Enhanced Cryogenic Air Separation
A proven Process applied to Oxyfuel
Future Prospects

Dr.-Ing. Gerhard Beysel
1st Oxyfuel Combustion Conference
Cottbus, Sept 8th, 2009
1 Introduction

2 Air Separation Technologies

3 Potentials for Power Savings and Cost Reduction

4 Potentials for Large Capacities and Oxygen Demand for New Applications

5 Innovative Improvements at Cryogenic Air Separation
The Linde Group
The Divisions

THE LINDE GROUP

Linde Gas  Linde Engineering

(Headquarter Munich, Germany)

50 000 employees  2006  Sales 17 billion US$
Linde Engineering Division
Product Lines & Key Plant Types

Olefin Plants
- Products:
  - Ethylene
  - Propylene
  - Butadiene
  - Aromatics
  - Polymers

Natural Gas Plants
- Products:
  - LNG
  - NGL
  - LPG
  - Helium
  - NRU

Hydrogen and Synthesis Gas Plants
- Products:
  - H2/CO/Syngas
  - Ammonia
  - Gas removal
  - Gas purification

Air Separation Plants
- Products:
  - Oxygen
  - Nitrogen
  - Rare gases
Carbon Capture Technologies (CCS) - From the ASU Perspective -

<table>
<thead>
<tr>
<th>Technology</th>
<th>Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Pre-Combustion (IGCC)</td>
<td>![Pre-Combustion Process Diagram]</td>
</tr>
<tr>
<td>2. Oxyfuel (Oxycoal)</td>
<td>![Oxyfuel Process Diagram]</td>
</tr>
<tr>
<td>3. Post-Combustion (PCC)</td>
<td>![Post-Combustion Process Diagram]</td>
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</tbody>
</table>
Air Separation Plants
Simplified Air Separation Process

Air compression, precooling and purification
heat exchange, refrigeration, rectification and internal compression
product distribution
Alternative Air Separation Technologies

Cryogenic Air Separation (ASU)
- the principles invented one century ago (Dr. Carl von Linde)
- developed for large volumes of oxygen and nitrogen with high purities
- commercialized for industrial application in a wide range
- the source for Industrial Gas Companies supply schemes
- Continuous development and improvement, >25% power saving possible

Polymeric Membranes and Molecular Sieves (PSA, VSA)
- advantageous for small volumes - at lower purities
- produced at ambient temperatures and as needed on-site

Oxygen Production by Chemical Air Separation (MOLTOX)
- Developed and pilot tested by Air Products with DOE funding in early 1990s
- >40% power saving predicted, compared with cryogenic processes
- Status and future of the process unknown (material- and corrosion problems)

High Temperature Ceramic Membranes (ITM)
- Developed and pilot testing (5t/d) since 2005 by Air Products with DOE funding
- 150 tpd under development;
- >30% power saving predicted
# Alternative Air Separation Technologies
- Potentials to Reduce Power Consumption and Cost

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Alternative Air Separation Technologies
- Potentials to Supply Large Product Flows

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Typical Oxygen Demand for New Applications

<table>
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<tr>
<th>New Applications</th>
<th>Capacity [MW]</th>
<th>Oxygen [tons/day ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>IGCC (demo)</td>
<td>250 - 300 MW</td>
<td>- 2.000 1)</td>
</tr>
<tr>
<td>IGCC, Oxyfuel (demo)</td>
<td>300 - 600 MW</td>
<td>2.000 - 5.000 1)</td>
</tr>
<tr>
<td>CTL, Polygeneration (project)</td>
<td>1500 MW</td>
<td>25.000 1)</td>
</tr>
<tr>
<td>GTL (demo)</td>
<td>12.000 bpd</td>
<td>2.500 2)</td>
</tr>
<tr>
<td>GTL (commercial scale)</td>
<td>35.000 bpd</td>
<td>7.000 2)</td>
</tr>
<tr>
<td>GTL (commercial scale)</td>
<td>140.000 bpd</td>
<td>30.000 2)</td>
</tr>
</tbody>
</table>

Cryogenic ASUs: Single train sizes with a capacity of 5,000 tons/d are available. Capacities < 7,000 ton/d under development.

1) Low purity oxygen <95%
2) High purity oxygen >99.5%
Cryogenic Air Separation – Capacity Increase

1902:
5 kg/h
(0.1 ton/day)

2006:
1,250 Mio kg/h
(30,000 ton/day)
Air Separation Plants – Shell „Pearl“ GTL Project
Qatar
30,000 tons/day Oxygen
Air Separation Plants – Shell „Pearl“ GTL Project
Qatar
30,000 tons/day Oxygen
Large Tonnage ASU
Coldbox Shipment for „Pearl“ GTL project
Cryogenic Air Separation Process Optimization
Air Separation Process
Conventional Design (mit Einblaseturbine)

- Oxygen: 95%, gaseous, at ambient pressure

Features:
- PNitrogen: up to 30% of airflow available
Air Separation Process Advanced Alternative Design
(mit warmer PGAN-Turbine)

- Oxygen: 95%, gaseous, at ambient pressure

Features:
- reduced energy consumption/power recovery by expanding PGAN
- heat integration
Air Separation Process
Advanced Alternative Design ("Dual Reboiler"-Design)

- Oxygen: 95%, gaseous, at ambient pressure

**Features:**
- reduced process air pressure
- reduced power consumption
Air Separation Process
Advanced Alternative Design (3-column Design)

- Oxygen: 95%, gaseous, at ambient pressure

**Features:**
- reduced process air pressure
- reduced power consumption
### Conventional Process Schemes / - Applications

<table>
<thead>
<tr>
<th>kWh/Nm³ ¹)</th>
<th>kWh/Nm³ ²)</th>
<th>kWh/t (metric ton) ³)</th>
<th>kWh/t (short ton) (= 907,2 kg) ³)</th>
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</table>

**Conversion Figures:**

| 1 | 0.95 | 699 | 635 |

| 0.35 kWh/Nm³ | 0.33 kWh/Nm³ | 245 kWh/t | 222 kWh/t |

**Conventional ASU, Oxygen Purity >99.5%**

¹) used by ASU vendors (Linde et al) and commonly used for process calculation = 1,429 kg  
²) used by Gas Companies  
³) 1 Nm³
### Air Separation Units
### Cryogenic Oxygen / Specific Energy Consumption

**Advanced Process Schemes for New Applications, e.g. IGCC, Oxyfuel, IGSC**

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</tr>
</thead>
<tbody>
<tr>
<td><strong>Advanced, energy optimized ASU, 95 % Purity Oxygen</strong></td>
<td>0,25</td>
<td>0,237</td>
<td>175</td>
<td>159</td>
</tr>
</tbody>
</table>

*Power consumption reduced by > 25% !!*

Above Figures are related to 100% Oxygen (contained Oxygen), normal ambient conditions for design: 20°C, 15°C CW, 60% rel. humidity, at sea level.

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**THE LINDE GROUP**

**Linde AG** Engineering Division
Power Plant Specific Requirements and their consequences
Specific Power Plant Requirements:

- lowest possible power consumption
- CAPEX and OPEX optimization
- operation range from 60 to 105%
- load change > 2% per minute
- oxygen purity 95%
- low product pressure

Differences between Power Plant Standards and conventional Industrial Gases Standards
Air Separation Units
Specific Requirements for Power Plants

If project specific requirements:

- Design margin of 5%,
- turndown to 63%,
- design for maximum ambient conditions,
- liquid production

are not to be considered for design,

potential for further power saving of 8%. 
## Impact of Turndown Requirement on Main Air Compressor Efficiency

(For a typical ASU)

<table>
<thead>
<tr>
<th>Turndown</th>
<th>Power at motor terminal Comparison</th>
<th>Additional power</th>
</tr>
</thead>
<tbody>
<tr>
<td>75 to 80%</td>
<td>18 500 kW</td>
<td>100 %</td>
</tr>
<tr>
<td>63%</td>
<td>19 100 kW</td>
<td>+ 600 kW</td>
</tr>
<tr>
<td>56%</td>
<td>19 500 kW</td>
<td>+ 1000 kW</td>
</tr>
</tbody>
</table>
### Impact of Different Ambient Air Temperatures

<table>
<thead>
<tr>
<th>Ambient Air Temperature</th>
<th>-17°C</th>
<th>9°C</th>
<th>30°C</th>
<th>33°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective Air Volume Flow</td>
<td>91%</td>
<td>100%</td>
<td>107%</td>
<td>109%</td>
</tr>
</tbody>
</table>

plus 5% design margin
plus turndown requirement
Load change scenario: Ramping of process parameters
→ Target > 2%/min – fluctuation of oxygen purity?

Load change scenario - conventional process scheme considered
ramping > 4 %/min
Steps to low power consumption of ASU:

✓ apply highly efficient air separation process
✓ select appropriate compressor model
✓ identify possibilities for power/heat integration
✓ pick advantageous driver option
✓ check operations requirements carefully (turn down, design margin, etc.)
Advanced Cryogenic Air Separation
- innovative improvements for new applications

- Advanced Structured Packings instead of sieve tray columns available
  reducing pressure drop, increasing turndown capacity

- Advanced process control systems, ALC (AutomaticLoadChange) available
  Dynamic Simulation

- Compressors with higher efficiency, larger turndown range development

- High efficient Heat Exchangers available

- Advanced process schemes ¹)

¹) Large Scale Low Purity Oxygen Requirement (e.g. 95%) - is a novelty in Cryogenic ASU applications
  leads to a step change energy reduction compared to traditional applications!
Linde has built an air separation plant and a CO2 purification and liquefaction plant for Vattenfall’s first oxyfuel pilot plant for coal-based power generation with CO2 capture.
Groundbreaking Ceremony May 2006
Oxyfuel Pilot Plant Schwarze Pumpe
Official Inauguration and start-up: Sept. 9th 2008
Vattenfall Oxyfuel Powerplant Schwarze Pumpe
Linde Scope: ASU, CO2 Plant;
Technologiepartnership
Vattenfall Oxyfuel Powerplant Schwarze Pumpe
ASU with LCO2 Tank
Vattenfall Oxyfuel Powerplant Schwarze Pumpe
CO2 Plant with LCO2 Tanks
„Coal or pet coke gasification, Oxygen for CO2-free power generation, Hydrogen for refinery applications, LNG, and Gas To Liquids, are all energy related development trends where Linde is engaged and offers appropriate technologies and know-how.“

Linde - the Pioneers of Air Separation – we are able to respond to the challenge of producing cleaner fuel & energy for the growing worldwide demand.

(Dr. Aldo Belloni , CEO-Linde)
Thank you for your attention.