Lignite Drying and Upgrading Technology and Its Application to Power Generation System

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Outline

- Background
- Introduction to Lignite Drying and Upgrading Technology
- Application of Lignite Drying to Power Plants
- Research Progress of Our Team
- Further Research Plan
Background

- Lignite—-the lowest rank, shallow buried, easy open mining, high moisture content, high volatile content, low calorific value, easy spontaneous ignition.

- China’s lignite resource mainly distributes in inner Mongolia (older lignite) and Yunnan (younger lignite).

- High moisture content is the main restraint for lignite application in power plants: higher transportation cost, lower grindability, higher heat loss of exhaust gas etc.

- Lignite drying and upgrading technology can effectively solve the above problems.
Introduction to Lignite Drying and Upgrading technology

- **Surface moisture**
  Adhering to the surface of coal particulates or in the bigger capillary cavities

- **Inherent moisture**
  A naturally combined part of the coal deposit

- **Crystallized moisture**
  Chemically combined with the mineral matters in coal

Classification of moisture in lignite
Lignite drying curve

**Transient Region**

**CONSTANT RATE REGION:**
- Free moisture is removed.
- Drying rate is a function of only particle size and moisture content.
- The heat and mass transfer rates are directly proportional to the driving forces of temperature and humidity gradient.

**DECREASING RATE REGION:**
- Inherent and chemically-bound moisture is removed.
- Particle size, temperature, and residence time are important parameters.
- Drying rate might become diffusion-controlled. Since diffusivity increases with temperature, higher temperatures are beneficial.
Evaporative Drying

- Drying medium: air, flue gas, superheated steam
- Heating type: direct contact, indirect contact
- Material status: fixed bed, fluidized bed, entrained bed

Non-Evaporative Drying

- Thermal dewatering
- Thermal mechanical dewatering
- Solvent extraction dewatering
Hot gas drying (many years ago)

- **Direct contact** between lignite and hot flue gas. Moisture absorbs heat in flue gas and evaporates.
- The drying medium hot flue gas is **easy to obtain** in power plants, from furnace or rear flue gas pass.
- **Low oxygen content** in flue gas can inhibit the possibility of ignition and explosion during lignite drying process.
- **Drying in coal pulverizer** belongs to the drying methods by hot flue gas, which is one of the most applied methods in power plants at present.
Rotary tube drying

- **Non-direct contact** between steam and lignite.
- If no air infiltrates, all at the rear is water vapor. Hence, the latent heat of vaporization is convenient to recover.
- Bulky device, low drying capacity.
Superheated steam drying (recently)

- Direct contact between lignite and superheated steam.
- Ignition and explosion during lignite drying process can be avoided due to the inertia of superheated steam.
- No mass transfer resistance between moisture in lignite and superheated steam, with high drying rate.
- Steam from turbine can be used as drying medium in lignite-fired power plants.
- If the latent heat of vaporization in off-gas can be entirely recovered, the energy consumption of drying by superheated steam is only about 1/5 of that dried by hot air. Hence, drying by superheated steam has energy saving potential.
Mixed-bed drying

- Applied in *circulating fluidized bed*, hot bed material supplies heat for drying.
- Drying off-gas is cyclic utilization, with heat transfer occurring in drying tube and lignite being dried.
- Drying off-gas is water vapor, easy to be recovered and utilized.
- **Drying by fluidized bed**

- **Direct contact** between lignite and drying medium, with lignite particulates suspending.

- Fluidizing medium can be hot air, hot flue gas and superheated steam.

- **Built-in heat exchanger** can be arranged to supply more heat for drying.
# Research status

<table>
<thead>
<tr>
<th>Investigator</th>
<th>Year</th>
<th>Fluidized medium</th>
<th>Other experimental conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turan Calban (Turkey)</td>
<td>2003</td>
<td>Air (60 ~ 80 °C)</td>
<td></td>
</tr>
<tr>
<td>Markus Henneberg (Germany)</td>
<td>2003</td>
<td>Air (50 ~ 300 °C)</td>
<td>Al₂O₃ particles instead of coal particles</td>
</tr>
<tr>
<td>Włodzimierz Ciesielczyk (Poland)</td>
<td>2005</td>
<td>Air (40 ~ 80 °C)</td>
<td>(NH₄)₂SO₄, silica gel, sand particles were used</td>
</tr>
<tr>
<td>H. Groenewold (Germany)</td>
<td>2007</td>
<td>Air (50 ~ 150 °C)</td>
<td>Built-in heat exchanger existed</td>
</tr>
<tr>
<td>Olaf Hoehne (Germany)</td>
<td>2010</td>
<td>Steam (1.1~ 7 bar)</td>
<td>Built-in heat exchanger existed</td>
</tr>
</tbody>
</table>
Achievements and Prospect

- High drying rate, compact structure, easy to achieve large-scale.
- Built-in heat exchanger can supply most heat, decrease fluidized medium flow, reduce dryer size and decrease energy consumption of fan.
- If water steam is used as drying medium, spontaneous ignition of lignite can be avoided, with high mass transfer efficiency achieved.
- Fluidized medium and hot fluid in built-in heat exchanger can be extracted from boiler or turbine, which is easy to integrated with power generation system.
Thermal dewatering

- Simulate the coal forming process under high temperature and high pressure to reduce the moisture content in lignite.

- Temperature: 280~350°C; Pressure: 1~13 MPa

- Non-evaporative drying method, moisture in lignite extracted in liquid form.
Achievements and Prospect

- Thermal dewatering simulates the coal-forming process, actually upgrading the lignite to like bituminous coal.
- Except for drying, thermal dewatering also reduce the hydrosopicity and increase the calorific value.
- Some inorganic and organic matter are also removed during this process.
- The technological requirements are high, difficult to realize large-scale.
## Research status

<table>
<thead>
<tr>
<th>Researcher</th>
<th>Year</th>
<th>Experimental</th>
</tr>
</thead>
<tbody>
<tr>
<td>Murray et al. (Australia)</td>
<td>1971</td>
<td>150 ~ 300 °C</td>
</tr>
<tr>
<td>George Favas et al. (Australia)</td>
<td>2001</td>
<td>250 ~ 350 °C</td>
</tr>
<tr>
<td>Weidong Zhao et al. (Zhejiang University)</td>
<td>2009</td>
<td>200 ~ 320 °C</td>
</tr>
</tbody>
</table>
- **Thermal mechanical dewatering**
  - Combined action of temperature and mechanical force.
  - Moisture extracted in liquid form.
  - Bergins et al. in Germany studied thermal mechanical dewatering from 2005.
  - Artanto et al. in Australia carried out similar study from 2007.
  - Yongzhou Wan et al in China Mining University have also done some work.
Achievements and Prospect

- Good drying result, removal rate of moisture higher than 60%.
- The tendency of spontaneous ignition and hygroscopicity reduce obviously.
- Technological requirements are easy realized: temperature lower than 200 °C, pressure lower than 2 Mpa.
- Some inorganic matter is removed together with moisture, which and reduce the slagging and ash deposition.
- More work are needed to realize large-scale.
Solvent extraction dewatering

- Principle: variation of water solubility in nonpolar solvent
- Common solvent: DME (dimethyl ether), supercritical CO₂, toluene, anisole etc.

DME drying experimental device by Hideki and Hisao
## Research status

<table>
<thead>
<tr>
<th>Researcher</th>
<th>Year</th>
<th>Solvent</th>
<th>Experimental conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Noriyuki Okuyama (Japan)</td>
<td>2005</td>
<td>1-methylnaphthalene</td>
<td>300~ 420 °C</td>
</tr>
<tr>
<td>Yoshiki Sato (Japan)</td>
<td>2004</td>
<td>Decalin</td>
<td>380~ 440 °C 2 MPa</td>
</tr>
<tr>
<td>Hideki Kanda (Japan)</td>
<td>2008</td>
<td>DME</td>
<td>&lt;100 °C &lt;1 MPa</td>
</tr>
</tbody>
</table>
Achievements and Prospect

- The tendency of spontaneous ignition is reduced.
- For some solvents like DME, technological requirements and energy consumption are low.
- The organic solvent increases cost.
- The drying rate of this method is low, difficult to realize large-scale.
## Summary

<table>
<thead>
<tr>
<th>Drying method</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot gas/air drying</td>
<td>Simple device, mature technology</td>
<td>High energy consumption, possibility of ignition and explosion</td>
</tr>
<tr>
<td>Superheated steam drying</td>
<td>Waste heat recovery, high heat and mass transfer ability</td>
<td>Steam generation facility and waste heat recovery devices needed</td>
</tr>
<tr>
<td>Fluidized bed drying</td>
<td>High drying rate, easy to realize large-scale</td>
<td>High energy consumption</td>
</tr>
<tr>
<td>Thermal dewatering</td>
<td>No evaporation, low energy consumption</td>
<td>High technological requirements, waste water</td>
</tr>
<tr>
<td>Thermal mechanical dewatering</td>
<td>Low energy consumption,</td>
<td>Waste water</td>
</tr>
<tr>
<td>Solvent extraction dewatering</td>
<td>Low energy consumption</td>
<td>Low drying rate, cost of organic solvent</td>
</tr>
</tbody>
</table>
Conventional lignite power generation system

Schematic diagram

Fan-type milling and drying device
Reduction in coal consumption

Flow rate of dried coal as a function of coal moisture content and system configuration
Increase of boiler efficiency

Boiler efficiency improvement as a function of coal moisture content and system configuration
Increase of unit net efficiency

Improvement in net unit efficiency against coal moisture content and system configuration
Increase of power plant efficiency

Comparison of power plant efficiency among different lignite drying system
Lignite drying system of GRE corp.

- Drying heat from outlet of condenser
- Fluidized bed dryer with built-in heat exchanger
- Air as fluidized medium is heated by condensed water
- Condensed water as working medium in built-in heat exchanger
Lignite drying system of GRE corp.

Pilot Testing at Coal Creek Station
Lignite drying system of GRE corp.

Operation conditions:

- Drying capacity: 112.5t/h
- Decrease of moisture content after drying: 38.5% to 29.5%
- Increase of calorific value: 14000-16500 kJ/kg
- Decrease of pulverizer power consumption: 13.5%
- Decrease of flue gas amount: 3.3%
- Increase of boiler thermal efficiency: 3%

Problem:

- Limited by hot source temperature (50°C), difficult to further reduce moisture content.
- The condensed water temperature is lower than 50°C for most power plants, not suited to this drying system.
Lignite drying system WTA of RWE corp. in Germany

- Steam extracted from turbine, built-in heat exchanger
- Off-gas from dryer outlet is divided into some parts:
  - One part as fluidized medium.
  - Another part releases heat in heat exchanger.
  - The last part is emptied.
Lignite drying system WTA of RWE corp. in Germany

Photo of the prototype WTA plant at Niederaussem
Operation conditions:
- Process 25% coal.
- Increase the unit generating efficiency by 1%.

Current conditions:
- A system is under construction, whose processing capacity satisfies whole coal supply achievement.

Problem: How to recover the latent heat of vaporization from more steam.
Application of lignite drying technology to power generation system has a huge energy saving potential. Research progress of our team is mainly shown as follows:

- Drying characteristics of lignite under different drying methods
- Changes of lignite properties due to drying
- Effect of drying on combustion in boiler
- Integration of lignite drying technology into power generation system
Experimental study on lignite drying in fixed bed

Schematic diagram of the packed bed dryer system

1, air pump; 2, nitrogen; 3 and 4, mass flow controller; 5, electrical heater; 6, temperature controller; 7, packed bed; 8, thermocouples; 9, gas distributor; 10, gravity sensor; 11, data acquisition unit; 12, computer.
Experimental study on lignite drying in fixed bed

- Drying in fixed bed can be divided into three stages: preheating stage, constant drying rate stage and reduction drying rate stage.
- Preheating stage: Lignite particles are heated.
- Constant drying rate stage: The surface moisture is removed.
- Reduction drying rate stage: The inherent moisture is removed.
Experimental study on lignite drying in fixed bed

Effect of drying medium temperature

Effect of drying medium flow rate

Drying rate increases with temperature and flow rate, but decreases with particle size.

Effect of particle size
Experimental study on lignite drying in packed bed

- Schematic diagram of entrained flow reactor for the rapid pyrolysis and combustion of coal particles

1: gas cylinder; 2: reducing valve; 3: mass flow meter; 4: mass flow controller;
5: coal supply device; 6: quartz tube reactor; 7: furnace; 8: thermocouple;
9: temperature controller; 10: filter; 11: sampler; 12, 13: data processing system
**Effect of drying on pyrolysis properties**

<table>
<thead>
<tr>
<th>Particle size/μm</th>
<th>Heating rate/°C·min⁻¹</th>
<th>Before drying</th>
<th>After drying</th>
</tr>
</thead>
<tbody>
<tr>
<td>75~100</td>
<td>20</td>
<td>32.34%</td>
<td>37.18%</td>
</tr>
<tr>
<td>100~125</td>
<td>20</td>
<td>31.98%</td>
<td>37.49%</td>
</tr>
<tr>
<td>125~150</td>
<td>20</td>
<td>31.87%</td>
<td>37.6%</td>
</tr>
<tr>
<td>100~125</td>
<td>10</td>
<td>32.14%</td>
<td>38.53%</td>
</tr>
<tr>
<td>100~125</td>
<td>30</td>
<td>31.75%</td>
<td>37.38%</td>
</tr>
<tr>
<td>100~125</td>
<td>40</td>
<td>31.18%</td>
<td>38.15%</td>
</tr>
</tbody>
</table>

- Yield of volatile matter increases after drying.
- The breakage of hydrogen bonds occurs, resulting in more volatile matter yield.
- More oxygen-containing functional groups are created during drying.
### Effect of drying on combustion properties

By thermogravimetric analysis

<table>
<thead>
<tr>
<th>Oxygen content/ %</th>
<th>Particle size /μm</th>
<th>Heating rate/° C·m in⁻¹</th>
<th>$T_1/^° C$</th>
<th>$T_{max}/^° C$</th>
<th>$T_2/^° C$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Raw</td>
<td>Dried</td>
<td>Raw</td>
<td>Dried</td>
</tr>
<tr>
<td>21</td>
<td>100 ~125</td>
<td>10</td>
<td>328.31</td>
<td>343.58</td>
<td>424.29</td>
</tr>
<tr>
<td>21</td>
<td>100 ~125</td>
<td>20</td>
<td>329</td>
<td>342.11</td>
<td>440.47</td>
</tr>
<tr>
<td>21</td>
<td>100 ~125</td>
<td>30</td>
<td>330.94</td>
<td>341.4</td>
<td>454.95</td>
</tr>
<tr>
<td>21</td>
<td>100 ~125</td>
<td>40</td>
<td>337.99</td>
<td>338.54</td>
<td>483.46</td>
</tr>
<tr>
<td>21</td>
<td>75 ~100</td>
<td>20</td>
<td>332.93</td>
<td>336.95</td>
<td>451.51</td>
</tr>
<tr>
<td>21</td>
<td>125 ~150</td>
<td>20</td>
<td>332.08</td>
<td>341.38</td>
<td>436.35</td>
</tr>
<tr>
<td>5</td>
<td>100 ~125</td>
<td>20</td>
<td>344.74</td>
<td>343.12</td>
<td>480.18</td>
</tr>
<tr>
<td>10</td>
<td>100 ~125</td>
<td>20</td>
<td>341.43</td>
<td>344.2</td>
<td>481.28</td>
</tr>
<tr>
<td>15</td>
<td>100 ~125</td>
<td>20</td>
<td>337.98</td>
<td>340.94</td>
<td>465.06</td>
</tr>
</tbody>
</table>
Effect of drying on pollutant emissions

Rapid pyrolysis

During 800~950 °C, conversion of HCN increases with temperature; Above 1000 °C, conversion of HCN reduces with the increase of temperature.

HCN conversions of received basis lignite and after drying lignite are both higher than that of dry basis lignite.
Effect of drying on pollutant emissions

Rapid combustion

- Conversion of NO increases with the increase of temperature.
- NO conversions of received basis lignite and after drying lignite are both higher than that of dry basis lignite.
Effect of fixed bed drying on lignite properties

- The ignition temperature of after drying lignite shows no variation, while the burnout temperature increases.

- Conversion of HCN first increases then decreases with the increase of temperature, reaching maximum value with 900-1000 °C. Moisture and air drying processing promote the conversion of fuel-N to HCN.

- Conversion of NO is raised with the increase of temperature during lignite rapid combustion. Moisture and air drying processing are both favorable to the conversion of fuel-N to NO.
Fluidized bed drying

Advantage: high drying rate, easy to realize large-scale, most close to engineering application.

Fluidized bed drying technology has been used in certain power plants abroad.

However, study on lignite drying by fluidized bed in China has not fully conducted, further research are necessary.
Experiments on fluidized bed drying

 Fluidized bed drying system

1. fan; 2. control valve; 3. pressure meter; 4. differential pressure transmitter; 5. flow meter; 6. heater; 7. controller of heater; 8. electrically heated boiler; 9. trap; 10. temperature acquisition boards; 11. fluidized bed dryer; 12. feeder; 13. built-in heat exchanger; 14. sampling aperture; 15. air distributor; 16. filter; 17. discharge valve
Experiments on fluidized bed drying

Drying rate increases with temperature and flow rate, decreases with particle size.
Application of lignite drying to power generation system

Main research contents:

- Design different drying systems for lignite-fired power plants based on corresponding drying methods.
- Make comparisons and analyses on these systems based on thermodynamics, determine the key parameters.
- Determine the optimal drying system, taking into account initial cost, operation etc.
Our research

- Prototype: 1000 MW power generation unit firing lignite.
- Propose a new power generation system equipped with lignite drying unit based on the original system.
- Recover part of waste heat to further increase the overall power generation efficiency.
- A patent application has been completed.
The configuration of a conventional 1000 MW power plant
Configuration of a power plant with superheated steam-fluidized bed drying
Configuration of a power plant with hot-air-fluidized bed drying
Power generation system with fixed bed dryer

Exhaust Gas → Coal Fines

Dried Coal → Dryer

Raw Coal → Steam

Air

Air Heater

Condenser

Condensate Pump

Feed Pump

No.8 → No.7 → No.6 → No.5 → No.4 → No.3 → No.2 → No.1
Our progress

Complete the analyses on the original and new systems through programmed calculations:

- Effect of moisture content in lignite on the system
- Effect of drying degree on the system
- Effect of drying medium/heating medium on the system
- Effect of the connection type of waste heat recovery equipment on the system

Integration with lignite drying unit increases the power plant efficiency obviously.
### Thermodynamic analysis of the power generation system with fixed bed dryer

**Overall system efficiencies under typical conditions**

<table>
<thead>
<tr>
<th></th>
<th>Conventional lignite-fired plant</th>
<th>Plant with fixed bed dryer</th>
<th>Plant with external dryer</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Moisture content/%</strong></td>
<td>45</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td><strong>High calorific value /MJ</strong></td>
<td>12.758</td>
<td>17.397</td>
<td>17.397</td>
</tr>
<tr>
<td><strong>Thermal efficiency /%</strong></td>
<td>78.59</td>
<td>84.24</td>
<td>84.24</td>
</tr>
<tr>
<td><strong>Coal consumption/kg·s⁻¹</strong></td>
<td>194.04</td>
<td>181.35</td>
<td>181.35</td>
</tr>
<tr>
<td><strong>Thermal cycle efficiency/%</strong></td>
<td>49.79</td>
<td>48.19</td>
<td>49.79</td>
</tr>
<tr>
<td><strong>Generated power/MW</strong></td>
<td>950.00</td>
<td>919.49</td>
<td>950.00</td>
</tr>
<tr>
<td><strong>Overall generation efficiency/%</strong></td>
<td>38.16</td>
<td>39.59</td>
<td>40.90</td>
</tr>
</tbody>
</table>
Thermodynamic analysis of the power generation system with fixed bed dryer

Effect of moisture content

- As the moisture content in lignite reduces from 40% to 10%, the high calorific value increases and the thermal efficiency increases from 80.35% to 86.83%.

- The boiler efficiency increases linearly with the removal ratio of moisture.
The overall efficiency becomes lower with higher extraction steam pressure.

The power plant efficiency decreases with the increase of the exhaust gas temperature.
The patent: A high moisture lignite drying system integrated into thermal power plants
Some important achievements

- By pre-drying the LRC to the moisture content of 25%, the flow rate of the raw coal can be reduced by 6.5%, and the overall efficiency increases for the power plant with steam and hot air pre-drying are 1.16% and 1.43%, respectively.

- The boiler efficiency increases from 80.35% to 86.83% (HHV basis), and the overall efficiencies of the power plants are increased linearly, as the coal moisture content vary from 40% to 10%.

- Using a higher extraction steam parameters in the immersed heater can cause a lower overall efficiency.

- Changing the exhaust gas temperature has weak effect on the overall efficiency of the power plant with hot air pre-drying.
Further research plan

- Study on non-evaporative drying (thermal dehydration)
  - Drying capability and rate
  - Change of lignite properties: hydroscopicity, combustion and pollutant emission characteristics

- Numerical simulation of lignite combustion in boiler
  - Obtain the temperature distribution, NO\textsubscript{x} distribution etc.
  - Compare the combustion performance between raw lignite and drying lignite, provide reference for application of drying technology in power generation system.
Further research plan

- Further improve the design of drying system, obtain the optimal of energy saving and economy.
  - Design the optimal drying system specific to different geographic location, climate, coal property et al.
  - Optimize the parameters and increase the overall efficiency of power plant specific to certain lignite drying system
- Further research on the key equipment of lignite drying system
  - The drying performance of certain dryer
  - The heat transfer performance of heat exchanger
  - Study on anti-wear and anti-corrosion of some components
Thank you!