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Shangjian Hu\textsuperscript{a}, Chengbo Man\textsuperscript{a}, Xuezhong Gao\textsuperscript{a,b}, Jianwen Zhang\textsuperscript{a,b}, Xueyuan Xu\textsuperscript{b} & Defu Che\textsuperscript{a}

\textsuperscript{a} School of Energy and Power Engineering, Xi'an Jiaotong University, Xi'an, China
\textsuperscript{b} Shanghai Boiler Works Ltd., Shanghai, China

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Energy Analysis of Low-Rank Coal Pre-Drying Power Generation Systems

Shangjian Hu,1 Chengbo Man,1 Xuezhong Gao,1,2 Jianwen Zhang,1,2 Xueyuan Xu,2 and Defu Che1
1School of Energy and Power Engineering, Xi’an Jiaotong University, Xi’an, China
2Shanghai Boiler Works Ltd., Shanghai, China

Low-rank coal (LRC) is widely used for power generation in many regions of the world. However, due to the high moisture content of LRC, the overall efficiency of LRC-fired power plants without a pre-drying system is relatively low. Studies show that the overall efficiency can be improved by pre-drying the coal, and the fluidized bed drying technique is found to be a desirable choice because of its high drying rate, high processing capacity, and low maintenance cost. In this paper, two novel, fluidized-bed, LRC pre-drying systems were integrated into a 1000 MW LRC-fired power plant. Superheated steam and hot air were used as the fluidizing medium. Models for each component of these power generation systems were developed based on material and energy balances. The performances of these power plants were calculated under the typical operating conditions, and parametric analyses were also performed to evaluate the effect of operating parameters. The power generation efficiency is found to increase remarkably with a properly operated LRC pre-drying system.

Keywords Coal drying; Fluidized-bed drying; Heat recovery; Low-rank coal; Power plant

INTRODUCTION

Low-rank coal (LRC), including lignite and sub-bituminous coal, occupies about 50% of the world’s coal reserve. LRC is usually easy to mine and its price is relatively low. In many regions of the world, LRC is the main fuel for electric power generation. However, the high moisture content of LRC (typically 30–60% on wet basis) leads to low heating value, low thermal efficiency in combustion, and high transportation cost. This characteristic restricts the widespread use of LRC. In a conventional LRC-fired power plant, raw coal is dried with hot flue gas aspirated from the furnace by fans or beater mills. After drying, the dried pulverized coal is entrained in the cooled flue gas and supplied to the combustion system. In such a case, a large amount of high-grade heat is consumed to remove the coal moisture, but it is difficult to utilize the latent heat of the water vapor in the flue gas. Heat loss of the exhaust gas is larger due to its high water vapor content. This causes a relatively low efficiency for a conventional power plant fueled with LRC. In addition to this, the direct use of high-moisture LRC also leads to larger equipment size, higher capital costs, higher operational costs, and higher emission of greenhouse gases. Using pre-dried LRC is found to be a good choice for solving these problems.

After decades of research and development, numerous technologies for LRC drying and dewatering are now available, such as rotary tube drying, fluidized bed drying, mechanical thermal dewatering (MTE), hydrothermal dewatering, solvent dewatering, etc. Although many of these newly developed drying methods have been proved to have extremely low energy consumption, most of them remain at the laboratory scale. The most commonly used driers for drying brown coal are the rotary drum type. However, considering energy consumption, construction costs, and processing capacity of the rotary-drum-type dryers, they are often still not economical enough to meet the large demands for coal-handling in a power plant.

Among these drying technologies, due to the high drying rate, high processing capacity, and low maintenance cost of fluidized bed drying, it offers a desirable choice for LRC drying. Experimental and theoretical investigations have been carried out by many researchers to study the drying process of LRC in fluidized beds. Diamond et al. and Calban et al. performed experimental studies on the effects of drying temperature, fluidizing gas velocity, particle size, bed height, and initial moisture concentration on the drying rate in batch hot-air-fluidized bed dryers. Potter et al. measured the heat transfer coefficient for brown coal in a steam-fluidized bed dryer. Chen et al. developed a model to simulate the continuous drying of coal in a superheated steam-fluidized bed dryer. Berghel reported an increase in drying efficiency by installing heating tubes in a spouted-bed, superheated steam dryer.

Correspondence: Defu Che, School of Energy and Power Engineering, Xi’an Jiaotong University, Xi’an 710049, China; E-mail: dfche@mail.xjtu.edu.cn

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dryer. Hoehne et al.[29] found that the overall heat transfer coefficient in a steam-fluidized bed dryer increased with increasing operating pressure.

As drying is an energy-consuming process, the cycle efficiency of a power plant can be significantly improved by the optimum choice of the drying process.[6] Several studies have been performed to evaluate the impact of LRC pre-drying on the performance of LRC-fired power plants. Kakaras et al.[30] carried out thermal energy analyses on power generation systems with integrated LRC pre-drying processes. Liu et al.[31] found that the efficiency of a lignite-fired power plant could be improved by 1.72%–1.87% when the coal moisture was reduced from 39.5% to 19.5% using a rotary-tube steam dryer. Sarunac[32] employed an air-fluidized bed dryer to reduce coal moisture content from 38.5% to 23.5% and found a 1.7% increase in net unit efficiency. In the Niederaussem K. Plant in Germany, 25% of input fuel was dried by low-pressure steam, and the latent heat of the vapor was recovered in a feed water heater, thus the power generation efficiency of the unit was increased by around 1%.[8]

Although many studies have demonstrated that the overall power generation efficiency can be improved by a fluidized-bed LRC pre-drying system, less research has been done concerning the effects of drying medium, heating source, and operating parameters on the overall power generation efficiency. These are essential factors in the optimization design of an LRC pre-drying power generation system. The objective of the present work is to conduct an energy analysis to examine the performance of a large-scale power plant with different fluidized-bed LRC pre-drying systems. A parameter analysis will be performed to evaluate the effects of operating parameters and waste heat recovery on the overall power generation efficiency. The results of this study might be helpful for providing guidance for the design of an effective LRC pre-drying power plant.

SYSTEM DESCRIPTION

Two novel, supercritical, pulverized LRC-fired power generation systems with fluidized bed LRC pre-drying are studied in this paper. Hot air or superheated steam is used as the fluidizing medium. An immersed heater is employed in the dryer to provide part of the heat for coal drying. Extraction steam from the steam turbine is used as the heat source for drying. The employment of the immersed heater can increase the drying rate, reduce the flow rate of the fluidizing medium, and consequently reduce the operation cost of the LRC pre-drying system. The conventional and the pre-drying power plants will be introduced in the following sections.

Conventional Power Plant

Figure 1 shows a typical schematic diagram of a conventional, supercritical pulverized power plant. The main steam from the boiler is expanded in the high-pressure (HP) turbine, then reheated in the boiler, further expanded in the intermediate-pressure (IP) and low-pressure (LP) turbines, then condensed in the condenser, and finally returned to the boiler as water. Boiler feed water is heated by four low-pressure feed water heaters (Nos. 1–4), one deaerator (No. 5), and three high-pressure feed water heaters (Nos. 6–8). Extraction steam from the steam turbine provides the heat for the feed water heaters. The boiler feed pump is driven by a small steam turbine.

![FIG. 1. Configuration of a conventional power plant.](image-url)
In this conventional LRC power station, mill drying is used. Coal is milled and dried simultaneously in the beater mills. Recycling of high-temperature furnace gas is used to evaporate the large amount of moisture in the coal.

Power Plant with Superheated Steam-Fluidized Bed Drying
Figure 2 shows the power plant with a superheated steam-fluidized bed pre-drying system. The pre-drying system is composed of a fluidized bed dryer with an immersed heat exchanger, a precipitator, heat-recovery equipment, and the auxiliary equipment, such as the fans and pipelines.

In the superheated steam-fluidized bed drying system, the exhaust gas from the dryer is approximately pure water vapor. A part of the exhaust gas is recycled as the fluidizing medium through the recirculation fan. The recycled steam can only obtain a finite enthalpy rise after passing through the recirculation fan. Heat provided by the fluidized steam accounts for merely a small proportion, which is negligible. The heat for drying is mainly supplied to the fluidized bed through steam condensing in the immersed heater. Heating steam is extracted from the low-pressure (LP) steam turbine in the steam cycle. Condensate from the immersed heater returns to the steam cycle. The immersed heater provides most of the heat for the drying process.

Part of the latent heat of the exhaust gas is recovered in the waste heat exchanger for heating part of the feed water from the condenser. The extraction steam requirement for feed water heaters Nos. 1 and 2 can be reduced by the employment of exhaust heat recovery.

Power Plant with Hot-Air-Fluidized Bed Drying
Figure 3 shows the power plant with a hot-air-fluidized bed pre-drying system. The pre-drying system is composed
of a fluidized bed dryer with an immersed heater, a precipitator, an air heater for raising the temperature of fluidizing air, and the auxiliary equipment, such as the fans and pipelines.

Ambient air passes through the air heater to raise the temperature. Hot air is not only used as the fluidized medium of the dryer, but also simultaneously provides part of the drying heat. The immersed heater in the dryer can provide additional heat for drying, which can improve the drying rate. The heat for the air heater and the immersed heater is provided by steam condensing. Heating steam is extracted from the low-pressure (LP) steam turbine in the steam cycle. Condensate from the heaters returns to the steam cycle.

The exhausted gas from the dryer is a mixture of air and water vapor, and the saturation temperature of the vapor is very low (about 45°C). Hence, it is not economical to recover the waste heat of the exhausted gas.

For the sake of safety, the temperature of the air entering the dryer should not be too high, and some additional safety measures should be used to reduce the hazard of spontaneous combustion or exploration.[33]

MODELS

Based on material balance, energy balance, and together with some assumptions, models for each component of the above-mentioned systems are developed. Then, the method for calculating the overall efficiency of the power plant is introduced.

General Assumptions

In order to assess the performance of each system on a consistent basis, some common assumptions are made in the simulations for all three power generation systems. These assumptions are for the convenience of comparison; they will not affect the results of our simulations.[30,31,34,35]

1. The mass flow rates of the main steam for all study cases are kept unchanged.
2. The parameters of the steam cycle and the internal efficiency of the steam turbine are identical.
3. Heat loss and steam leakage in the steam cycle are ignorable.
4. The excess air coefficient and the boiler exit flue gas temperature at the outlet of air preheater are not changed.
5. The boiler heat losses remain the same, except for the heat loss due to the exhaust gas.
6. Power consumption of the auxiliary equipment remains unchanged and is negligible.

Ultimate Analysis and Heat Value of the Coal to be Dried

The drying process only changes the moisture content of LRC, and the element composition on the dry basis remains unchanged. A constituent content of LRC after the drying process can be calculated by

$$X_{\text{dry}} = X_{\text{ar}} \cdot \frac{100 - M_{\text{dry}}}{100 - M_{\text{ar}}}$$

where $X_{\text{dry}}$ is the constituent content of LRC after the drying process, $X_{\text{ar}}$ is the constituent content of LRC on the as-received basis, $M_{\text{dry}}$ is the moisture content (wet basis) after the drying process, $M_{\text{ar}}$ is the moisture content (wet basis) on the as-received basis.

Reducing the moisture content by thermal drying can increase the heat value of LRC. The available chemical energy of the fuel may be quantified using either the higher heating value (HHV) or the lower heating value (LHV). The overall efficiency of a power plant based on the fuel LHV will be higher than that on HHV.[8] In this study, fuel calorific values and efficiencies are given on the basis of HHV. The HHV of the dried coal can be obtained by the following equation:

$$Q_{\text{HHV,dry}} = Q_{\text{HHV,ar}} \cdot \frac{100 - M_{\text{dry}}}{100 - M_{\text{ar}}}$$

where $Q_{\text{HHV,dry}}$ is the HHV of the coal after the drying process, and $Q_{\text{HHV,ar}}$ is the HHV of the coal on the as-received basis.

Boiler

The model of the boiler is shown in Fig. 4. A heat balance equation of the boiler can be written as follows:

$$Q_{\text{in}} = Q_1 + Q_2 + Q_3 + Q_4 + Q_5 + Q_6$$

where $Q_{\text{in}}$ is the heat entering the boiler, $Q_1$ is the heat absorption of water and steam in the boiler, $Q_2$ is the heat loss due to exhaust gases, $Q_3$ is the heat loss due to unburned gaseous combustibles, $Q_4$ is the heat loss due to unburned solid combustibles, $Q_5$ is the heat loss due to unburned solid combustibles, and $Q_6$ is the heat loss due to unburned solid combustibles.
to radiation and convection, \( Q_6 \) is the other heat loss of the boiler. The value of \( Q_2 \) can be calculated from the properties of the coal and the operating conditions of the boiler, and recommended values of \( Q_3/Q_6 \) are available.\[36\] Thus the value of \( Q_1 \) can be obtained by the following equation:

\[
Q_1 = Q_{in} - (Q_2 + Q_3 + Q_4 + Q_5 + Q_6) \tag{4}
\]

The thermal efficiency of the boiler is defined as

\[
\eta_B = \frac{Q_1}{Q_{in}} \times 100, \%
\tag{5}
\]

The heat absorption of water and steam in the boiler can also be obtained by

\[
Q_1 = D_{fw} \cdot (h_0 - h_t) + D_{rh} \cdot \sigma_{rh}
\tag{6}
\]

where \( D_{fw} \) is the flow rate of the feed water, \( h_0 \) is the enthalpy of the main steam, \( h_t \) is the enthalpy of the boiler feed water, \( D_{rh} \) is the flow rate of the reheat steam, \( \sigma_{rh} \) is the enthalpy rise of the steam passing through the re heater.

The dry coal consumption rate can be calculated by

\[
B_{dry} = \frac{Q_1}{(Q_{HHV, dry} \cdot \eta_B)}
\tag{7}
\]

The fuel consumption rate of the as-received coal is defined as

\[
B_{ar} = B_{dry} \cdot \frac{100 - M_{dry}}{100 - M_{ar}}
\tag{8}
\]

**Feed Water Heaters**

There are two kinds of feed water heaters in the feed water heating network. One is the mixing type, which is often used as the deaerator. As shown in Fig. 5, extraction steam from the turbine directly joins the feed water to raise the feed water temperature. The other is the surface type. As shown in Fig. 6, extraction steam from the turbine condenses and heats the feed water without mixing with it. The condensate of the heating steam of a surface-type feed water heater flows into the next heater with lower extraction steam pressure. The flow rate of heating steam of the feed water (streams (i) in Figs. 5 and 6) can be calculated using the heat and mass balance method provided in Lin.\[37\] For the mixing-type feed water heater,

\[
D_{s(i)} = \frac{D_{t(i)} \cdot [h_{i(i)} - h_{i(i-1)}] - D_{s(i)} \cdot [h_{ts(i+1)} - h_{ts(i)}]}{h_{s(i)} - h_{ts(i)}}
\tag{9}
\]

For the surface-type feed water heater,

\[
D_{s(i)} = \frac{D_{t(i)} \cdot [h_{i(i)} - h_{i(i-1)}] - D_{s(i)} \cdot [h_{ts(i+1)} - h_{ts(i)}]}{h_{s(i)} - h_{ts(i)}}
\tag{10}
\]

where \( D \) is the mass flow rate of a stream, and \( h \) is the specific enthalpy of a stream. The subscripts “s,” “t,” or “ts” identify the specified stream which is presented in Figs. 5 and 6. The flow rate of the extraction steam for each feed water heater can be calculated from No. 8 to No. 1 sequentially using Eqs.(9) and (10).

**Drier**

Moisture removed from the wet coal during the drying process can be calculated by

\[
M_{evap} = B_{ar} \cdot \left(1 - \frac{100 - M_{ar}}{100 - M_{dry}}\right)
\tag{11}
\]

**Superheated Steam-Fluidized Bed Dryer**

The model of a superheated steam-fluidized bed dryer is shown in Fig. 7. Temperature rise of the recycled steam passing through the recycle fan is limited. Thus the fluidized medium provides only a minor part of the heating
duty for the drying process, and it is negligible compared to that provided by the immersed heater. The amount of the extraction steam required for the superheated steam-fluidized bed dryer can be calculated by

\[
D_{\text{dry}} = \frac{I_{\text{DC}} + I_{\text{WV}} - I_{\text{WC}}}{h_{S,\text{dry}} - h_{S,\text{dry}}} \tag{12}
\]

where \( I_{\text{DC}} \) is the enthalpy of the dry coal leaving the dryer, \( I_{\text{WV}} \) is the enthalpy of the water vapor leaving the dryer, and \( I_{\text{WC}} \) is the enthalpy of the wet coal entering the dryer.

**Hot-Air-Fluidized Bed Dryer**

The model of a hot-air-fluidized bed dryer is shown in Fig. 8. Steam flow rate of the air heater can be calculated by

\[
D_{\text{dry, AH}} = \frac{I_{\text{HA}} - I_{\text{CA}}}{h_{S,\text{dry}} - h_{S,\text{dry}}} \tag{13}
\]

where \( I_{\text{HA}} \) is the enthalpy of the hot air leaving the air heater, and \( I_{\text{CA}} \) is the enthalpy of the cold air entering the air heater.

The flow rate of the steam in the immersed heater can be calculated by

\[
D_{\text{dry, IH}} = \frac{I_{\text{DC}} + I_{\text{EG}} - I_{\text{HA}}}{h_{S,\text{dry}} - h_{S,\text{dry}}} \tag{14}
\]

where \( I_{\text{EG}} \) is the enthalpy of the exhaust gas at the outlet of the dryer.

The flow rate of heating steam for the hot-air-fluidized bed dryer can be calculated as follows:

\[
D_{\text{dry}} = D_{\text{dry, AH}} + D_{\text{dry, IH}} \tag{15}
\]

**Power Output**

The power output of the steam turbine can be calculated by

\[
W = \sum D_i \cdot (h_0 - h_i) + \sum D_j \cdot (h_0 + \sigma_{\text{rh}} - h_j) + D_{\text{pump}} \cdot (h_0 + \sigma_{\text{rh}} - h_{\text{pump}}) + D_{\text{con}} \cdot (h_0 + \sigma_{\text{rh}} - h_{\text{con}}) + D_{\text{dry}} \cdot (h_0 + \sigma_{\text{rh}} - h_{\text{dry}}) \tag{16}
\]

where \( D_i \) is the flow rate of the extraction steam without reheating, \( D_j \) is the flow rate of extraction steam that has been reheated, \( D_{\text{pump}} \) is the flow rate of the extraction steam for the main feed water pump turbine, and \( D_{\text{con}} \) is the flow rate of steam entering the condenser.

**Efficiency**

The efficiency of the steam turbine cycle is defined as

\[
\eta_0 = \frac{W}{Q_1} \tag{17}
\]

The overall efficiency of the power generation system is defined as

\[
\eta = \eta_0 \cdot \eta_B \cdot \eta_P \cdot \eta_M \cdot \eta_{\text{GEN}} \tag{18}
\]

where \( \eta_B \) is the insulation efficiency of the pipeline, \( \eta_M \) is the mechanical efficiency of the turbine, and \( \eta_{\text{GEN}} \) is the electric generator efficiency.
RESULTS AND DISCUSSION

In order to evaluate the performance of the power plants with pre-drying systems, calculations were conducted using the above-mentioned models. Calculations under typical operating conditions were carried out for each plant. The effects of drying degree and heating steam parameters on the efficiency of the power plant were studied. The performance of the power plant with a hot-air pre-drying system at different exhaust gas temperatures was also studied. In addition, the influence of heat recovery on the superheated steam pre-drying power plant was investigated. The results will be presented and discussed in the following.

Power Plant Performances under Typical Operating Conditions

Tables 1 and 2 present the calculation details of the typical operating condition. Table 1 lists the main parameters, Table 2 lists the parameters of the feed water heater network. Brown coal with moisture content (wet basis) of 45% on an as-received basis is employed in the study. The ultimate analysis and HHV of the coal are shown in Table 3. In typical operating conditions, final moisture content (wet basis) of the dried coal is specified to be 25%.

Reasonable operating conditions for each pre-drying system should be applied according to the corresponding drying characteristics of LRC. In order to maintain the steam atmosphere in the superheated steam-fluidized bed dryer, its temperature should be kept above 100°C. In contrast, hot-air drying can be performed at a much lower temperature. The temperature difference between the coal particle and the immersed heater should be large enough to keep the drying rate at an acceptable level. The main operating conditions of the superheated steam and the hot-air pre-drying systems are listed in Tables 4 and 5, respectively.

For the sake of comparison, performance of a conventional power plant using external dried LRC is studied. In this case, wet coal is first dried in a separate facility and then delivered to the plant. The heat consumption associated with coal drying is not considered in the analysis of power plant efficiency, therefore the maximum efficiency can be achieved by using external drying.

Calculation results for the typical operating conditions of different power generation systems are summarized in Table 6. By reducing the moisture content (wet basis) from 45% to 25%, HHV of the brown coal increases from 12.758 MJ to 17.397 MJ, and the thermal efficiency of the boiler based on the HHV increases from 78.59% to 84.24%. Moreover, the use of an LRC pre-drying process leads to a reduction of 6.5% of the flow rate of the raw coal.

Extraction steam reduces the efficiency of the steam cycle for both superheated steam and hot-air pre-drying systems.

---

**TABLE 1**

Main parameters of the typical operating conditions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main steam flow rate, kg/s</td>
<td>721.9</td>
</tr>
<tr>
<td>Main steam parameters</td>
<td>24.8 MPa/600°C</td>
</tr>
<tr>
<td>Boiler feed water parameters</td>
<td>30.3 MPa/289°C</td>
</tr>
<tr>
<td>Steam parameters before reheating</td>
<td>5.6 MPa/364°C</td>
</tr>
<tr>
<td>Reheated steam parameters</td>
<td>5.1 MPa/600°C</td>
</tr>
<tr>
<td>Turbine exhaust steam parameters</td>
<td>4.4 kPa/2315 kJ/kg</td>
</tr>
<tr>
<td>Excess air ratio of boiler</td>
<td>1.15</td>
</tr>
<tr>
<td>Environment temperature, °C</td>
<td>20</td>
</tr>
<tr>
<td>Flue gas exit temperature (after the air preheater), °C</td>
<td>150</td>
</tr>
<tr>
<td>Heat loss due to unburned gaseous combustibles $Q_3$</td>
<td>0</td>
</tr>
<tr>
<td>Heat loss due to unburned solid combustibles $Q_4$</td>
<td>0.01 × $Q$</td>
</tr>
<tr>
<td>Heat loss due to radiation and convection $Q_5$</td>
<td>0.003 × $Q$</td>
</tr>
<tr>
<td>Other heat loss of boiler $Q_6$</td>
<td>0.002 × $Q$</td>
</tr>
<tr>
<td>Heat-supply pipe efficiency</td>
<td>99%</td>
</tr>
<tr>
<td>Mechanical efficiency of the steam turbine</td>
<td>99.5%</td>
</tr>
<tr>
<td>Generator efficiency</td>
<td>99%</td>
</tr>
</tbody>
</table>

**TABLE 2**

Parameters of the feed water heater network

<table>
<thead>
<tr>
<th>Feed water heater</th>
<th>Heating steam enthalpy (kJ/kg)</th>
<th>Drain water enthalpy (kJ/kg)</th>
<th>Inlet feed water enthalpy (kJ/kg)</th>
<th>Outlet feed water enthalpy (kJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2487.3</td>
<td>152.6</td>
<td>128.3</td>
<td>248.2</td>
</tr>
<tr>
<td>2</td>
<td>2619.3</td>
<td>270.5</td>
<td>248.2</td>
<td>344.2</td>
</tr>
<tr>
<td>3</td>
<td>2842.2</td>
<td>–</td>
<td>344.2</td>
<td>506.3</td>
</tr>
<tr>
<td>4</td>
<td>3035.8</td>
<td>529.6</td>
<td>506.3</td>
<td>647.1</td>
</tr>
<tr>
<td>5</td>
<td>3192.7</td>
<td>–</td>
<td>647.1</td>
<td>764.0</td>
</tr>
<tr>
<td>6</td>
<td>3390.6</td>
<td>814.0</td>
<td>803.8</td>
<td>928.5</td>
</tr>
<tr>
<td>7</td>
<td>3091.3</td>
<td>944.6</td>
<td>928.5</td>
<td>1179.8</td>
</tr>
<tr>
<td>8</td>
<td>3156.1</td>
<td>1211.3</td>
<td>1179.8</td>
<td>1272.6</td>
</tr>
</tbody>
</table>
systems. The efficiency of the steam cycle with superheated steam-fluidized bed pre-drying is found to be slightly lower than that with hot-air pre-drying. This is because the superheated steam-fluidized bed pre-drying uses higher condition steam as the heat source of the immersed heater.

In Table 6, the electricity generation decreases from 950 MW to 913.21 MW and to 919.49 MW for the superheated steam and the hot-air pre-drying power plant, respectively. Improvements of the overall efficiency for the superheated steam and the hot-air pre-drying power plants are 1.16% and 1.43%, respectively. It should be noted that the most significant efficiency increase takes place in the power plant using external LRC drying. But this is only because the energy consumption of the external coal drying is not considered in the calculation.

Effect of Drying Degree

Performances of the above-mentioned pre-drying power plants with different drying degree (varying from 40%–10%) are analyzed to illustrate the influence of drying degree on the overall efficiency of these plants. Figure 9 shows the variations of coal HHV and boiler efficiency with coal moisture content. It can be seen that the HHV increases linearly as coal moisture content decreases. The boiler efficiency increases from 80.35% to 86.83% (HHV basis) when the coal moisture content decreases from 40% to 10%. The reason is that the heat loss of the boiler due to exhaust gas decreases with decreasing coal moisture content. Figure 10 shows the overall efficiency against coal moisture reduction for different pre-drying power generation systems. It can be seen that the overall efficiencies of the power plants are increased linearly as coal moisture content is reduced. The efficiency with hot-air-fluidized bed drying is slightly higher than that with superheated steam-fluidized bed drying. The calculated values of the power plant efficiency in Fig. 10 are comparable with the results of Ref.[32].

Effect of Extraction Steam Parameters

In this study, extraction steam from the steam turbine provides the heat duty during the drying process. Performances of the power plants with different extraction steam parameters are calculated to study the influence of extraction steam parameters. For superheated steam drying, the pressure of the extraction steam is set equal to that of feed water heater Nos. 4, 5, and 6, respectively, and in contrast, for the hot-air drying, which is Nos. 3, 4, and 5, respectively. Figures 11 and 12 present the effects of the extraction steam parameters on the efficiency of power plants with superheated steam and hot-air drying, respectively. The results show that the overall efficiency becomes lower with

<table>
<thead>
<tr>
<th>Table 3</th>
<th>Ultimate analysis and HHV of the LRC on an as-received basis</th>
</tr>
</thead>
<tbody>
<tr>
<td>C (wt.%)</td>
<td>H (wt.%)</td>
</tr>
<tr>
<td>32.49</td>
<td>2.32</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 4</th>
<th>Parameters of superheated steam-fluidized bed pre-drying system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture content in the dried LRC, (%, wet basis)</td>
<td>25</td>
</tr>
<tr>
<td>Temperature of the dryer exhaust gas, °C</td>
<td>110</td>
</tr>
<tr>
<td>Parameters of heating steam of the immersed heater</td>
<td>0.56 MPa / 3035.8 kJ/kg</td>
</tr>
<tr>
<td>Parameters of condensate of the immersed heater</td>
<td>126.0°C / 529.6 kJ/kg</td>
</tr>
<tr>
<td>Waste heat recovery of dryer exhaust gas</td>
<td>Not Applied</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 5</th>
<th>Parameters of hot-air-fluidized bed pre-drying system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture content in the dried LRC, (%, wet basis)</td>
<td>25</td>
</tr>
<tr>
<td>Temperature of the dryer inlet air, °C</td>
<td>120</td>
</tr>
<tr>
<td>Temperature of the dryer exhaust gas, °C</td>
<td>60</td>
</tr>
<tr>
<td>Static bed height in the dryer, m</td>
<td>0.5</td>
</tr>
<tr>
<td>Superficial velocity of particles, m/s</td>
<td>3</td>
</tr>
<tr>
<td>Mean residence time</td>
<td>300</td>
</tr>
<tr>
<td>Parameters of heating steam of the air heater</td>
<td>0.22 MPa / 2842.2 kJ/kg</td>
</tr>
<tr>
<td>Parameters of condensate of the air heater</td>
<td>87.6°C / 366.9 kJ/kg</td>
</tr>
<tr>
<td>Parameters of heating steam of the immersed heater</td>
<td>0.22 MPa / 2842.2 kJ/kg</td>
</tr>
<tr>
<td>Parameters of condensate of the immersed heater</td>
<td>87.6°C / 366.9 kJ/kg</td>
</tr>
</tbody>
</table>
higher extraction steam pressure. Similar results were obtained in Refs. [30,32]. As long as the drying duty can be met, low-extraction steam pressure is preferred to guarantee high power plant efficiency.

**Effect of Exhaust Temperature**

Figure 13 shows the effect of exhaust temperature on the efficiency of a power plant using hot-air drying. The results show that the power plant efficiency decreases with the increase of the exhaust temperature. When the exhaust temperature drops from 80°C to 60°C, the efficiency rises about 0.1%. This trend is not affected as the moisture reduction varies from 0.1 to 0.3 kg/kg. It can therefore be concluded that changing the exhaust gas temperature from 80°C to 60°C shows no significant effect on the overall efficiency of the power plant. On the other hand, a rise in the exhaust temperature may increase the drying rate remarkably and may further result in reduction of capital investment and operating cost. The exhaust

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**TABLE 6**
Calculation results for the typical operating conditions

<table>
<thead>
<tr>
<th></th>
<th>Conventional LRC power plant</th>
<th>Superheated steam FBD power plant</th>
<th>Hot-air FBD power plant</th>
<th>Power plant with external LRC drying</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture content (%)</td>
<td>45</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>HHV, MJ</td>
<td>12.758</td>
<td>17.397</td>
<td>17.397</td>
<td>17.397</td>
</tr>
<tr>
<td>Boiler efficiency $\eta_B, %$</td>
<td>78.59</td>
<td>84.24</td>
<td>84.24</td>
<td>84.24</td>
</tr>
<tr>
<td>Flow rate of raw coal, kg/s</td>
<td>194.04</td>
<td>181.35</td>
<td>181.35</td>
<td>181.35</td>
</tr>
<tr>
<td>Steam cycle efficiency $\eta_i, %$</td>
<td>49.79</td>
<td>47.87</td>
<td>48.19</td>
<td>49.79</td>
</tr>
<tr>
<td>Electricity generated, MW</td>
<td>950.00</td>
<td>913.21</td>
<td>919.49</td>
<td>950.00</td>
</tr>
<tr>
<td>Overall efficiency $\eta, %$</td>
<td>38.16</td>
<td>39.32</td>
<td>39.59</td>
<td>40.90</td>
</tr>
</tbody>
</table>

![FIG. 9](image9.png)

**FIG. 9.** Coal HHV and boiler efficiency as a function of coal moisture content.

![FIG. 10](image10.png)

**FIG. 10.** Effect of coal moisture reduction on power plant efficiencies with different pre-drying systems.

![FIG. 11](image11.png)

**FIG. 11.** Effect of extract steam parameters on the efficiency of a power plant with superheated steam pre-drying.
temperature should therefore be chosen with caution when designing an LRC pre-drying system.

**Effect of Heat Recovery**

For the superheated steam-drying process, latent heat in the exhaust gas can be recovered by heating a part of the feed water from the condenser. The exhaust gas amount is small at a low degree of drying (0.1 kg\/kg); recovering all the latent heat of the exhaust gas is only enough to heat 40% of the feed water. At a higher degree of LRC drying, the available latent heat and subsequently the heated feed water amount will be larger. When the coal moisture reduction value exceeds about 0.2 kg\/kg, all feed water can be heated, and the extraction steam for the feed water heaters Nos.1 and 2 can be cancelled. Even then, a substantial part of the energy remains unused, and the excess water vapor has to be discharged into the environment. Figure 14 shows the ratios of heated feed water amount to the total feed water amount and the recovery rate of waste heat in the exhaust gas versus coal moisture reduction value. Figure 15 shows the effect of heat recovery on the efficiency of a power plant with superheated steam drying. An overall efficiency increase of about 0.35% can be achieved by recovering the latent heat of the water vapor in the exhaust gas.
CONCLUSIONS

In this study, LRC pre-drying power generation systems were designed based on a conventional power plant with a capacity of 1000 MW, models for each component of these power generation systems were developed based on material and energy balances, and calculations based on these models were conducted to evaluate the performances of these power plants. The main conclusions of this work can be drawn as follows:

1. By pre-drying the LRC to a 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.
2. 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 varies from 40% to 10%.
3. Using higher extraction steam parameters in the immersed heater can cause a lower overall efficiency.
4. Changing the exhaust gas temperature has a weak effect on the overall efficiency of the power plant with hot-air pre-drying.
5. Recovering the latent heat of the exhaust water vapor brings about a 0.35% increase in the overall efficiency for the superheated steam pre-drying power plant.

NOMENCLATURE

- $B_{ar}$: Fuel consumption rate of the as-received coal
- $B_{dry}$: Dry coal consumption rate
- $D$: Mass flow rate
- $D_{dry}$: Amount of the extraction steam required for the dryer
- $D_{dry, AH}$: Flow rate of the steam in the air heater
- $D_{dry, IH}$: Flow rate of the steam in the immersed heater
- $D_{fw}$: Flow rate of the feed water
- $D_{rh}$: Flow rate of the reheat steam
- $h$: Specific enthalpy of steam
- $h_0$: Enthalpy of the main steam
- $h_f$: Enthalpy of the boiler feed water
- $I_{CA}$: Enthalpy of the cold air entering the air heater
- $I_{DC}$: Enthalpy of the dry coal leaving the dryer
- $I_{EG}$: Enthalpy of the exhaust gas at the outlet of the dryer
- $I_{HA}$: Enthalpy of the hot air leaving the air heater
- $I_{WC}$: Enthalpy of the wet coal entering the dryer
- $I_{WV}$: Enthalpy of the water vapor leaving the dryer
- $M_{ar}$: Moisture content on an as-received basis
- $M_{dry}$: Moisture content after the drying process
- $M_{evap}$: Moisture removed from the wet coal during the drying process
- $Q_1$: Heat absorption of water and steam in the boiler
- $Q_2$: Heat loss due to exhaust gases
- $Q_3$: Heat loss due to unburned gaseous combustibles
- $Q_4$: Heat loss due to unburned solid combustibles
- $Q_5$: Heat loss due to radiation and convection
- $Q_6$: Other heat loss of the boiler
- $Q_{HHV, ar}$: HHV of the coal on an as-received basis
- $Q_{HHV, dry}$: HHV of the coal after the drying process
- $Q_m$: Heat entering the boiler
- $X_{ar}$: A constituent content of LRC on an as-received basis
- $X_{dry}$: A constituent content of LRC after the drying process
- $W$: Power output of the steam turbine

Greek Letters

- $\eta_0$: Efficiency of the steam cycle
- $\eta_B$: Thermal efficiency of the boiler
- $\eta_{GEN}$: Electric generator efficiency
- $\eta_M$: Mechanical efficiency of the turbine
- $\eta_P$: Insulation efficiency of the pipeline
- $\sigma_{rh}$: Enthalpy rise of the steam passing through the reheater

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REFERENCES


