華中科技大學
Huazhong University of Science & Technology

RECENT PRACTICES IN INDUSTRIAL AND LARGE SCALE DEMONSTRATION OF OXY-FUEL COMBUSTION IN CHINA

富氧燃烧的工业示范与大型化研发进展

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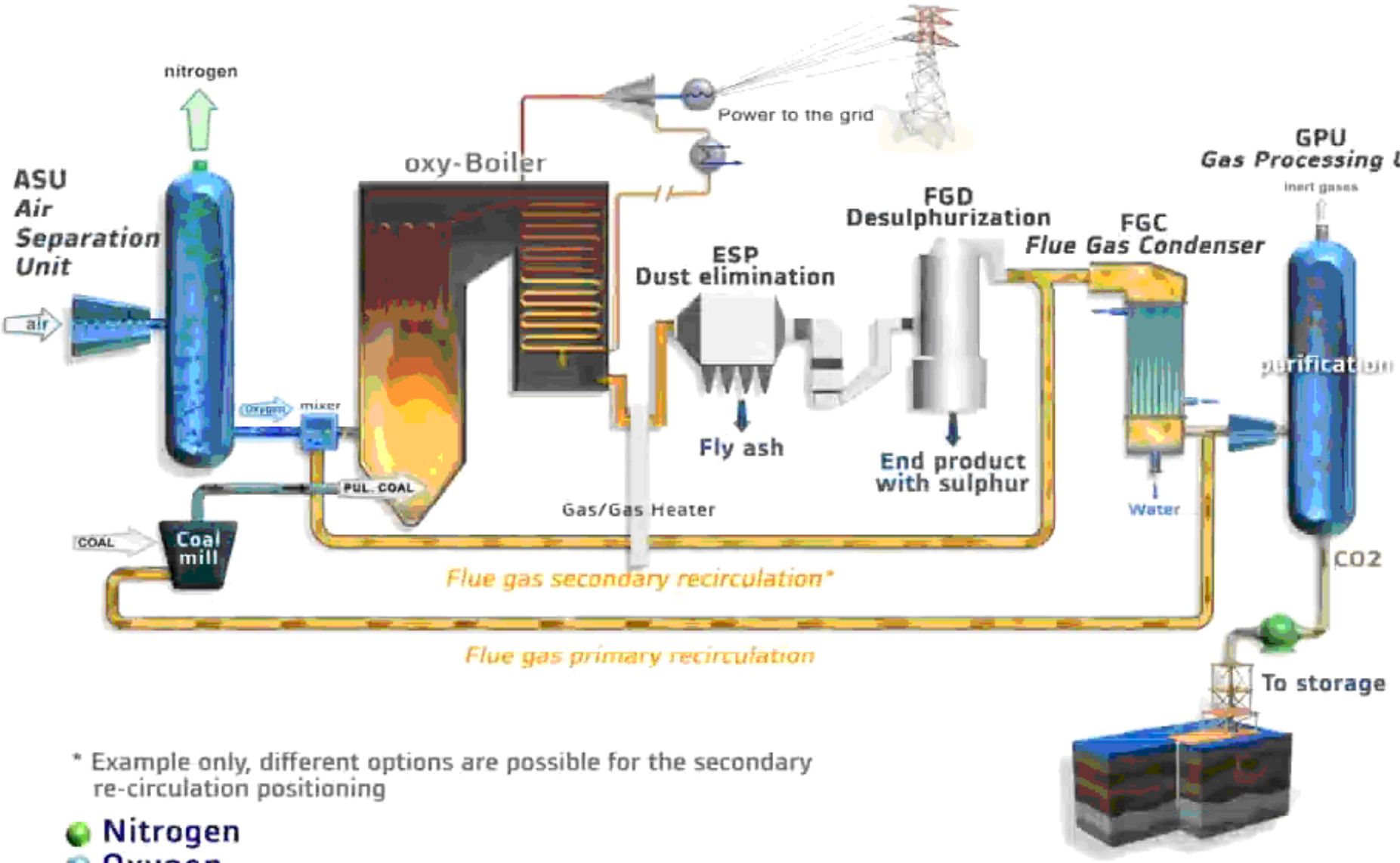
Oxy PC Power Plant



* Example only, different options are possible for the secondary re-circulation positioning

Nitrogen
Oxygen
CO2
PUL. COAL= Pulverized coal
Pumps
Compressors

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Oxy-combustion R&D roadmap of HUST-SKLCC
中国富氧燃烧技术研发示范路线图

Fundamental Study
Concept validation
Pollutant control
Burner development

1995年 实验室微型实验

2006 年 0.3MW$_t$ 中试试验

2011 年 3MW$_t$ 全流程验证试验系统

2014年 35MW$_t$机组半工业示范

2016年 200MW$_e$机组工业示范

2020 年 300MW$_e$以上机组商业应用

1t/h~10t/h
Key component develop
Design method
ASU-oxyfuel integration

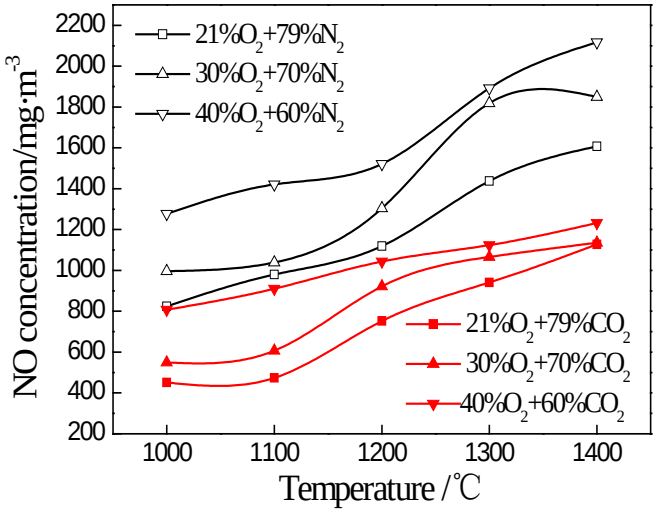
Millions ton/a
Oxyfuel power generation
Full chain system
long term demonstration

1995~2007 → Lab/bench scale

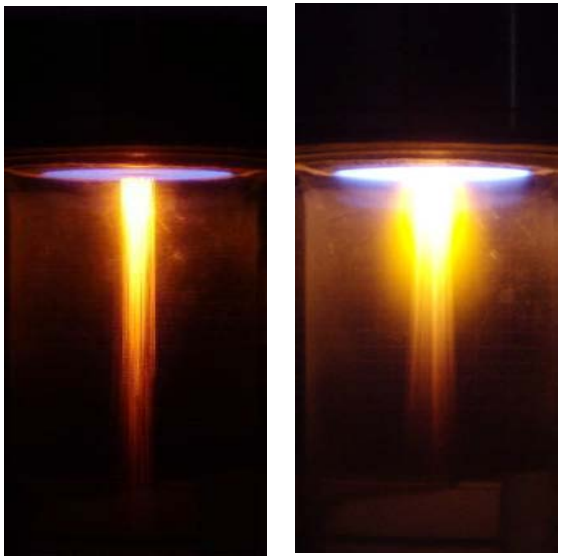
2008~2014 → pilot/semi-industry

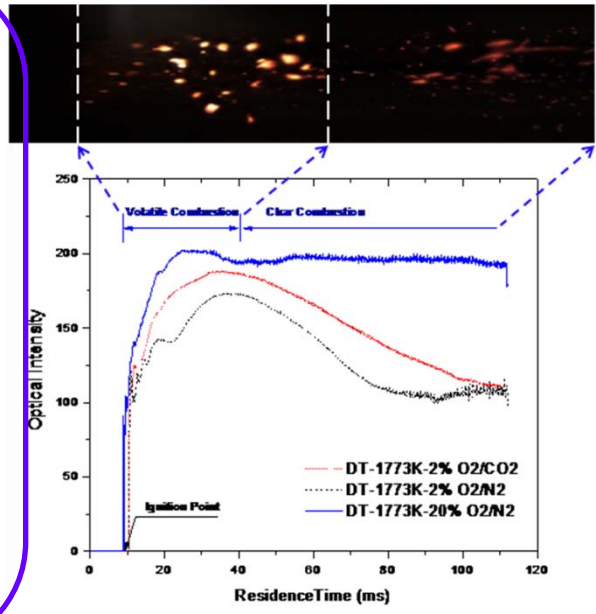
2014~2020 → Large scale

Fundamental research on oxyfuel in China
富氧燃烧基础研究

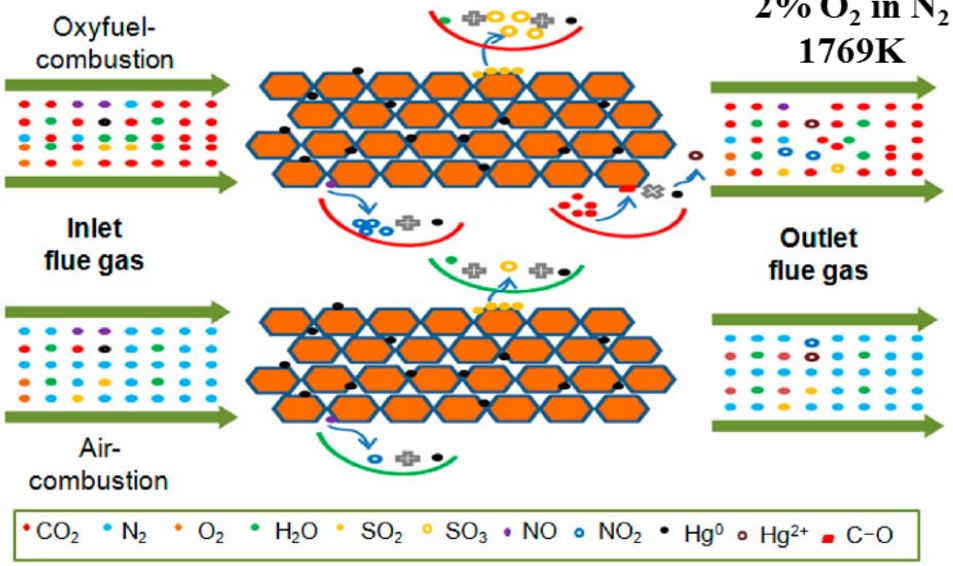


Comparison of NO concentration in oxy-fuel combustion with air





Optical intensity profiles of DT bituminous coal under oxyfuel combustion



中国典型煤种富氧燃烧特性，以及包括痕量元素在内的污染排放、矿物质的变化行为、辐射传热模型、过程动态模拟、经济技术分析等多方面都开展了系统的工作

Papers 研究论文

HUST is listed as the first among the 638 worldwide institutes according to the number of SCI papers on Oxyfuel Combustion

以“Oxyfuel Combustion”或“Oxy-fuel Combustion”为主题SCI检索，全球638个机构，HUST发表论文数排名第一

0.3MW Oxy-fuel facility 0.3MW富氧燃烧台架

Item (units)		value
coal（kg/h）		35
Heat capacity（KW）		300
Reactor （mm）	diameter	600
	height	8300
Total air（kg/h）		390
oxygen（kg/h）		89.7
PA/SA ratio		1：4
Mean velocity of flue gas （m/s，1500℃）		2.07
Cross-sectional Heat load （MW/m2）		1.06
Volume Heat Load（MW/m3）		0.128

Targets: >95% CO_2

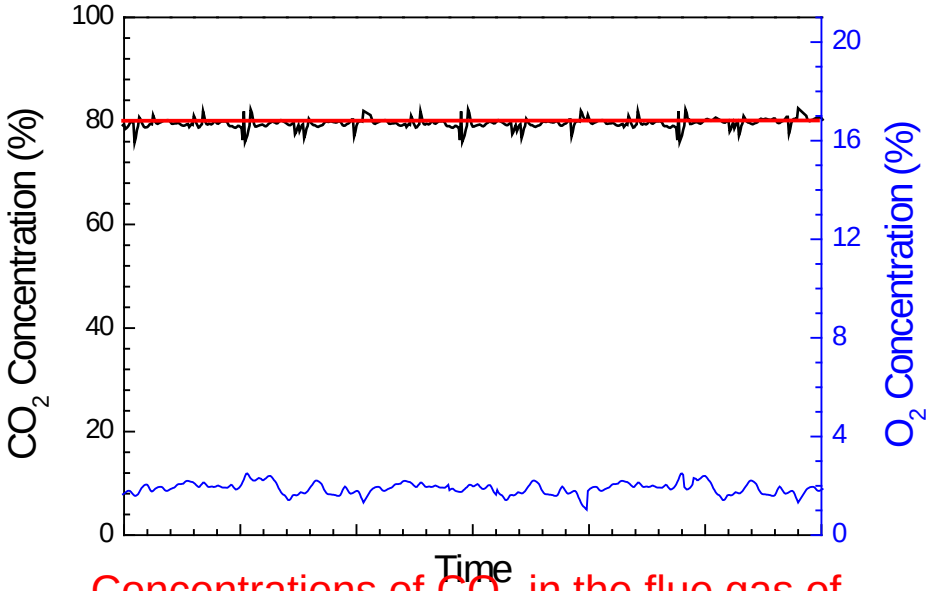
~80%De-NOx; >90% DeSOx; 60~80%DeHg

3MW Oxy-fuel Full Chain System 全流程示范

Conception Design from *Mar. 2011*; Construction work start from *Feb. 28th., 2012*; Finished at *Dec. 18th 2012*. 2012年建成投入使用

Experimental Results 实验结果

- CO_2 enriched as 82%vol, dry in flue gas;
- 干烟气CO_2浓度达到82%；
- Full chain operation to get liquid CO_2;
- 得到高纯度的液态 CO_2 （>95%）；
- Burn-out rate can be more than 95%;
- 燃尽率>95%、NOx减排50~70% 、脱硫效率>95%
- Design of boiler, burner, injector etc. validated; Experiences on air-oxy, oxy-air Transition , air leakage monitoring and avoid etc.
- 关键部件的设计与验证；实现了由空气向富氧燃烧方式的顺利切换。



Concentrations of CO_2 in the flue gas of $3MW_{th}$ oxyfuel combustion (dry basis)

Equipments Development 设备开发

This project focuses on some major issues in the process of oxyfuel combustion. 涵盖富氧燃烧关键环节

Oxyfuel burner
燃烧器

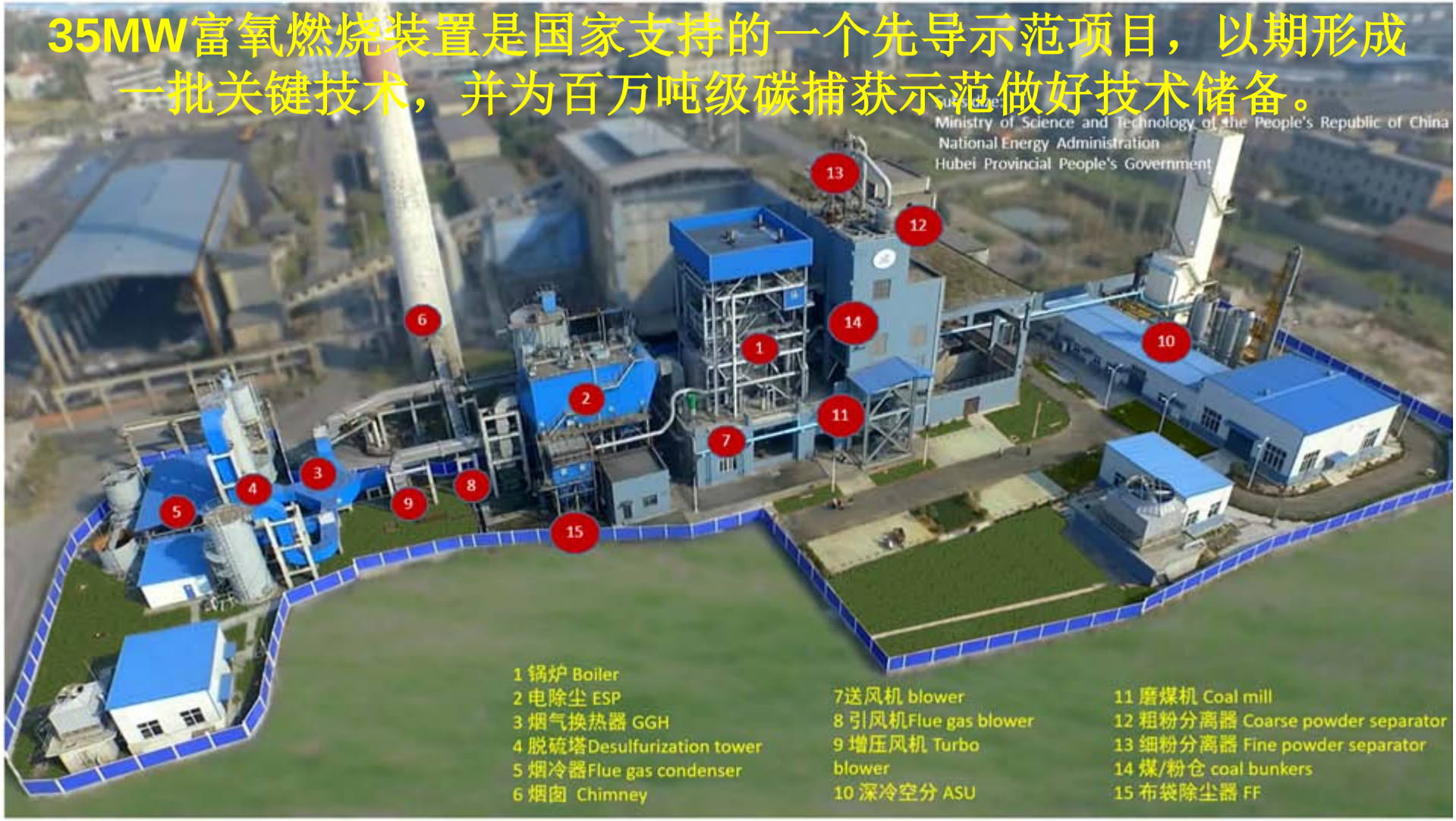
Oxyfuel boiler
锅炉岛

CPU system
空分

Chinese patents

35MW全景/ Bird View of 35MWth Plant

35MW富氧燃烧装置是国家支持的一个先导示范项目，以期形成一批关键技术，并为百万吨级碳捕获示范做好技术储备。



Concept Design	2010.3
Granted by MOST	2010.10
Feasibility Study	2011.5
Engineering Design	2012.9
Field Construction	2012.12
Commision	2015.1-9

Large oxy-fuel combustion pilot worldwide 同类项目

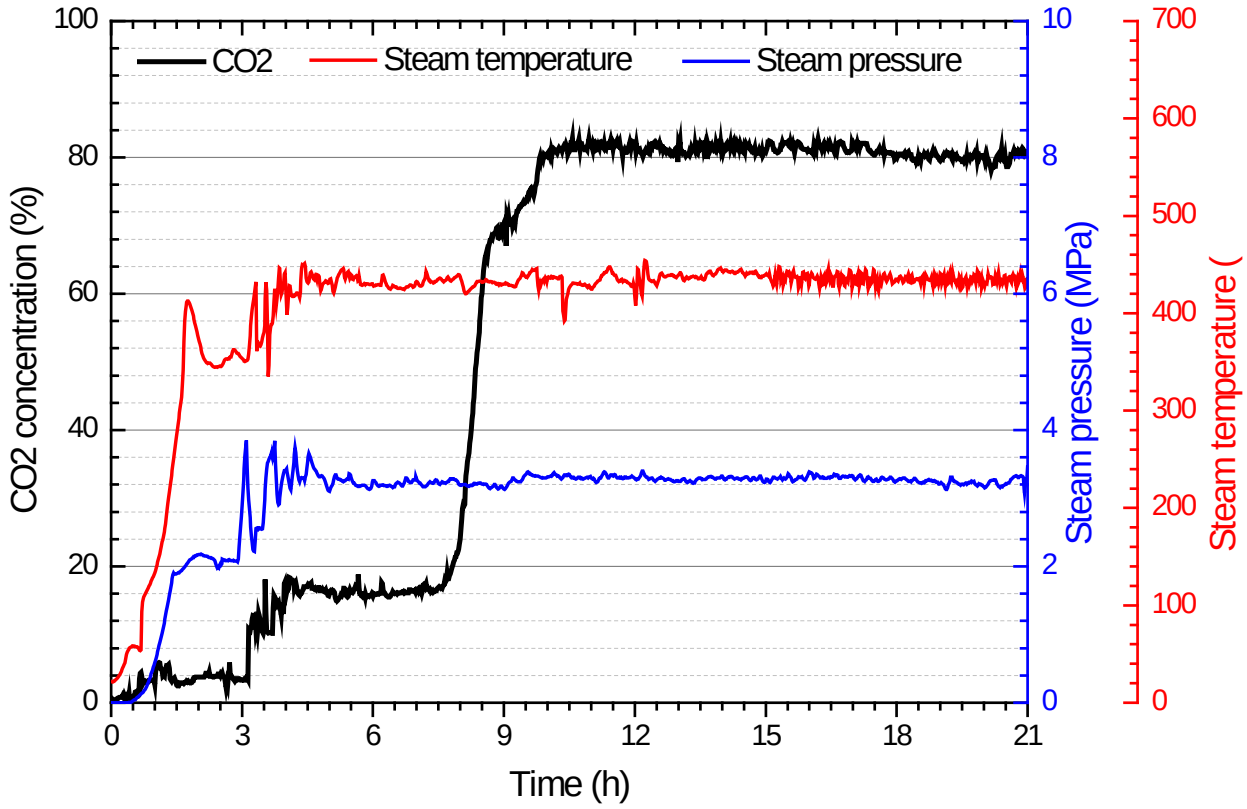
Name	scale	MW	new /retrofit	Start year	Burners	RFG	power	CPU	CO_2 purity	FGCD
Vattenfall	Pilot	30	New	2008	1	Wet	No	Yes	75-80	ESP WFGD
Callide	Demo	100	retrofit	2010	6	Wet	Yes	Yes	72-77	FF
CIUDEN	pilot	20	new	2010	4	Wet	No	Yes	67-72	SCR FF
Yingcheng	Demo	35	retrofit	2011	3	Dry /Wet	Yes	Yes (2nd Phase)	78-82(dry) 68-72(wet)	ESP WFGD

CIUDEN富氧燃烧项目，西班牙(2012)
CIUDEN project, Spain (2012)

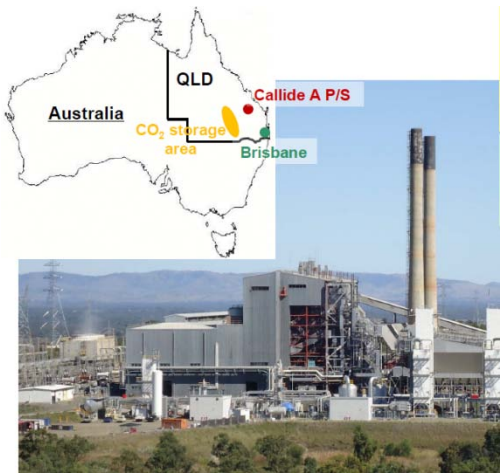
应城30MW煤粉富氧项目，中国（2014）
Yingcheng 30MW project, China (2014)

CO_2 enrichment at low cost 低成本高浓度CO_2捕集

HUST-OXY Feature 1：high CO_2 conc. at low cost
特色1：高浓度CO_2富集



oxyfuel combustion



Callide 30MWe
55%vol,wet or
77%vol,dry

Steady air to oxy combustion switching and stable operation under oxy mode. The CO_2 conc. in flue gas reaches *82.7%vol,dry*, among the highest worldwide. 实现很高浓度的CO_2富集

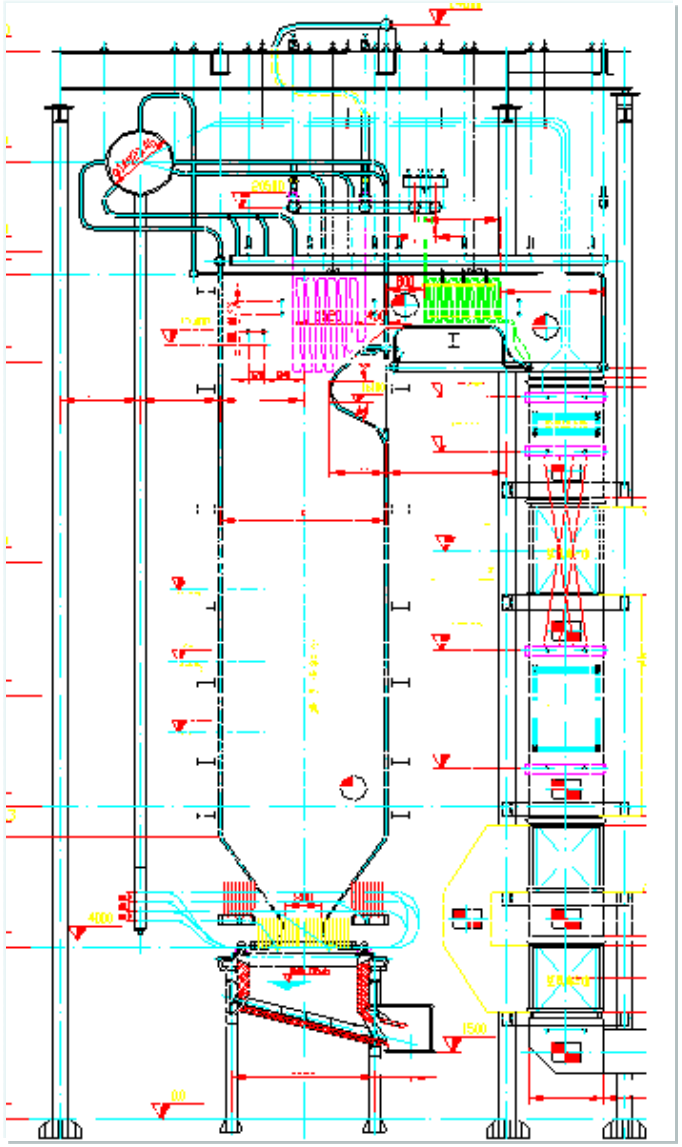
Typical Industrial Boiler 典型的工业锅炉

HUST-OXY feature 2：steam for power & salt production
特色2： 可满足电力和制盐需求

name	unit	data
BMCR	t/h	38.5
Steam pressure	MPa	3.82
Steam temperature	℃	450
Drum pressure	MPa	4.32
Overall width	mm	12000
Overall depth	mm	12000
Overall height	mm	24600
boiler width	mm	4733
Boiler depth	mm	3533

- Standard medium temperature/medium pressure steam parameter；
- Steam feed into ；
- Steam used to salt production and power generation。

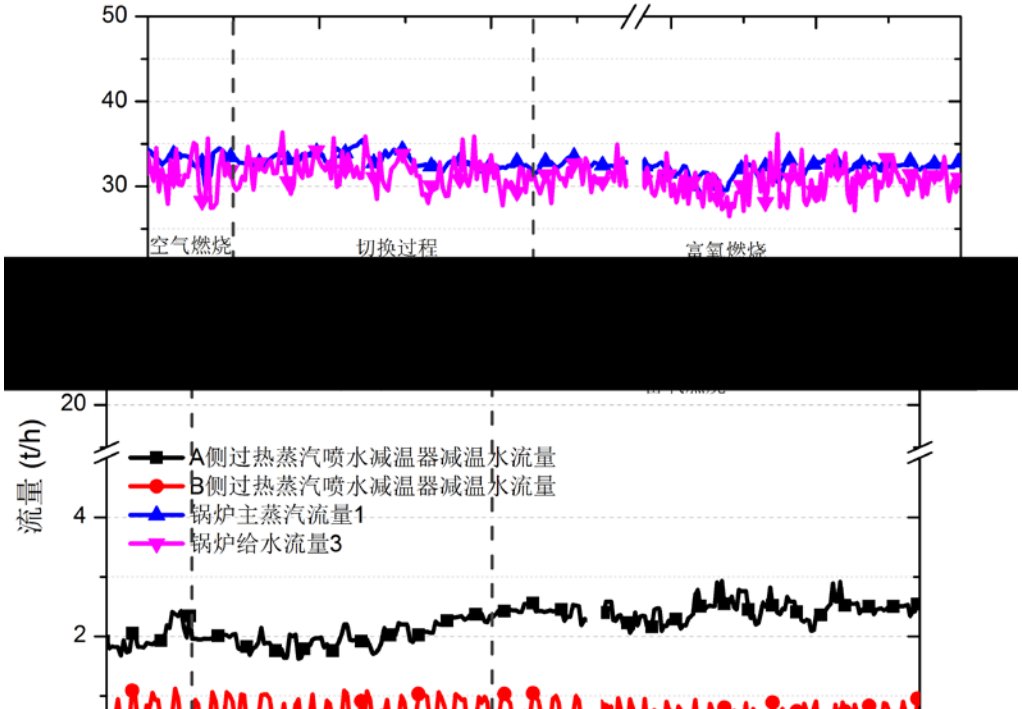
Air/Oxy Combustion Compatible Design 双模式设计



Layout of 35MW Boiler

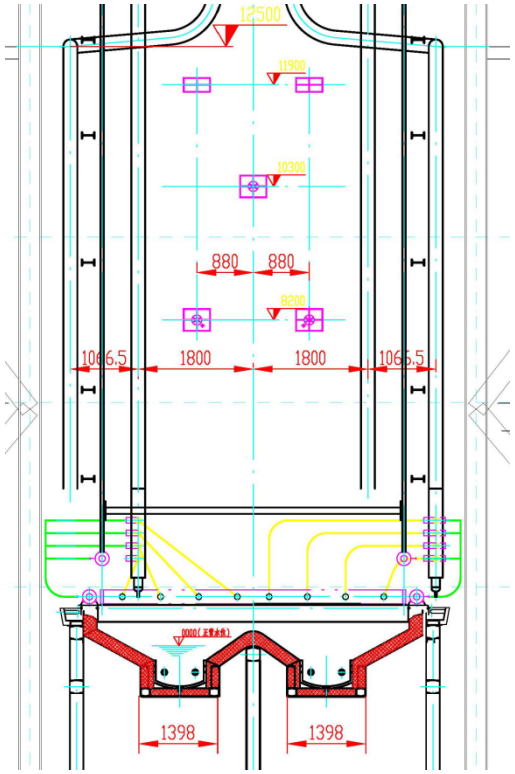
HUST-OXY Feature 3：Dual operation mode
特色3：双运行模式

- ✓ Primary/Secondary oxidant preheat separately；
- ✓ Individual Oxygen Injection for PA/SA；
- ✓ Overlapping arrangement of economizer and FGHX;
- ✓ GGH added to avoid acid corrosion



Multiple scalable burners 喷嘴设计

HUST-OXY feature 4：triple burners set-up
特色4：三喷嘴设计

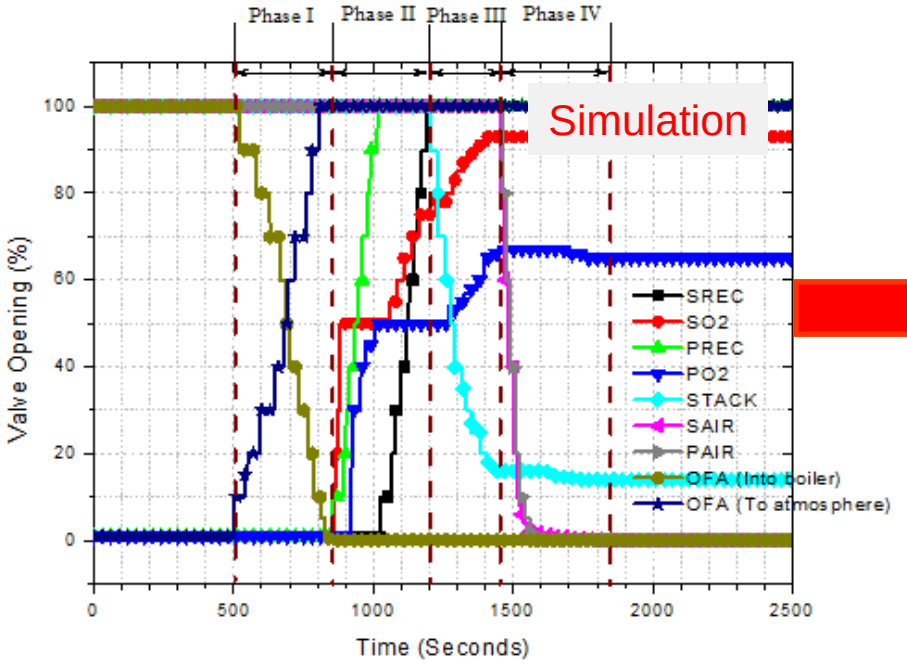


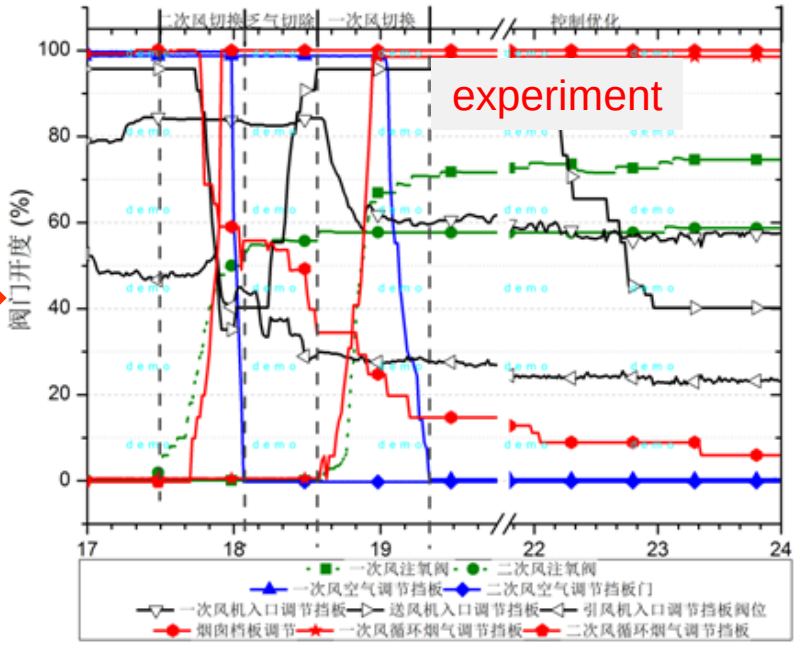
- ✓ Three primary burners and two OFA at front wall;
- ✓ Flame stability proved at air/oxy dry/oxy wet mode;
- ✓ Scaling up from 0.3MW → 3MW → 12MW；
- ✓ Easy for further scaling up

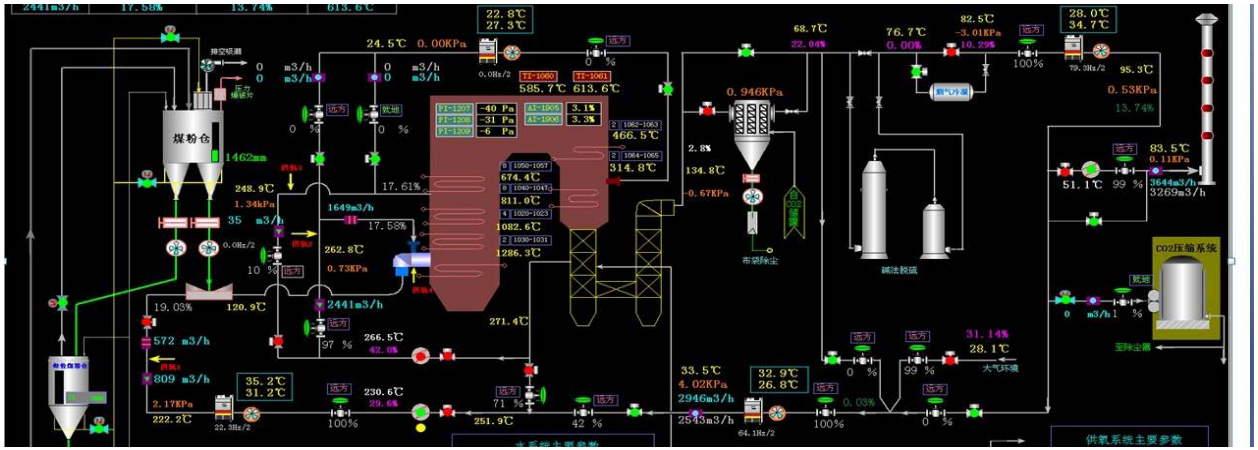
Flexibility in Mode Switch 灵活切换

HUST-OXY feature 5：Dynamic simulation instruct mode switch

特色5：动态模拟指导切换





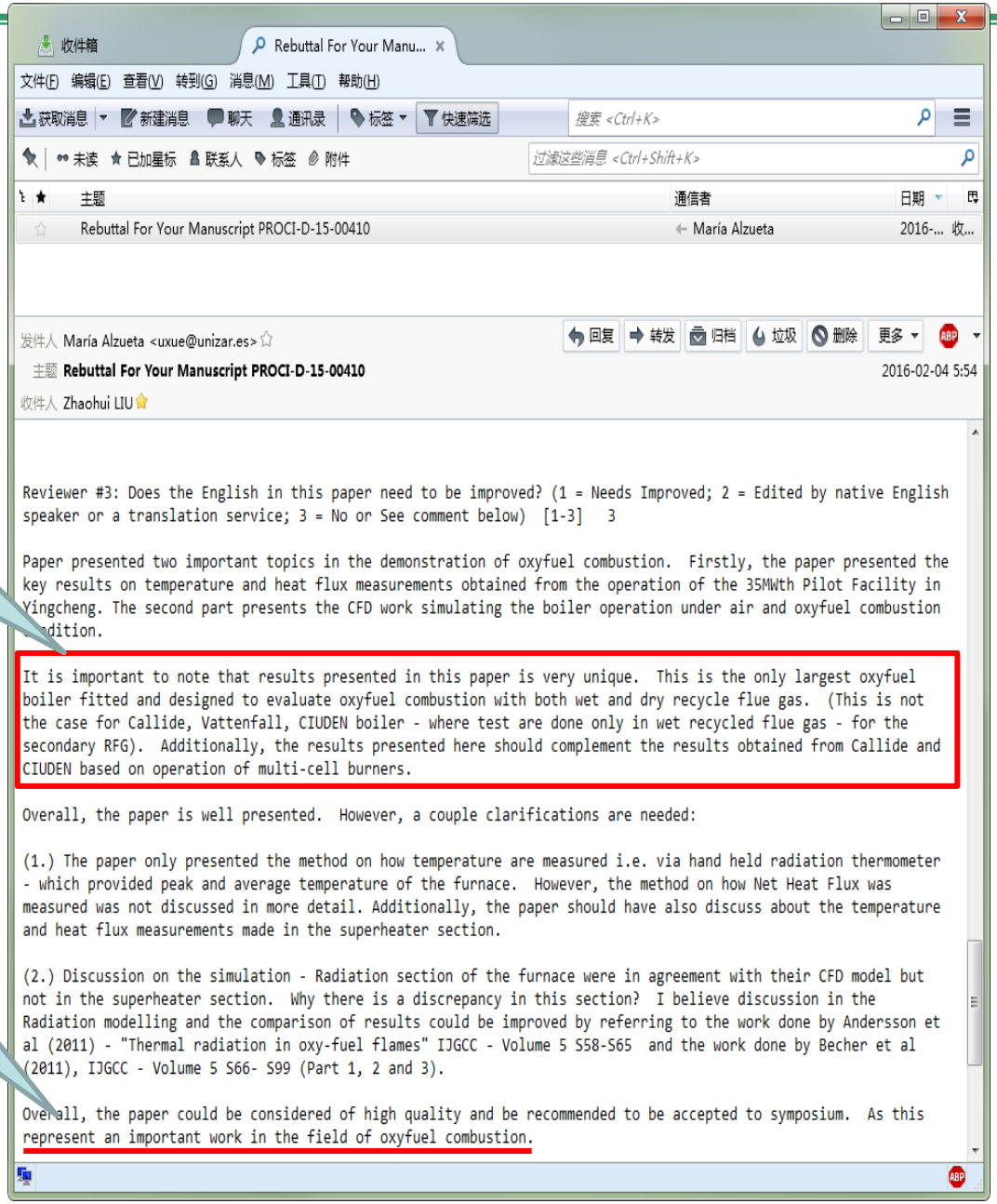


Both wet and dry recycle flue gas 实现了干-湿循环

在工业规模上所得到干、湿循环结果，为世界上已有装置所独有的；多燃烧器布置也是该装置的显著特点。

这是富氧燃烧领域的一项重要工作

----Comments from PCI2016



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主题 **Rebuttal For Your Manuscript PROCI-D-15-00410** 2016-02-04 5:54

收件人 Zhaohui LIU

Reviewer #3: Does the English in this paper need to be improved? (1 = Needs Improved; 2 = Edited by native English speaker or a translation service; 3 = No or See comment below) [1-3] 3

Paper presented two important topics in the demonstration of oxyfuel combustion. Firstly, the paper presented the key results on temperature and heat flux measurements obtained from the operation of the 35MWth Pilot Facility in Yingcheng. The second part presents the CFD work simulating the boiler operation under air and oxyfuel combustion condition.

It is important to note that results presented in this paper is very unique. This is the only largest oxyfuel boiler fitted and designed to evaluate oxyfuel combustion with both wet and dry recycle flue gas. (This is not the case for Callide, Vattenfall, CIUDEN boiler - where test are done only in wet recycled flue gas - for the secondary RFG). Additionally, the results presented here should complement the results obtained from Callide and CIUDEN based on operation of multi-cell burners.

Overall, the paper is well presented. However, a couple clarifications are needed:

(1.) The paper only presented the method on how temperature are measured i.e. via hand held radiation thermometer - which provided peak and average temperature of the furnace. However, the method on how Net Heat Flux was measured was not discussed in more detail. Additionally, the paper should have also discuss about the temperature and heat flux measurements made in the superheater section.

(2.) Discussion on the simulation - Radiation section of the furnace were in agreement with their CFD model but not in the superheater section. Why there is a discrepancy in this section? I believe discussion in the Radiation modelling and the comparison of results could be improved by referring to the work done by Andersson et al (2011) - "Thermal radiation in oxy-fuel flames" IJGCC - Volume 5 S58-S65 and the work done by Becher et al (2011), IJGCC - Volume 5 S66- S99 (Part 1, 2 and 3).

Overall, the paper could be considered of high quality and be recommended to be accepted to symposium. As this represent an important work in the field of oxyfuel combustion.

Nomination 推荐报奖

ISA Power Industry Division

2016 FACILITIES AWARD NOMINATION FORM

This is an outstanding nomination.

------Labbe, Donald
ISA-PowerID Chair

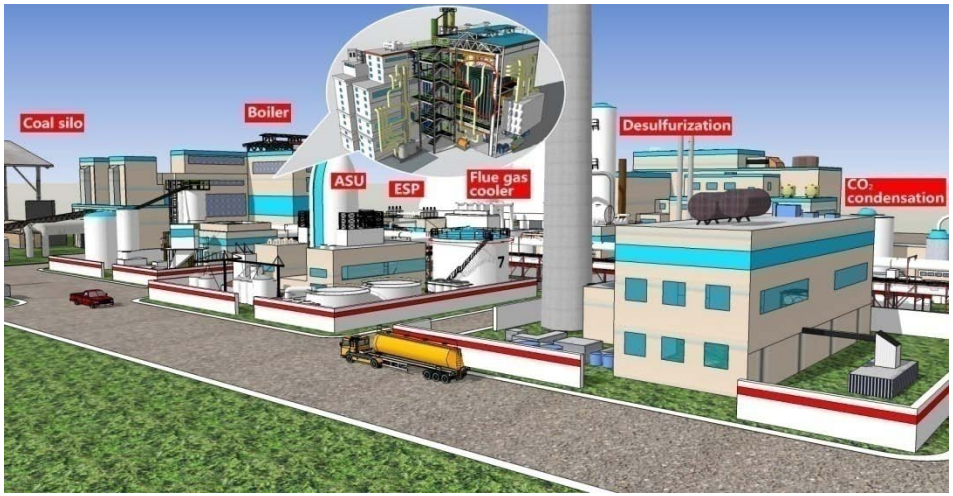
Facility Name and Location:

35MW Oxyfuel Combustion Plant, Hubei Yingcheng, China

Description of Facility:
Yingcheng 35MW oxy-fuel combustion plant is a key milestone for demonstration of oxy-fuel combustion carbon capture technology at industrial scale, beside those efforts at Schwartze Pumpe, Callide, and CUIDEN etc. worldwide. It composes most components of oxy-fuel technology, such as air separation unit (ASU), boiler, flue gas cleaning devices (FGCD), and flue gas recycling system etc.. The CO_2 concentration in its flue gas reached 82 % vol,dry in Sept. 2015, which proved the readiness of oxy-fuel combustion technology for future large scale demonstrations.

This is the only largest oxyfuel boiler fitted and designed to evaluate oxyfuel combustion with both wet and dry recycle flue gas. (This is not the case for Callide, Vattenfall, CIUDEN boiler - where test are done only in wet recycled flue gas - for the secondary RFG).

200 MWe DEMO 示范电厂



关键设备的原理进行了详细研究

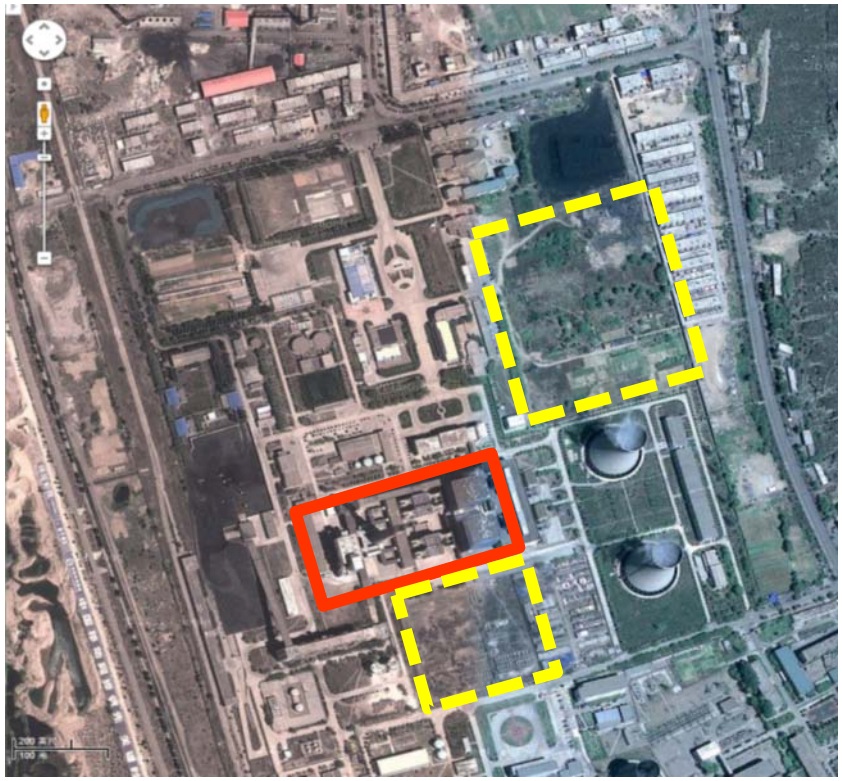
The common basic principles and key equipment of project was studied.

神华集团投资7000万进行可行性研究

Invested more than ￥ 70 million in the feasibility study

200MW Oxy-combustion Demo Plant 大型示范电厂

- Guohua Power group
- Shenmu county, Shanxi
- Capacity 200 MWe
- CO_2 Sequestration



Erdos basin 鄂尔多斯盆地

Theoretical sequestration capacity：262.4 billion tons.

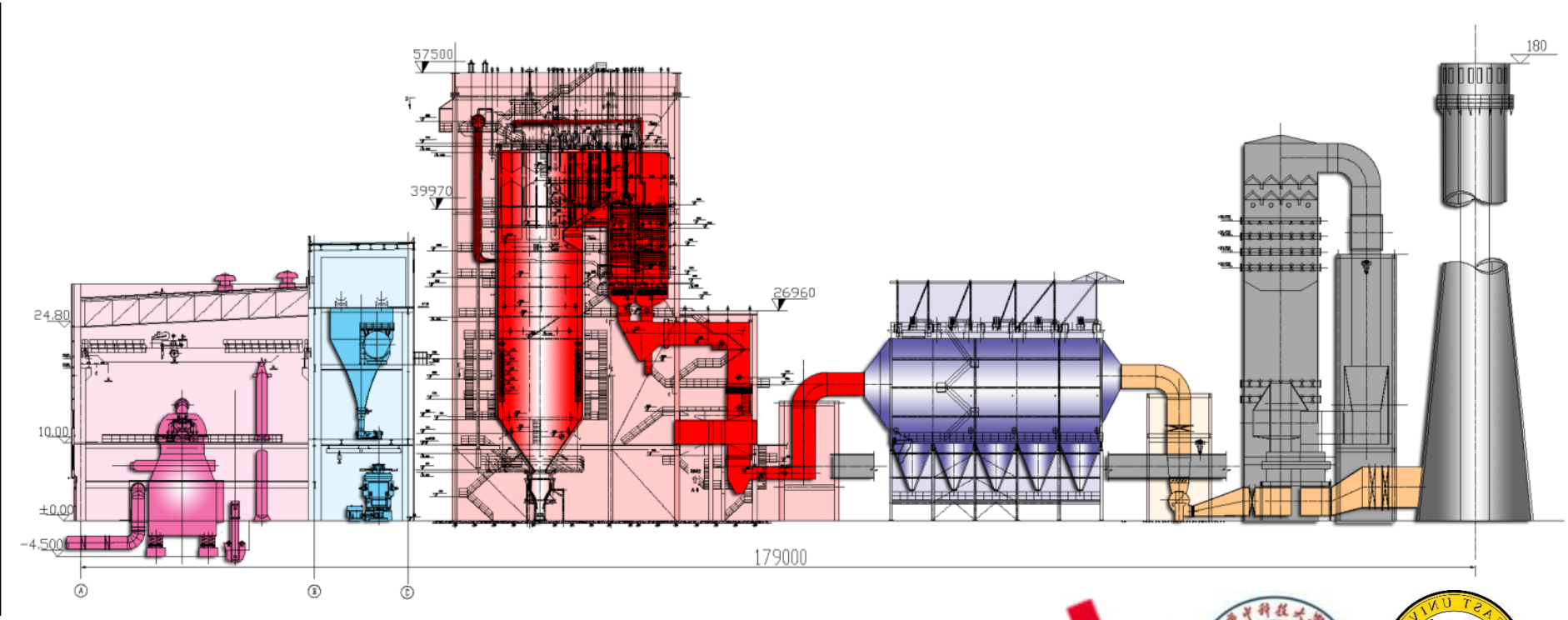
Saline aquifers：256.5 billion tons

Gas field: 1.1 billion tons

Oil field: 400 million tons

Coalbed: 4.5 billion tons

Features of 200 MWe Demo Project 大型示范特点

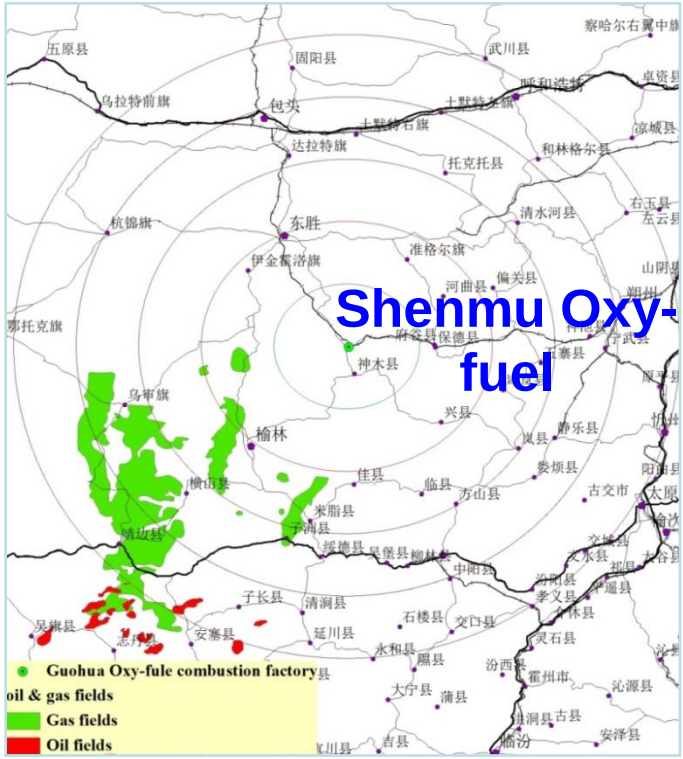


- air and oxy-combustion flexible / new bulit
- met Chinese enviromental legistration
- tangential / front wall firing system
- dry / wet circulation
- CO_2 Sequestration 10~100%

Technical Program for CO_2 transport and storage
运输及封存技术方案

CO_2 Pipeline alone the road for CO_2 aquifer storage; Open channel (favorite slope gradient) to transport saline water back for desalination and utilization.
CO_2管道沿着公路铺设；盐水运输根据地势坡度采用明渠

Landform of possible storage sites
封存场地地形地貌



Project scale 规模	CO_2 transport distance 运距	CO_2 storage technology技术	Well drilling钻井	Brine treatment盐水处理
1 million tons (Mt) per year 1Mt/a	The length of the main supercritical CO_2 pipeline is 70 kilometre (km), the water pipeline is also 70km.运距70km	CO_2 saline aquifer storage (90%) and CO_2 sale for EOR (10%) CO2 aquifer storage(100%) 90%CO_2咸水层封存，10%EOR	9 injection well, 4 production well, and 2 monitoring and control well注入井9口，生产井4口，监测及压力控制井2口	Transport to the point of centralized processing for industrial use集中脱盐处理后，售予工厂

Financial and Economics Analysis of Full CCS Chain
CCS全链条的财务和经济分析

Item 成本项	Conventional 常规电厂(单位：百万元 MCNY)	With CCS 配备CCS富氧燃烧电厂(单位：百万元 MCNY)
Power plant base cost 电厂	946.64	1,153.07
CO2 transport CO_2运输		114.09
CO2 storage CO_2 封存		554.50
Physical contingency 基本预备费	47.33	182.17
Price contingency 涨价预备费	42.10	84.88
Interest During Construction 建设期利息	59.72	120.39
Total 合计	1,095.80	2,209.10

Capital costs for Oxy-fuel + CCS plant increased by 102%, and cost of electricity increased by 109%, compared to a conventional one.

配备全流程CCS的200MW富氧燃烧发电项目比常规电厂建设投资增加102%，发电成本增加109%。

Scaling up trendency 大型化影响

机组容量	发电成本		CO_2减排成本	CO_2捕捉成本
	传统燃烧电站	富氧燃烧电站		
200MW	403	686	344	195
300MW	400	569	203	141
600MW	362	511	189	133
1000MW	322	446	173	125

- The cost of plant can significantly with the improvement of the plant capacity and parameters.

  随着机组容量的增加，富氧燃烧机组的各项成本均会降低，富氧燃烧机组发电成本与传统燃烧机组发电成本的差值越来越小

5th International Oxyfuel Combustion Research Network Meeting

2015-10-28与国际能源署（IEAGHG)联合主办了第五届富氧燃烧与会议，作主旨演讲介绍富氧燃研发进展

Technology block 技术障碍

There are still some problems required further investigations, including :

- Alternative technologies to reduce the costs of oxygen production;

制氧成本

- Heat transfer performance in large units;

改善传热性能

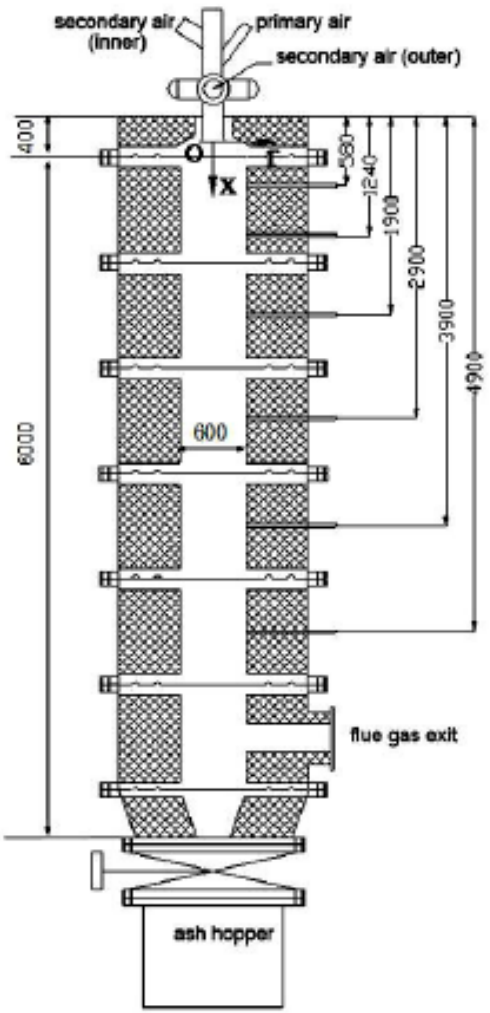
- Effect of recycled flue gas (high SO_2 ,SO_3 , CO_2 and moisture levels) on the system,etc.

循环烟气对系统影响

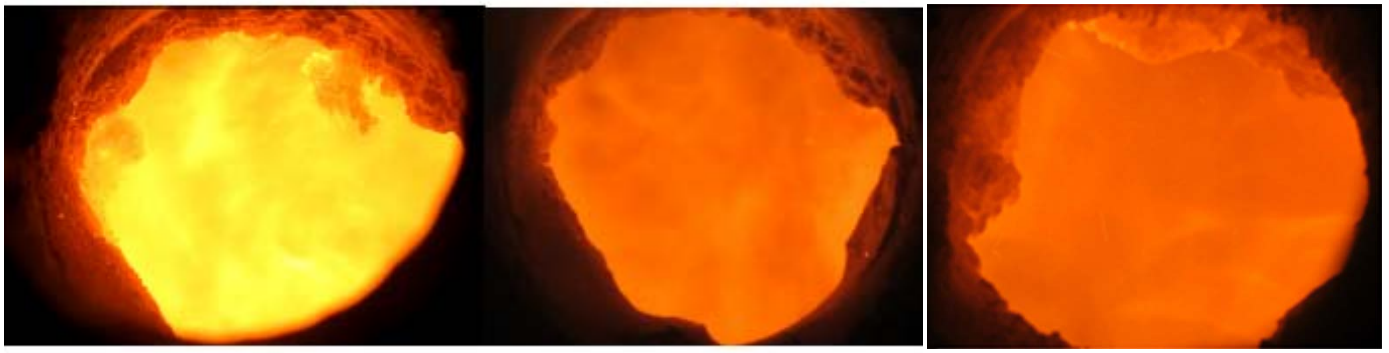
Innovation technology 新技术

- MILD-Oxyfuel combustion technology using high temperature recycling flue gas
  发展基于高温烟气再循环的新型 MILD-Oxyfuel 燃烧方式
- Coupling chemical looping oxygen production with flue gas recycling
  提出化学链制氧与烟气再循环解析的耦合新方法
- CLC technology
  the 2nd generation Oxy-fuel combustion technology
  化学链燃烧—第二代富氧燃烧

MILD-Oxyfuel combustion technology 无焰富氧燃烧



300KW test rig



Flame appearance of coal combustion

Flame-Air **MILD-Air** **MILD-Oxyfuel**

Combining MILD (Moderate & Intense Low Oxygen Dilution) combustion (i.e. Flameless Combustion) and Oxyfuel combustion will improve the combustion efficiency and decrease the pollutant emission.

Energy, 2011, 36: 6583-6595

Int J of Hydrogen Energy, 2011,36:15403-15413

CLC 化学链燃烧技术

Scale up (kw)

Commercialization

2006~

TGA and Chemisorption

Gas, coal

2008~

500W Fluidized bed

Coal, CH_4, syngas

2011~

5 kWth Continuous CLC Reactor

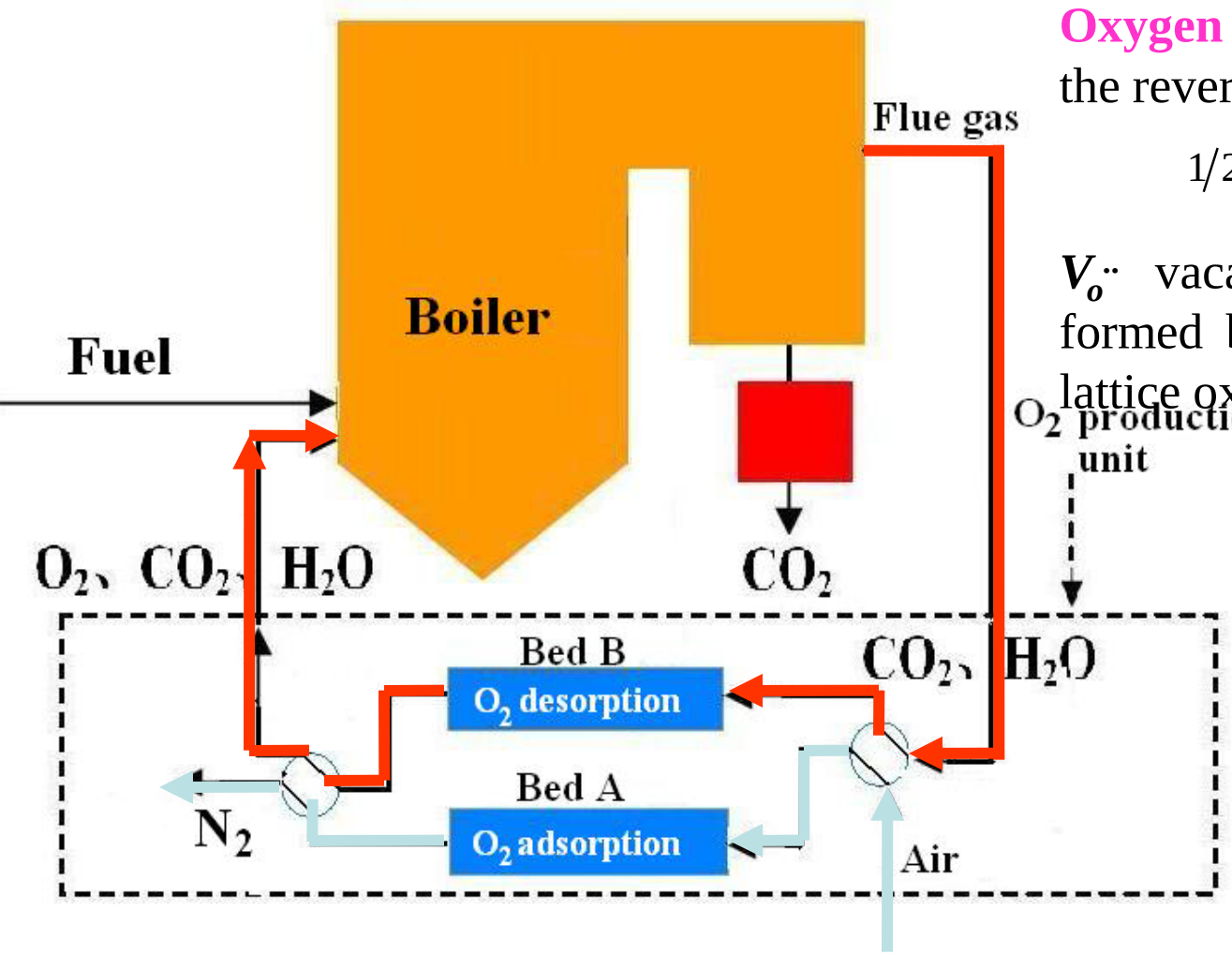
CH_4, coal

2014~

50 kWth Continuous CLC Reactor

Coal, CH4, coal gas…

Chemical looping oxygen production technology
化学链制氧技术



Oxygen production is based on the reversible defect reaction：

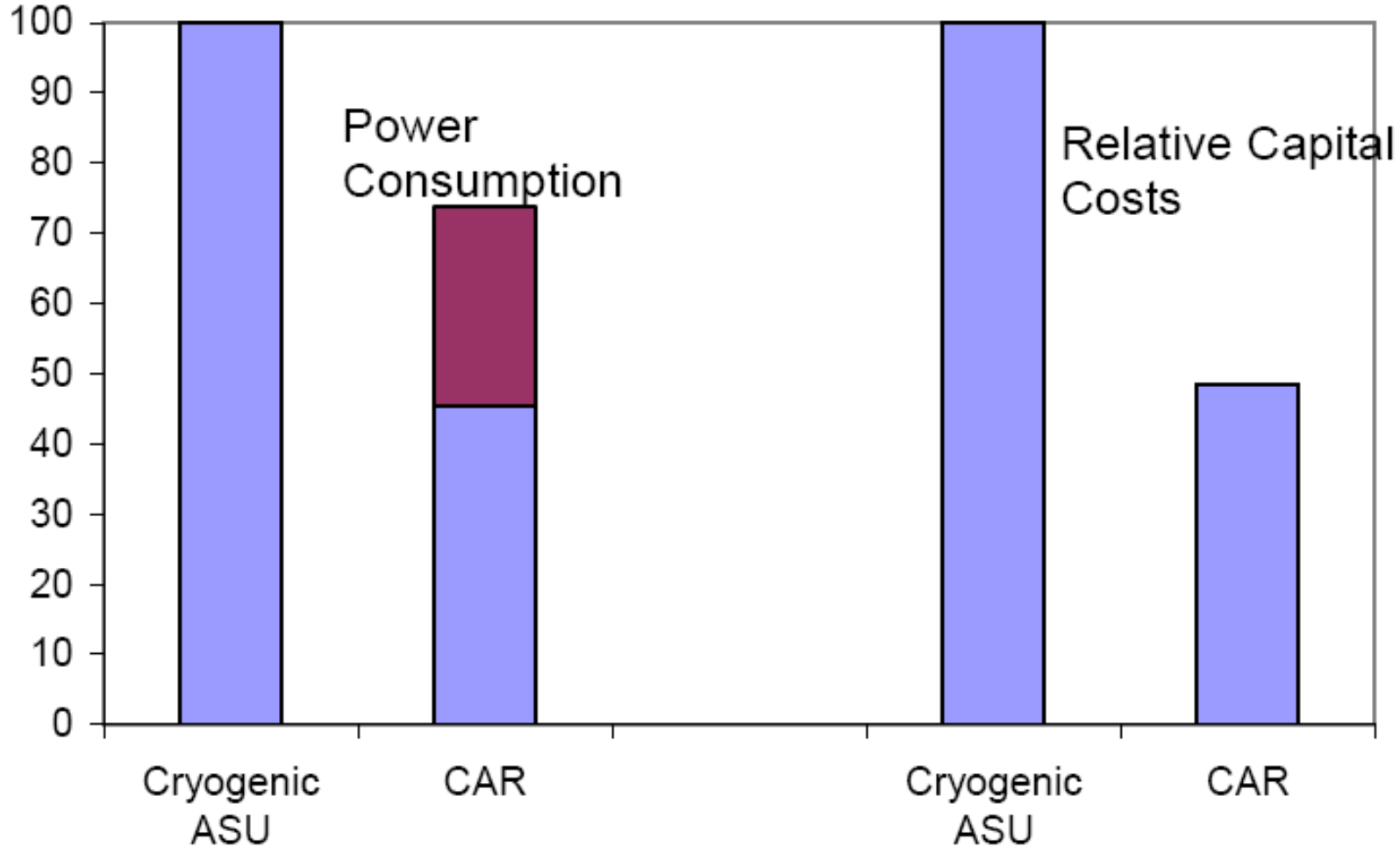
$$1/2\,O_2(g)+V_o^{\cdot\cdot} \Leftrightarrow O_o^{\times}+2h^{\cdot}$$

$V_o^{\cdot\cdot}$ vacancy oxygen，can be formed by doping process；$O_o^{\times}$ lattice oxygen；$2h^{\cdot}$ electron hole

Two fixed bed reactors are used to achieve the continuing oxygen production by oxygen desorption and adsorption.

Korean Journal of Chemical Engineering. 2009,26(3)
Proceedings of the CSEE,2011,31(35):90-96

Cost Analysis 制氧的成本分析



- **Capitalized cost reduction 50% 投资成本减少50%**
- **Running cost reduction 26% 运行成本减少26%**

Thanks for attention !