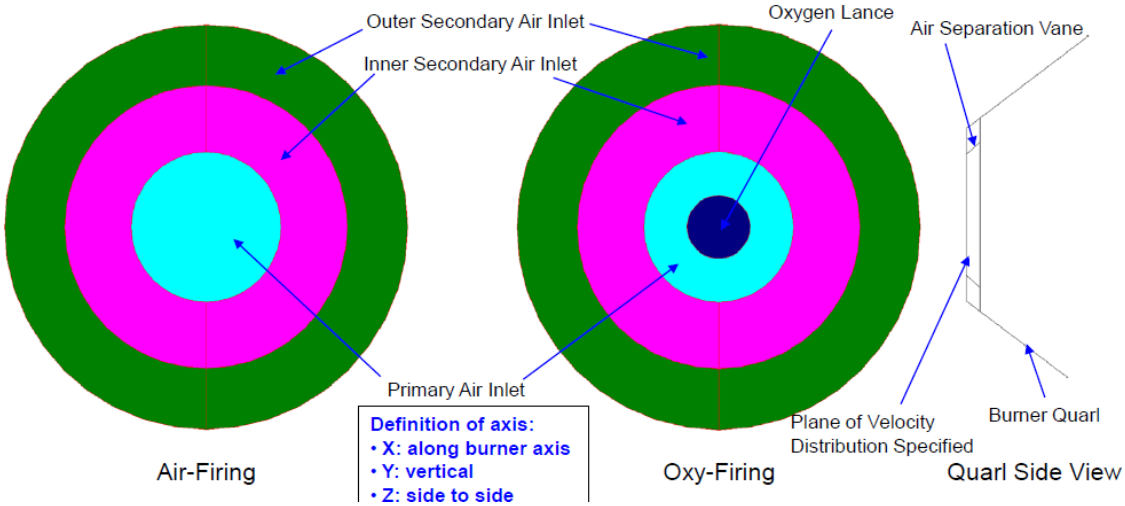
The mixture of primary air and secondary air are delayed by the dump ring structure



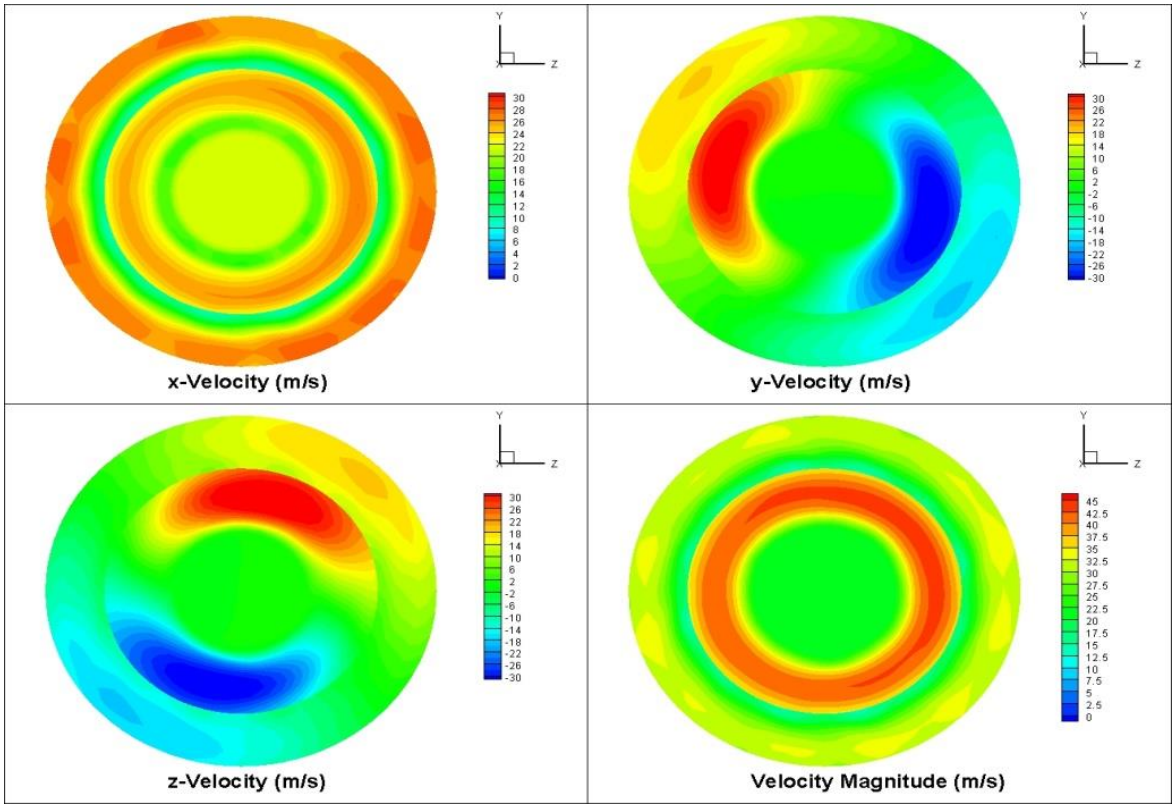
The simulation results of temperature and heat flux are mutually consistent with the 3MW pilot-scale boiler experiments.

2) B&W: descriptions on 1.8 MW SBS Boiler geometry, operating conditions and modeling results

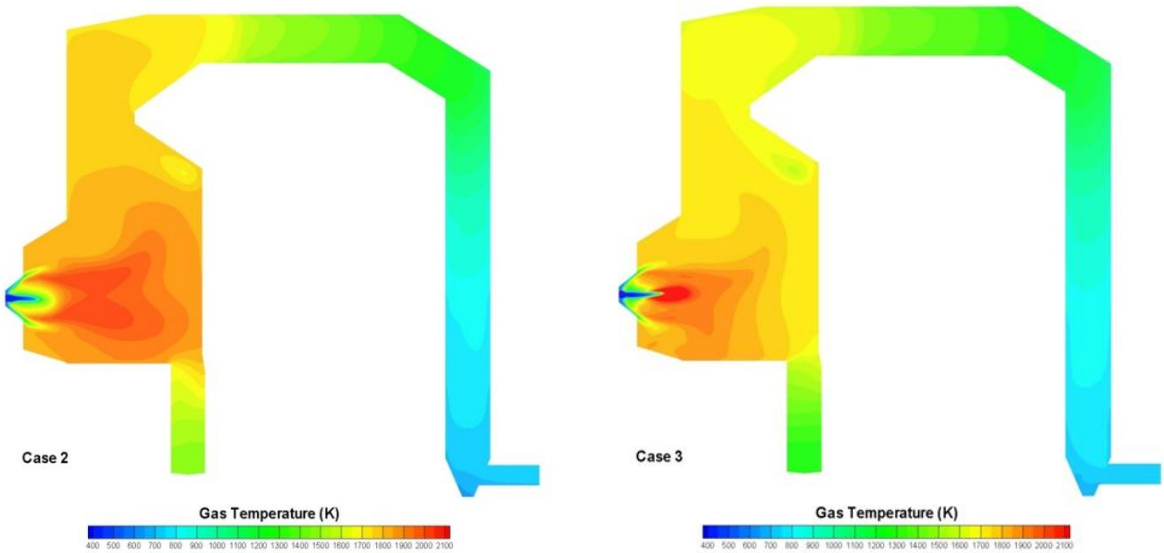




1.8 MW SBS boiler and burner geometry

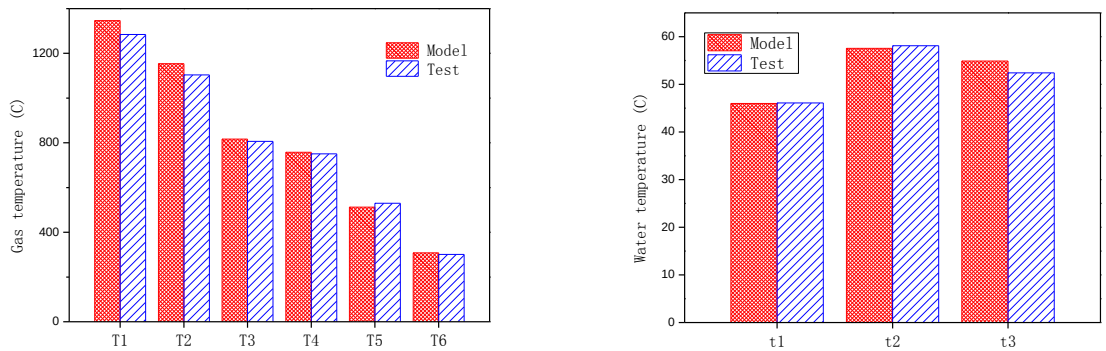


To multiply a constant to the velocity components, k and e in order to match the gas flow rate for oxy-firing and air-firing inlet.

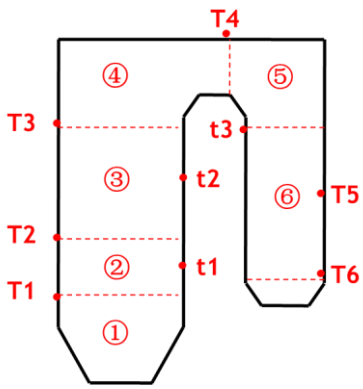


The gas temperature, CO concentration distributions of both oxy-firing and air-firing are simulated.

- Pilot-scale process modeling



Gas & water temperature



②③⑥ Heat transfer surface

Accomplishments of Current Year

- Completed combustion characteristics studies of Chinese and U.S. coals of different ranks
- Built pilot facility and completed benchmark testing
- Performed CFD and process model development and validation
- Experimental benchmark of oxy-coal combustion 3MW FCS is successful using 3MW FCS. 35MW semi-industrial pilot facility design has finished and started construction work at the end of Dec. 2012. Feasibility study on 200MWe large scale demonstration is near completion.
- HUST and B&W joint papers on this subject were presented at the 2013 Pittsburgh Coal Conference:
  1) Shengteng Hu, Alan Sayre, Hamid Sarv, Xiaohong Huang, Zhaohui Liu, *Char Burnout of US and Chinese Coals under oxy-combustion Conditions*. 30th Annual International Pittsburgh Coal Conference, Sept. 16 - 19, 2013
  2) Xiaohong Huazhong, Zhaohui Liu, Shengteng Hu, *Devolatilizaiton characteristics US and Chinese Coals under oxy-combustion Conditions*. 30th Annual International Pittsburgh Coal Conference, Sept. 16 - 19, 2013

Future Work Plans

- In 2014, CFD simulations of the pilot scale facilities, and process modeling will be continued.

- New oxyfuel concepts with staged combustion and combined NOx & SOx reduction technologies will be explored in pilot facilities: 1)Study novel staged oxy-combustion concept; 2)Develop combined NO_x and SO_2 reduction technologies
- Test campaigns in 35MW semi-industrial facility will be organized.
- HUST and B&W will start knowledge sharing on feasibility study of large scale demonstration projects.
- The team will continue pursuing commercial demonstration opportunities for the oxy-coal combustion technology.

Theme 6：Sequestration Capacity and Near-Term Opportunities

Research Objectives

The ultimate mission of the CERC theme 6 team is to develop project-ready, commercial-scale geological CO_2 storage, EOR and ECBM capabilities in China and USA. In addition, to improve estimates of CO_2 reservoir storage capacity and evaluate the long-term seal integrity. Finally, this work aims to develop an integrated framework model for evaluating capturing, transporting, utilizing, and storing CO_2. The four project areas selected are**:**

- Saline Formations at the Basin Scale
- Geologic Storage & EOR
- Geologic Storage & ECBM
- Simulation and Modeling

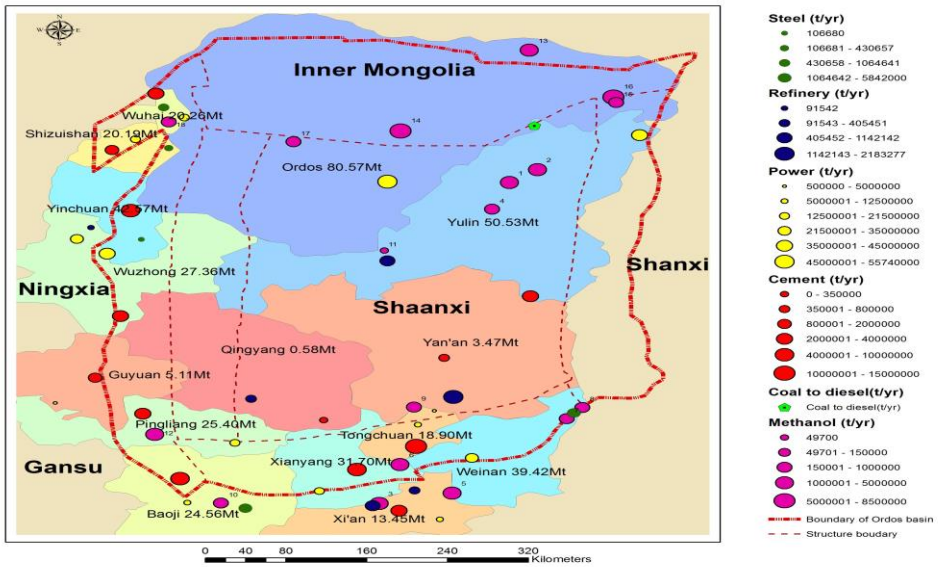
Research Outcomes

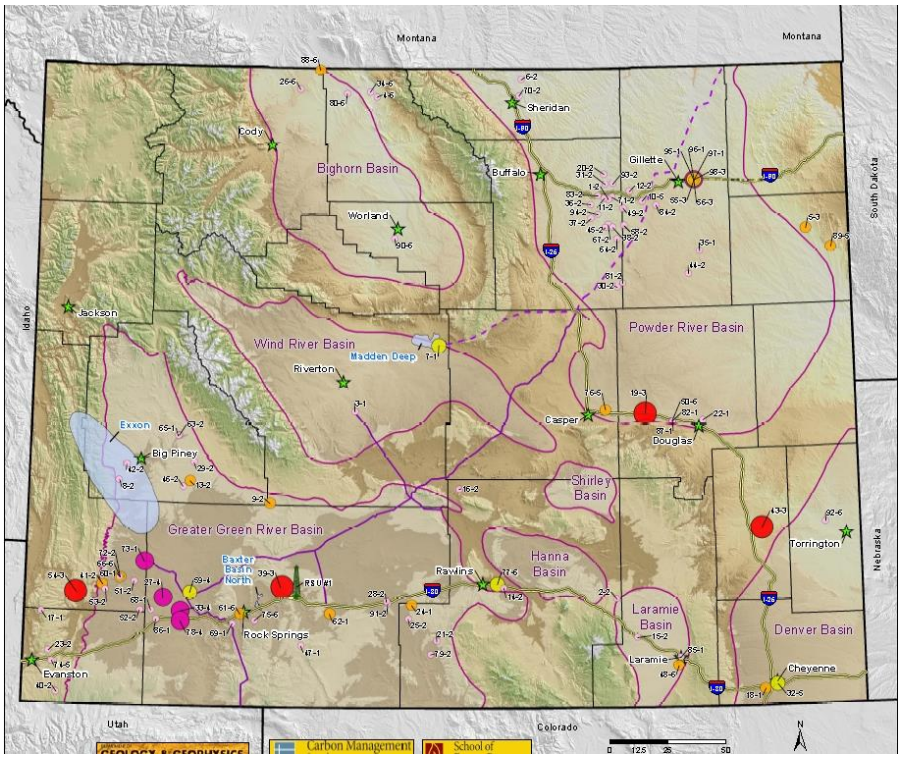
- Created functioning international research teams
- Created regional reservoir characterization of storage and utilization systems
- Exchanged technical information
- Exchanged visiting scholars
- Demonstrated CO_2 utilization through field test
- Conducted site suitability and priority evaluations by the site screening methodology
- CO_2-EOR pilot test: Conducted CO_2 injection test in 2 wells In the Ordos Basin.

CO_2 EOR Pilot test in Jingbian oil-field

- Prepare Wuqi CO2-EOR Demonstration Project in Yanchang Reservoirs in the Ordos Basin

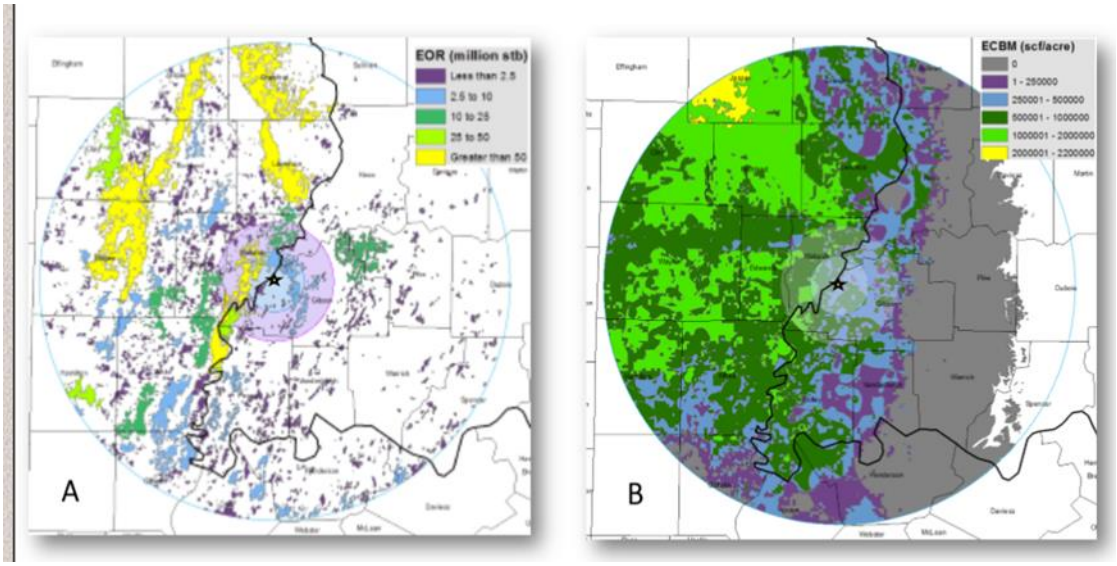
- Inventory the anthropogenesis CO2 resources in the Ordos Basin and Wyoming Basins

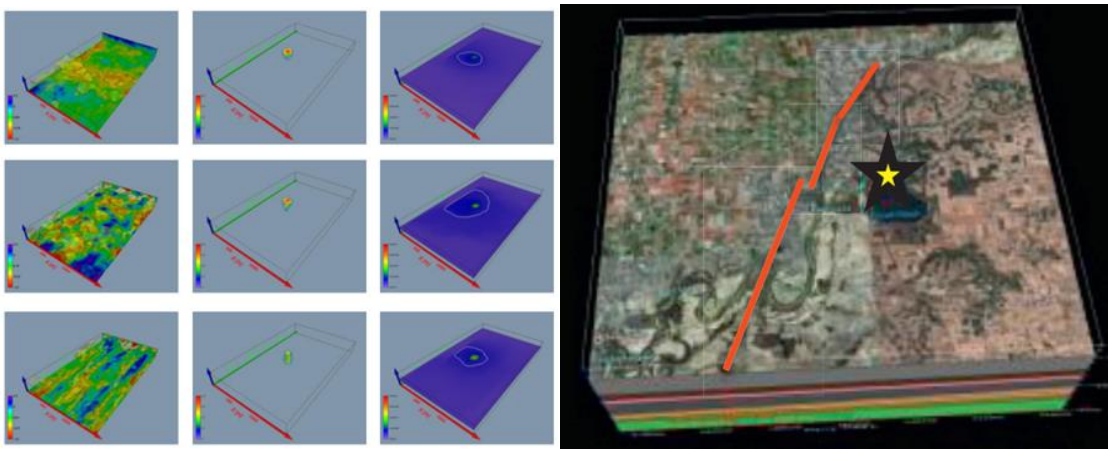




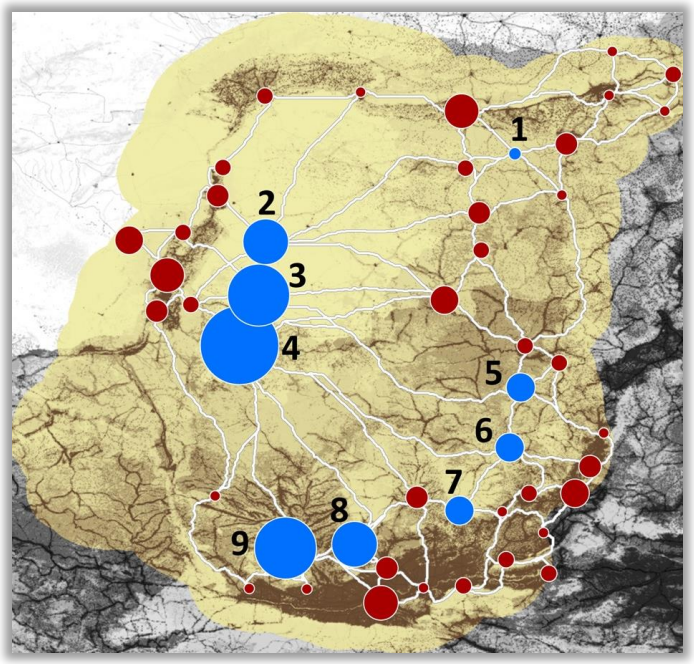
- Cross theme linkage on Gibson-3 with theme 4 post combustion

EOR ECBM





- Source Sink matching and pipeline plan for the Ordos Basin

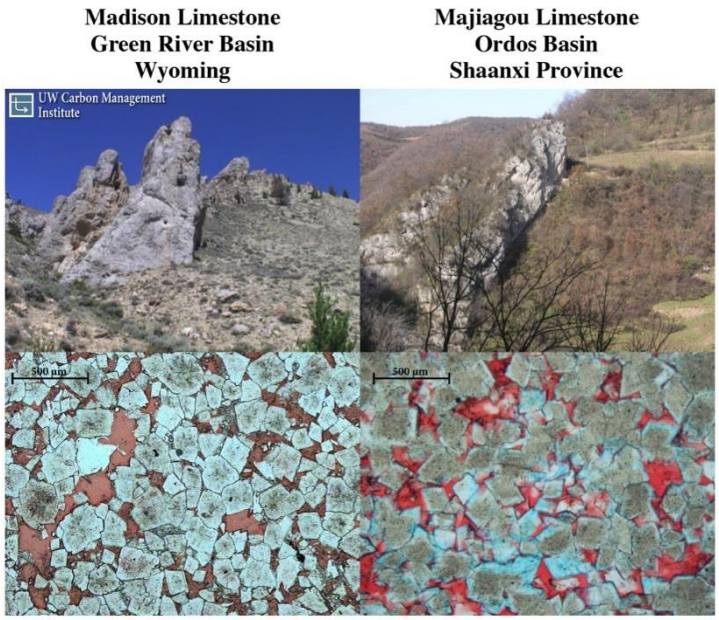


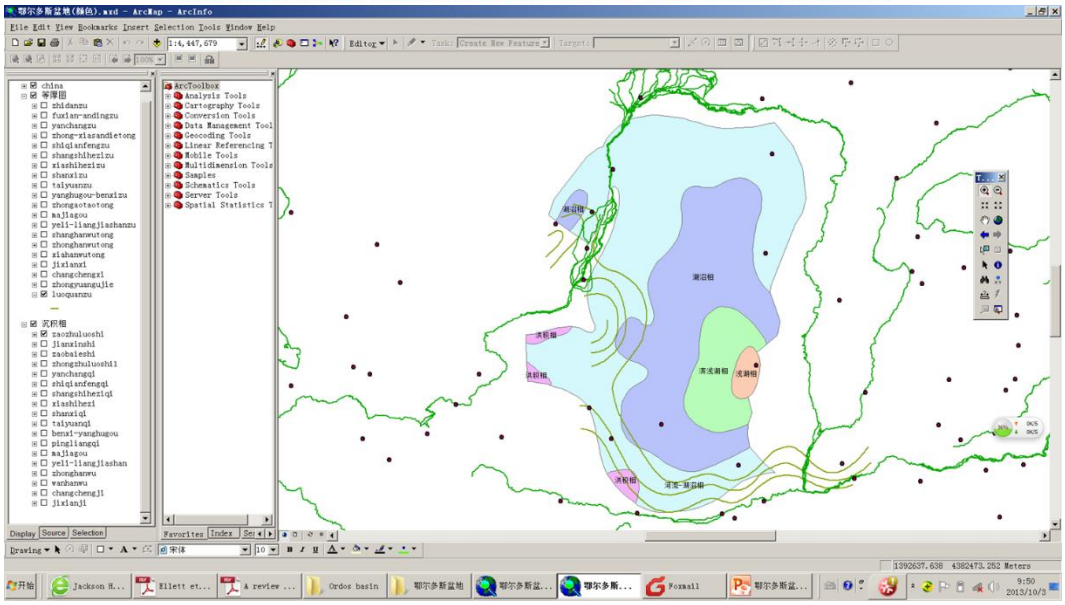
Unexpected Outcomes

- Reservoir heterogeneity causes large reduction in calculated storage capacity and injectivity even in high priority reservoirs
- ECBM may play a role in commercial development of CCUS in China.
- CO_2 injection requires pressure and displaced fluid management (water and mineral production)
- Uncertainty has not been accurately calculated in previous storage capacity calculations
- Strong interest in total system modeling lead to expanding international collaboration

Accomplishments of Current year

- Geodatabase created for the Ordos and Qingshui Basins and Wyoming and Illinois Basins

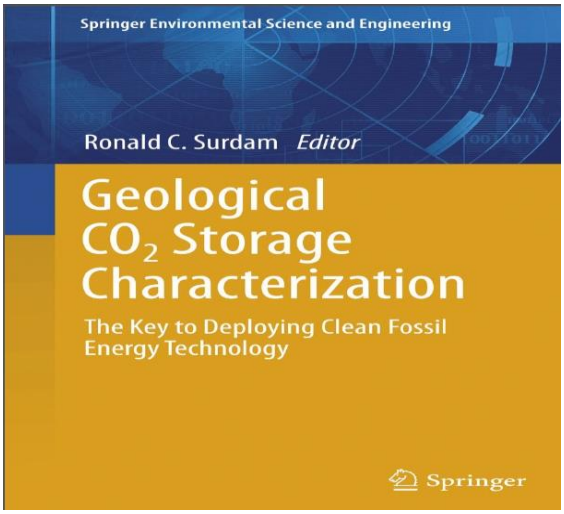




China ECBM geodatabase Qinshui Basin

- Published and presented results, top 12 speaker award at the 13th Annual Conference on carbon capture Utilization and Sequenstration, April 28 – May 1, 2014, Pittsburgh, Pennsylvania

- **A book titled Geological CO2 Storage Characterization –the key to deploying clean fossil energy technology is published by Springer.**



Future Work Plans

- Develop CO_2 EOR and ECBM demonstration projects in the Ordos and Qinshui Basins
- Improve estimates for storage capacity and injectivity in targeted basins with emphasis on quantifying uncertainty
- Exchange GIS products for China and US basins and organize a workshop for technical collaboration
- Develop comprehensive capture, transport, storage/utilization infrastructure model for the targeted basins
- Build more complete 3-D geologic models for evaluating targeted basins

Theme 7: Carbon Dioxide Utilization with Microalgae

Research Objectives

Theme 7 aims at demonstrating the use of microalgae for capture and recycle of CO_2 from coal-fired power plants, and the development of reliable cost estimates for this approach. The goals for each year are:

2011 - Set up methods for microalgal strain improvement and develop pilot-scale cultivation systems;

2012 - Obtain potential microalgae mutants showing fast growth and stress tolerance by mutagenesis. Optimize microalgae harvesting methods to reduce the cost;

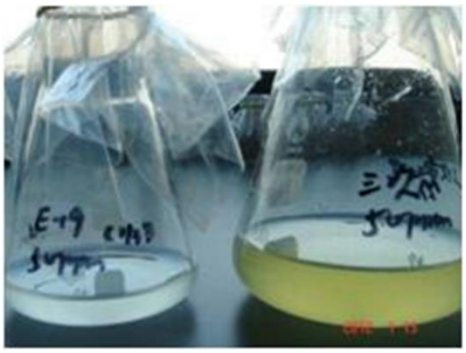
2013 - Selection of algae mutants with high oil yield and stress tolerance. Optimization of microalgae cultivation methods to increase biomass production, including operation of a pilot-scale system at a coal-fired power plant;

2014 - Optimize wet algal oil extraction methods; process cost reduction; develop reliable cost estimate for microalgal CO_2 capture and recycle;

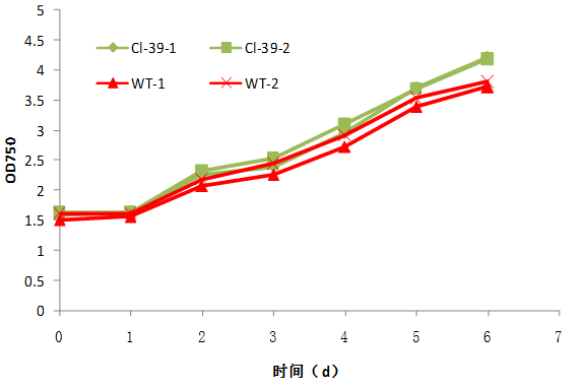
2015 - Continue process scale-up and integration of unit operations for CO_2 recycle using algae; finalize cost estimates.

Research Outcomes

- The oil-rich microalgae ENN11 was used as an initial strain, 2460 mutants being obtained with temperature and treatment A tolerance. After screening in 500 ml cultures, 6 high performance stains (right figure) were selected. After further selection and elevation in glass panel bioreactors, the best mutant Cl-39 can produce 15% more biomass than wild type algae, which is stable in productivity, and tolerant to stressful conditions, especially to chemical agent A and high temperature.

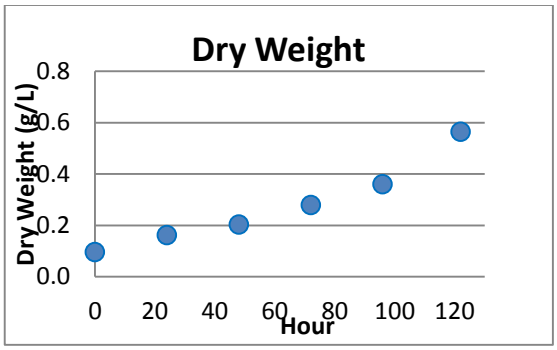


3 times EMS mutagenesis



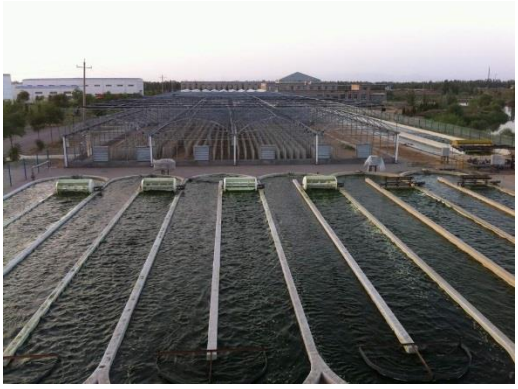
the best strain after outdoor evaluation

- To identify an algae strain well suited for winter cultivation, screening experiments were performed which resulted in the selection of snow algae *Chloromonas* (UTEX code SNO 11) for further study. The high productivity of *Chloromonas* was confirmed over the temperature range 4 - 15 ^{o}C (see below); the observation of significant growth at 4 ^{o}C is particularly encouraging.



Average dry weight for *Chloromonas* cultured at 4°C and for 5 days (3% CO_2)

- Growth System Optimization
  1) Average productivity in raceway ponds was increased to 19.5 g/m^2/d in May (excluding rainy days).
  2) Improvements: water recycling, high-density cultivation, pollution control.



- A pilot-scale/demonstration facility was constructed at Duke Energy's East Bend Station. Significant milestones included:
  1） Start-up in December 2012
  2） Winter growth demonstrated (averaging 10 g/m^2/d in December)
  3） Expansion of the reactor was completed in late summer (18,000 L)

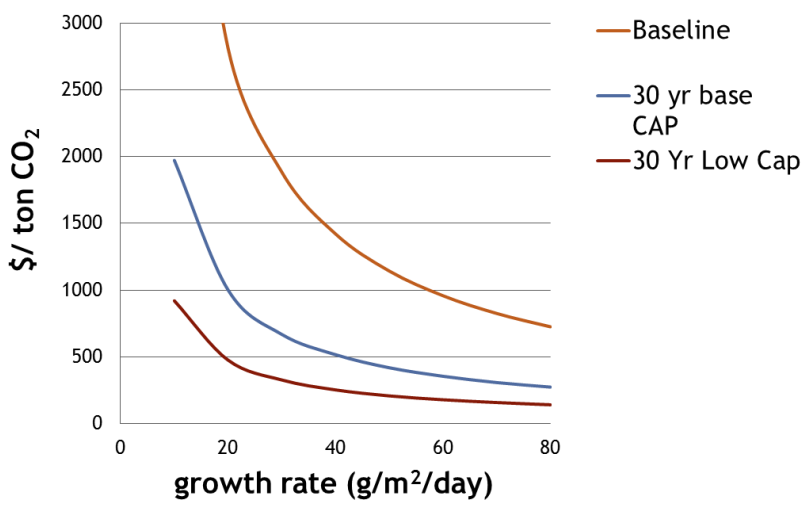
Demonstration facility installed at Duke Energy's East Bend Station

Based on data collected at East Bend, a techno-economic analysis of CO_2 capture and recycle using microalgae was conducted. The results are summarized in the table below. Although significant progress has been made in reducing capital and operating costs, the current cost of CO_2 capture is estimated at $1600/ton (based on a 10 year amortization period). However, increasing the payback period to 25 years and implementing PBR cost reduction measures could decrease this to under $500/ton CO_2. Note that these figures take no account of the value of the algal biomass produced.

Techno-economic Analysis

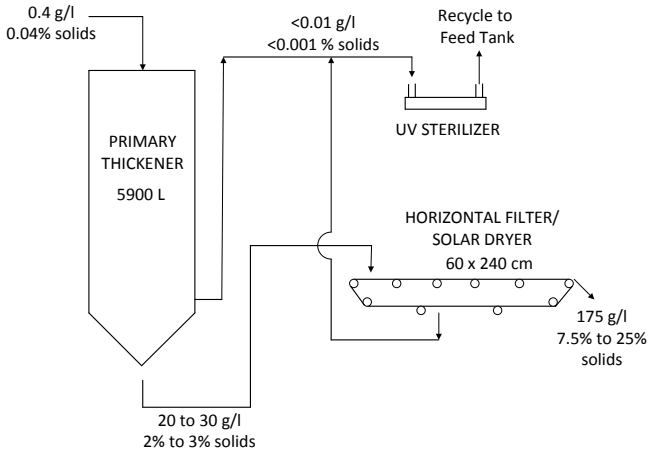
All values represented per ton of CO_2 removed			
	2009	2012	2013
Growing System:			
Photobioreactor	$8,508	$2,882	$1,590
Energy	$85	$17	$1
Nutrients	$209	$23	$15
Growth Subtotal	$8,802	$2923	1,606
Dewatering:			
1st Stage Dewatering	$72	$19	$15.13
2nd Stage Dewatering	$36	$1	$0.52
Dewatering Subtotal	$108	$20	$15.65
Total Cost:	$8,910	$2,943	$1,621

- An analysis was also performed to examine the effect of algae productivity on the cost of CO_2 capture:



Baseline = current technology w/ 10 yr payback; 30 yr Base Cap = current technology w/ 30 yr payback period; 30 yr Low Cap = engineering improvements w/ 30 yr payback period

- A low-cost approach to algae harvesting and dewatering was developed (see schematic below).



Schematic diagram of harvesting/dewatering process

After considering a number of options, sedimentation, thickening and filtration was selected as the preferred approach for algae harvesting and dewatering. Sedimentation was achieved by addition of a small dose of cationic polyacrylamide flocculant, the thickened biomass being dewatered by means of gravity filtration on multifilament filter media. Subsequent application of short duration vacuum after cake formation achieved a dewatered biomass product with a solids content of ~25% and >99% solids capture, corresponding to removal of over 95% of physically entrained water. Using this approach enabled recycling of essentially all of the water and soluble nutrients back into the process.

- Extraction methods were developed for the extraction of lipids from both wet (as harvested) and dry algae. Both methods are solvent-based and are relatively simple and straight-forward to perform. Conversion of the isolated lipids to both biodiesel (fatty acid methyl esters) and hydrocarbons (linear alkanes) was demonstrated. In the latter case, high yields of alkanes boiling in the diesel fuel range were obtained.

Accomplishments of Current Year

Significant progress has been made towards developing algae strains with improved properties (growth rate, stress tolerance); photobioreactor design; algae productivity; harvesting and dewatering; and oil extraction. A techno-economic analysis has shown that the capital cost of the algae cultivation system is critical with respect to the overall economics of CO_2 capture; algae productivity is also a significant factor.

Future Work Plans

- Increased focus will to be placed on improving microalgal photosynthetic efficiency and biomass productivity.
- Emphasis to be placed on decreasing costs associated with the algae cultivation system.
- Data sharing of techno-economic analyses between the US and China teams.

Theme 8 – Integrated Industrial Process Modeling and Additional Topics

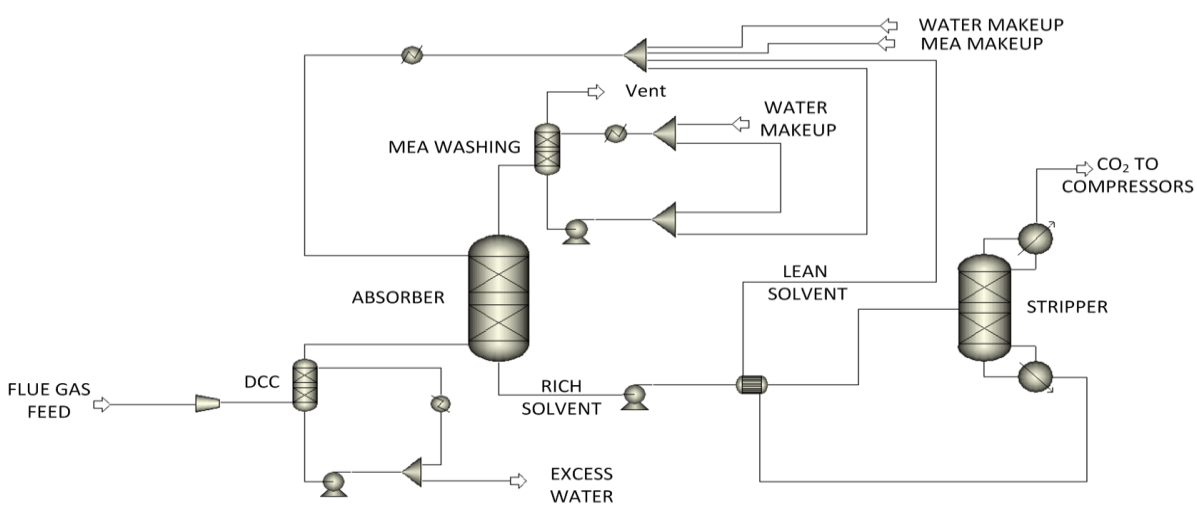
Research Objectives

This work focuses on the modeling and validation of carbon capture processes for traditional and advanced coal-fed power plants, including:

- Plant-wide modeling and control
- Dynamic modeling of plant-wide post-combustion CO_2 capture processes and resulting control issues for multi-train plants
- Implementation of advanced visualization techniques for immersive training system
- Process configurations of advanced IGCC processes
- Modular modelling of IGCC processes
- Life-cycle assessment of coal-to-chemical processes with carbon capture

Research Outcomes

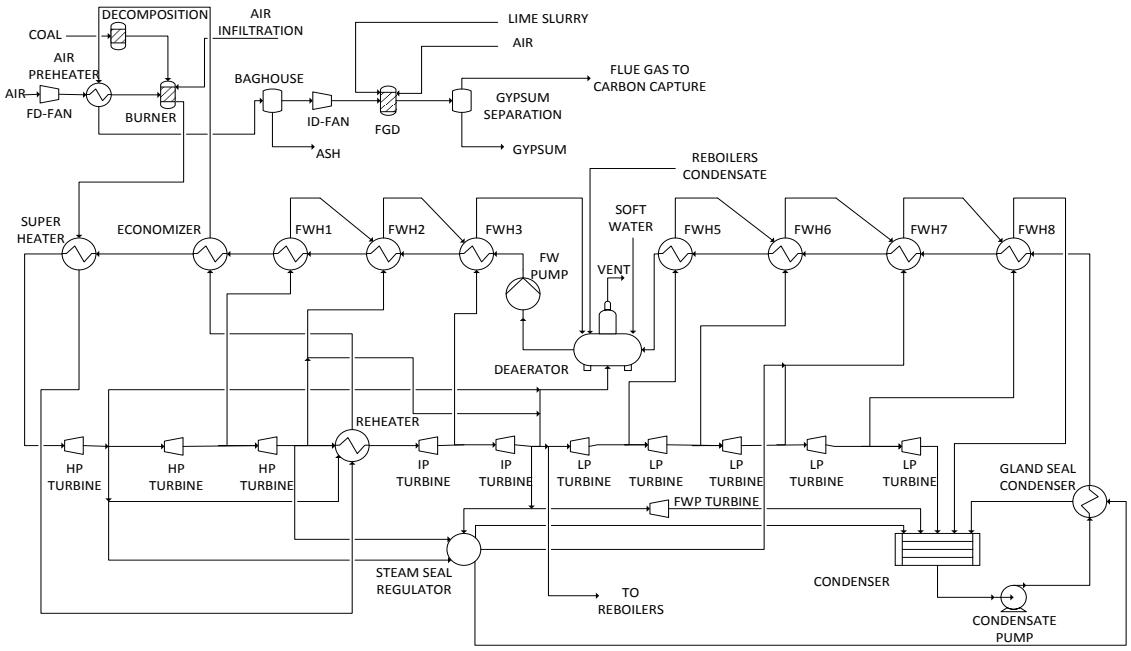
- A steady state model of a supercritical pulverized coal-fired (SCPC) power plant was developed in Aspen Plus (AP). This plant was design to have a net power of 550MWe without carbon capture and the steam inlet pressures to the high-, intermediate-, and low-pressure turbines were 242.3, 45.22 and 5.07 bar, respectively. The simulation results were consistent with the information given in the literature [1]This simulation was then integrated with an MEA carbon capture process by sending flue gas to the absorber and extracting steam from the low-pressure turbines, to use in the CO_2 stripper/MEA regenerator. All the heat exchanger sizes were calculated using the Aspen Exchanger Design and Rating software package. These were basically feed water heaters that were used to heat up the condensate using a steam feed and other hot and cold water feeds. The flowsheets for the CO_2 capture and SCPC plants are shown below.



Flowsheet for CO_2 capture using MEA

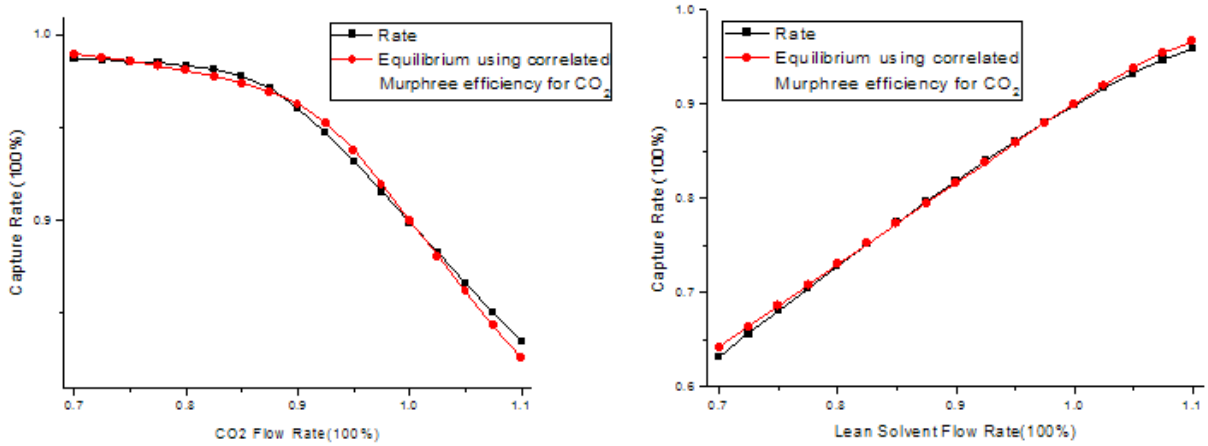
- The supercritical pulverized coal-fired power plant was simulated with and without a carbon capture process. The agreement between the flue gas composition in the model and the DOE report [1] was

very good. The overall plant efficiency with carbon capture drops by 9.2%, which is close to the value from literature.



Flowsheet for super-critical coal fed power plant

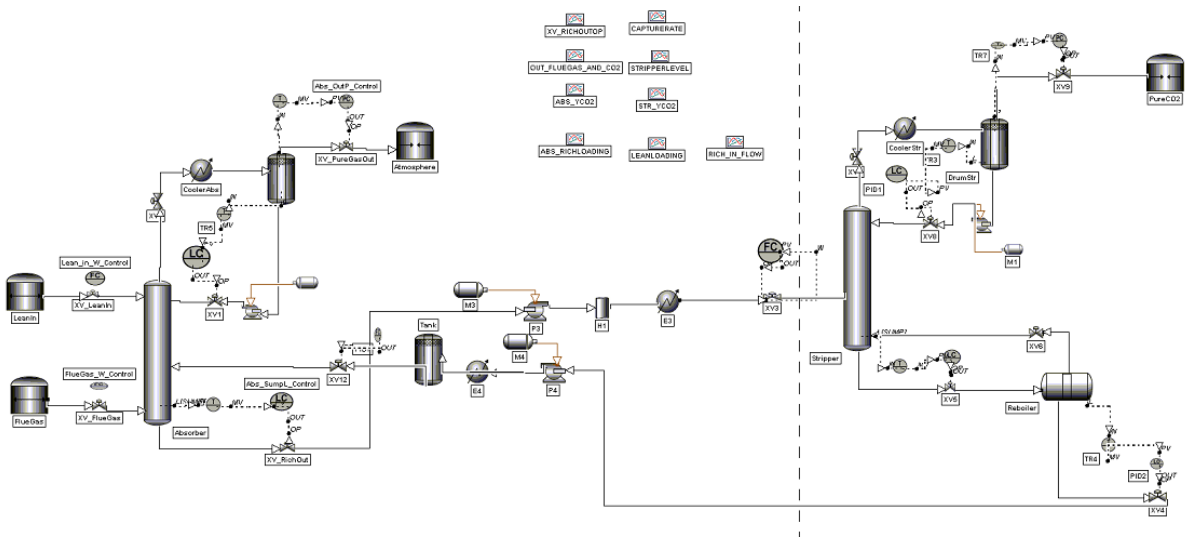
- The key features in the modeling of the power plant are a detailed representation of the steam system and a basic model of the coal combustion process. This "optimized" steady state simulation was used as the starting point for the full dynamic simulation of the power plant with a carbon capture process.
- A dynamic simulation of the steam-side of the pulverized supercritical power plant and MEA-based CO_2 capture process was completed using Aspen Plus Dynamics (APD) software. The CO_2 capture process involves the reaction of CO_2 with amine solution (MEA – monoethanol amine). The reaction kinetics are fast but may not reach equilibrium, especially in the relatively cold absorber; therefore, the rate-based model for distillation was used in the steady state (AP) simulation and the results were found to differ by as much as 3% from the results using the simple equilibrium-based unit operations models. However, the rate-based distillation model is not supported in APD and, therefore, a model was developed to correlate the single component Murphree efficiencies for CO_2 in the absorber as a function of operating conditions. A script was written in APD to adjust for non-equilibrium behavior using the model and the results from this model, shown below, were found to be in satisfactory agreement with a less than 1% difference between the simulated absorber columns in AP and APD.



- Efficiency Model for Dynamic Simulation Compared to Results from Rate-Based SimulationsInitial work was started on the design of process controllers for the power plant and the basic control structure for the CC process was established.
- The dynamic model of the power plant and a single train of MEA CO_2 capture were successfully simulated in APD and the design point in the dynamic simulation matched the design point in the AP simulation.
- Based on sizing calculations for the base case power plant, the treatment of the total flue gas stream may require 4-6 parallel trains of absorbers and strippers. To simulate the interaction between parallel trains of MEA absorbers/strippers, two parallel trains of CO_2 capture processes were simulated in APD and the dynamic response of this system was investigated.
- Using the two-train CC system in APD, both conventional PID controllers and model predictive controllers (MPC) were used to maintain the overall CO_2 capture for a change in coal input rate to the power plant. Before the application of MPC, a system identification procedure was necessary as the predicted control actions of MPC depend on the identified process model
- A tower model was also developed for the CO_2 absorption and regeneration processes based on gas-liquid phase equilibrium and stage efficiency using the Dynsim simulation platform. Stages are connected via flows of gas and liquid, and pressure drops.

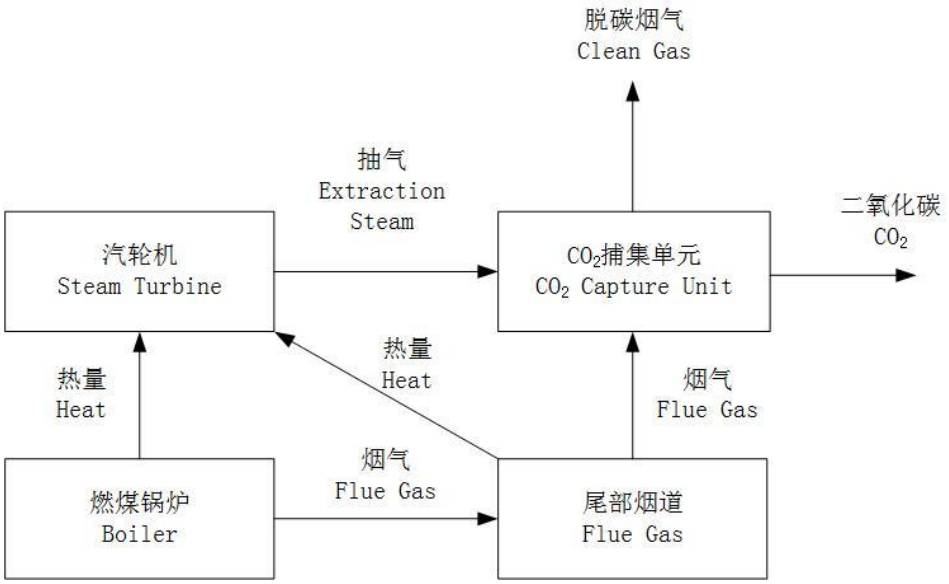
Simulation results of the dynamic model were compared successfully with real-life data and static simulation results (via ASPEN) of a pilot power plant with carbon capture at University of Texas, Austin. Comparison results show that the dynamic simulation results fit well with the operational data and static simulation results.

Dynamic behaviors of a CO_2 absorption process is then studied by adjusting flow rates of flue gas separately, flow rates of lean solution separately, and both simultaneously. Results show that the process is more sensitive to changes in flow rates of lean solution, and large changes in flow rates of lean solution (greater than 20%) could lead to unstable operation. It is suggested that a relatively stable ratio between these two flow rates should be kept if the flow rate of one or two of these flows have to be changed.



Flowsheet of dynamic simulation in Dynsim

- Performance comparison of three retrofitting plans for CO_2 capture: throttle valve, sliding pressure operation, and adding back-pressure turbines
  Three retrofitting plans are proposed to provide heat for CO_2 capture by extracting steam from a steam turbine. Plan A is to add a throttle valve between an intermediate pressure turbine and a low pressure turbine. Plan B is to allow an intermediate pressure turbine to operate at sliding pressure mode by changing its blades at the last stage. Plan C is to replace low pressure turbines with back-pressure turbines. Power generation, power supply, power consumed by compression, and power consumed by other auxiliary machinery in the three plans are provided. Results show that Plan C has the highest energy efficiency.
- Performance comparison of IGCC plants with ion transport membrane (ITM) air separation and cryogenic air separation
  Comparison results show that an IGCC plant with ITM air separation is superior to an IGCC plant with cryogenic air separation in all fronts. Increasing the integration degree and high-temperature nitrogen re-injection can lead to even higher energy efficiency.
- Development of modular models of key functional blocks of IGCC plants
  Modular models for coal gasification, air separation, sulfur removal, and combined cycle are developed with consideration of integration between these units. A case study is developed using a 9F gas turbine.



Flowsheet of the coal-fired power plant with post-combustion CO_2 capture

Accomplishments for the Current Year

A workshop on "Systems Modelling and Integration of Power Plants with CO_2 Capture" was held at Tsinghua University on May 27-28. Representatives from all Task 8 projects were in attendance. A workshop for Tsinghua University representatives was held at the AVESTAR Center at WVU on October 8, 2013 and the IGCC operating and immersive training systems were demonstrated. A full working dynamic model was developed for the SCPC plant and CO_2 capture process. The basic control structure for 2 parallel trains of MEA capture processes was developed, a system identification and analysis was performed and a linear MPC system was developed. Papers were presented at the Pittsburgh Coal Conference and American Institute of Chemical Engineering Conference.

Future Work Plans

- Develop advanced control strategies for multiple parallel carbon capture trains using non-linear MPC and robust control methods.
- NETL to develop strategies to assess Power Plant Cycling and Load-Following Operation under CRADA agreement with WVU, to be finalized in 2014.
- Benchmarking of the dynamic models of carbon capture processes developed by both US and Chinese sides with the same power plant data.
- Continue working on IGCC modular modeling, configuration of advanced IGCC processes, and LCA study of coal-to-chemical processes with carbon capture

References

Cost and Performance Baseline for Fossil Energy Plants Volume 1: Bituminous Coal and Natural Gas to Electricity - Cases 11 and 12, Revision 2, November 2010, DOE/NETL-2010/1397

IP Management

Objective

Educate and inform CERC participants with regard to intellectual property law and practice in both the U.S. and China as it relates to the CERC program. Support CERC participants and projects with regard to intellectual property issues associated with their research and development. Promote the CERC model for addressing IP issues to a wider audience and potential beneficiaries in the clean energy sector.

Outcomes

(1) IP Workshops

To improve a mutual understanding of the respective U.S. and China laws, public policy and practice with regard to intellectual property and the implications of undertaking research under the CERC program, the U.S.-China Clean Energy Forum presented to DOE and the Chinese a proposal for an IP Workshop in which Chinese and American experts would discuss with CERC ACTC participants applicable law, the TMP and government contracting requirements that impact IP rights. The first such workshop took place at HUST in Wuhan, China on May 25, 2011 and was attended by U.S. and Chinese CERC ACTC participants.

Expanding on this initial effort and after consultation with the Chinese, CEF initiated planning for *two* workshops, one in China and a second in the US, both open to *all* CERC participants. The first workshop was held in Haikou, Hainan Island, China on March 5-6, 2012. This first workshop gave presenters an opportunity to provide an overview of intellectual property law and practice in each the U.S. and China.

Following the success of the first CERC IP Workshop in China, a second workshop was planned for the U.S. for February 26-27, 2013, at Stanford Law School in Palo Alto, California. The agenda covered a wide range of business and research related IP topics and as the first CERC IP Workshop, was presided over by DoE's David Sandalow and JIN Xiaoming, head of international affairs for the Ministry of Science and Technology and CERC U.S. Director Robert Marlay and CERC China Director LIU Zhiming. CEF published a report from the second workshop and posted it on both the US and China CERC websites.

Approved by both DOE and MOST, more than 130 attendees heard from experts in IP law, business leaders and representatives of the two governments. The workshop presented the practical experience of business executives, researchers and their legal representatives with regard to IP law and policy in both the US and China. Issues addressed ranged from business issues such as the formation of a cross-border joint venture and IP in financing, to more technical legal issues including licensing of IP and protecting trade secrets.

ACTC members were both involved as presenters throughout the program and were well represented in the audience. *William Latta* of LP Amina Latta gave a brief background of LP Amina's R&D and commercialization in China, Germany and the U.S. to develop clean coal technologies, one of which is to the point of commercialization. To commercialize this technology they are working under the CERC platform, and has entered a Joint Venture in Shanxi province with the Chinese company Ge Meng). LP Amina has projects in 15 provinces working with coal plants across the country. As a result they had a reasonable assessment of IP protection and some of the issues in China prior to entering into their JV. He said that mutual understanding between parties is key to be able to get to the real issues about how

to set up a framework that protects both parties' interests. Their own JV agreement was established in summer 2012 and is expected to be operational by summer 2013. While they are still in the early stages of their collaboration, so far their IP strategy has proven robust. They constructed it by soliciting good advice including from large MNCs, and by building on their past practices.

ACTC's Dr. Julio Friedmann, Lawrence Livermore National Laboratory and Huang Yuehui, Chinese Society for Urban Studies, moderated a panel in which researchers were invited to "Quiz the Lawyers." The panelists, *Lu Xiaojun*, Tsinghua University, *Tiefei Dong*, University of Michigan, and *Robin Chiang*, Lawrence Berkeley National Laboratory; answered questions from the moderators and the audience on practical aspects of doing research in the CERC.

Friedmann noted that the value of cleantech is in deployment, and that while each CERC technology area is covered by one protocol, the nature of the projects and the technologies are different. This means that all the CERC participants likely think differently about how we make partnerships and protect our inventors.

The final panel of the conference featured ACTC's IP leadership, Stacy Baird for the U.S. and Yu Xiang for China, giving an update on the CERC's IP program.

Substantively, several key themes arose during the workshop presentations and discussions, which are summarized below.

- China has more *individual* patent inventors in CHINA than in the US, and this has implications for innovation and IP protection. There are increasingly incentives for individual researchers to benefit directly from their inventions, which was not the case in the past. However, the large number of inventors in China means there is also a risk of abusive litigation from non-practicing entities.
- China has enhanced its own IP protection primarily due an increased demand for protecting domestic innovations.
- There are many examples of innovations from elsewhere being commercialized in China, particularly in pharmaceuticals, but this is increasingly true for clean energy as well.
- While US PTO programs that aim to make it quicker and cheaper and easier to patent clean technologies can be useful (like the fast track system, green technology pilot program or patents for humanity programs), there are still real problems after the patent is issued in the form of excessive ligation or "patent thickets."
- Non-practicing entities (NPE or "patent troll") are companies entirely in the business of lawsuits, primarily asserting patents they've acquired from another party. NPEs file over half of all patent lawsuits in the United States. They frequently target startups that cannot defend themselves from litigation.
- NPEs are a significant issue in the US, however, they may find China a more difficult legal environment to win cases because China's courts require the patent holder to show the harm they suffered.
- Many firms are concerned about bringing "Easy IP" to China, even if it could have valuable applications there. IP that is easier to copy is frequently also easier to enforce in court since it easier to provide evidence to prove the infringement.
- While trade secrets can be difficult to protect because they are easy to lose, there are many simple actions firms can take to prevent loss, including disabling the use of USB drives or monitoring emails for large attachments.

- Trade secret protection presents a particular challenge in the Chinese context, due to a lack of mature legal protections for trade secrets. This is a problem because many companies rely on trade secret protections instead of patents when they want to keep their invention secret.
- Agreeing to the terms of an IP agreement may take time, but it worth the time upfront to come to full agreement prior to beginning work in order to avoid misunderstandings, disputes or at a minimum, having to go back and reopen an agreement for negotiation.
- It is as important to be selective in choosing your business partners in a bilateral venture as it is in undertaking a domestic venture. You want to make sure that your interests are aligned, and once in negotiations, make sure you have mutual understanding. Sometimes cultural differences can lead to differing understanding of legal terms being discussed such as "exclusivity" and "technology transfer."
- There are many reports of misperceptions between Chinese and US firms, due to cultural differences, and a lack of understanding of each other's IP rules and legal systems, which leads to concerns being overblown.
- There are major differences in the discovery process in China and the United States. While many believe the process is too cumbersome in the US, in China it is believed to be far too brief. Although in the US parties can be compelled to produce information that is adverse to their case, the same is not true in China.
- Joint Ventures (JVs) come with a unique set of IP protection concerns. The dual ownership structure makes it even more important to work out IP arrangements between the parent firms, planning ahead for how to handle things when/if the JV dissolves.
- There is increasingly extensive coordination between the US and Chinese patent offices which is being reflected in a gradual increase in consistency between the two legal systems. In addition, the United States Patent and Trademark Office (USPTO) and the State Intellectual Property Office of the People's Republic of China (SIPO) Patent Prosecution Highway (PPH) pilot program began on December 1, 2011 and streamlines the patent application process for inventors filing in both systems.
- "Innovation parks" are being used in China to promote international R&D cooperation with over 10 parks established to date, including the China-U.S. (Wuxi) Science and Technology Innovation Park.
- The CERC should be more widely understood in both countries as it may serve as a model in addressing IP in bilateral relations and its work on IP has value in cutting through the "fog of misunderstanding" around IP issues.

IN October, during the CERC-ACTC Joint Meeting and Midpoint Review in Jackson, Wyoming, the leadership of the IP Experts Working Group held a session reviewing the work to date and outlining future needs from the respective perspectives of the US and Chinese participants. The leadership teams subsequently met for a half-day session discussing ongoing projects, including the IP and Technology Transfer Guide and other potential outcomes for the Experts Working Group. There was in-depth discussion with the China CERC-ACTC IP experts on future plans and potential activities.

(2) Guidance Documents and Technical Assistance

The US-China Clean Energy Forum (CEF) and CERC leadership has come to recognized the need for a "toolkit" of resources to help researchers comply with the IP laws of both the US and China and implement the TMP. This "toolkit" would include several guidance and instructional documents.

As an outcome of the first IP Workshop, CEF has taken the lead in developing support materials and continue to provide Participants general technical support with regard to intellectual property issues arising with regard to CERC projects and in CERC-related contract negotiations.

We have completed the first "annotated" TMP drafted by CEF and Chinese CERC IP experts. The annotations, informed by experience in previous negotiations held by CERC Participants, will provide explanation as the meaning or implications of certain provisions and further, how to implement certain provisions of the TMP in specific projects. The "annotated" TMP was presented at the IP Workshop at Stanford on February 27, 2013, and will serve as a "living" document, to be revised as experience with the TMP grows.

CEF is working with two prominent law firms, one Chinese and the other based in the US, to develop the CERC guide to IP and technology transfer law and strategy for US and Chinese CERC participants. The guide will be based on the widely accepted handbook authored by the University of Michigan Technology Transfer Department. The CERC guide will provide researchers and SMEs a greater understanding of both US and Chinese laws and practice with regard to IP issues in the context of CERC projects. The guide will focus on issues that will involve researchers or background intellectual property from both countries. CEF expects to complete the initial draft the third quarter of 2013 and subsequently transmit the document for Chinese IP experts' contribution.

During the course of the first IP Workshop, several items were suggested that would be valuable for CERC researchers and SMEs in CERC. First, we made available the bilingual presentations from the IP Workshops have invaluable guidance and discussion of some of the issues of greatest concern along with a detailed overview of each workshop.

(3) Bilateral CERC Intellectual Property Experts Working Group

From the initial observations that IP was of central concern and interest for CERC Participants, interest grew among all CERC consortia to establish an IP Experts Group. In 2012, the US and China's CERC leadership agreed to establish a joint US-China Intellectual Property Experts Group to identify and implement approaches to enhance innovation, utilization, protection and management of intellectual property, for CERC and oversee the provision of technical assistance with regard to IP for CERC Participants.

The US-China CERC IP Experts Group will explore such ideas as new approaches to dispute resolution to minimize litigation risk and reduce the cost of disputes, such as alternative dispute resolution undertaken in a third-party country, under internationally accepted rules and enforced by both the U.S. and China, mechanisms to establish damages awards or injunctive relief, intellectual property risk insurance and other approaches to clarify legal relations of IP ownership and sharing between the project partners, to safeguard the legitimate interests of the partners, and to promote research and development and commercialization.

The Experts Group will oversee other initiatives to provide IP related services to CERC participants which could include executive training, researcher education on IP or consulting or negotiation facilitation services to CERC projects.

The proposal for a CERC IP Experts Working Group was been approved by both DOE and MOST. The US has agreed with the Chinese on an approximate size and general subject matter for the working group. The experts group will develop solutions for approval by both governments that could be piloted in CERC projects. The group will also oversee IP education and consultation and negotiation facilitation services for CERC participants.

CEF has identified the first participants to represent the US and held the first CERC IP Experts Working Group meeting at Stanford Law School on February 27, coinciding with the CERC IP Workshop. At that time, members were asked to undertake due diligence to identify possible issues that the working group could address. Both the US and China continue to work to identify members for the Working Group.

Consistent and Transparent Process to Bring New Participants into CERC

CEF identified a need to ensure there is a clear pathway and transparent uniform process to bring new business, industrial and non-governmental entities into one or more of the CERC consortia as participants. It was determined by CERC leadership that there would be an agreement between DOE and MOST that would describe the basic requirements and process for consortia inviting an entity to join CERC.

CEF worked with DOE and MOST to craft an agreement that outlines the requirements and process for CERC consortia leaders to bring new participants into their consortia. The agreement was adopted by both governments on February 27 at the IP Workshop at Stanford (described above). The procedures have been distributed to all CERC leadership and have been implemented. For example, this year, Ge Meng, a Chinese energy company based in Shanxi province and a partner in a joint venture with ACTC member LP Amina, joined the ACTC under the new procedures.

Future Work Plans

CEF is in the initial stages of discussion to hold a follow-on to the workshops, an “IP Summit” in China in the next year to discuss the lessons that can be learned from CERC with regard to IP.

As appropriate and sought by CERC Participants, CEF will continue to provide technical assistance to those Participants in project or IP-specific contract negotiations.

Further, we will be developing questions and answers for a researchers’ online “Frequently Asked Questions.” CEF has also established a regularly updated website of valuable information and links for researchers and SMEs, available at www.ipknowledge.org.

CEF, through the CERC IP Experts Working Group is evaluating approaches to expanding the availability of legal technical support for CERC projects. CEF has initiated discussions with law firms to explore the scope and costs for providing legal guidance to CERC Participants.

CERC IP Experts Working Group members are in the process of developing an outline to detail the structure and procedures for the Working Group. Working Group members are also identifying possible issues and solutions for the Working Group to evaluate for further action.

More broadly, CEF will work with CERC leadership to facilitate international coordination and cooperation through in-person bilateral consortium dialogues to be held twice each year. The meeting location is expected to alternate between the US and China. CEF and the IP Experts Working Group will communicate benefits of CERC’s IP Protocol and novel Technology Management Plans more broadly;

and extend the reach of CERC's IP innovations as they relate to the clean energy sector to others via web-based CERC products. CEF will support the Secretariat in exploring the hypothesis of transitioning IP aspects of the CERC platform and model to a longer term, sustainable tool for U.S.-China Clean Energy S&T cooperation.