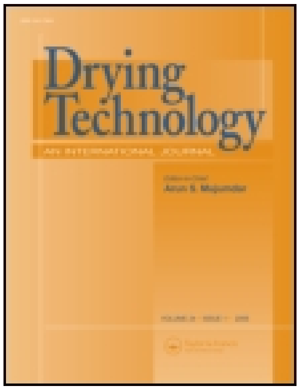

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Theoretical Study and Case Analysis for a Predried Lignite-Fired Power System

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Lignite is a type of low-rank coal, which is uneconomically transported over long distances and does not efficiently generate electricity. As a result, lignite utilization and application is very limited; lignite is mainly used as a low-level fuel that generates electricity inefficiently and can be distributed only in areas near lignite mines. With increasing requirements in efficiency and environmental protection, studying a new lignite-fired power system to improve the efficiency of direct lignite-fired power plants is very important. A rotary-tube dryer is mature drying equipment used in a pre-dried lignite-fired power system (PLPS). However, a comprehensive model approach on the influence of PLPS parameters on power generation efficiency and optimization has not been previously investigated. In the current paper, a PLPS theoretical model was developed based on basic thermal principles, and a case analysis was performed using this model as the theoretical foundation. Parameter influence was also calculated and analyzed. Results show that the PLPS theoretical model can evidently increase the efficiency of a conventional lignite-fired power system (CLPS) by approximately 1.87% when the condensate is sent to the de-aerator, and by 1.72% when the condensate is sent to the condenser at the calculation benchmark condition listed in this paper.

Keywords Case analysis; Energy analysis; Lignite-fired power system; Mathematical modeling; Rotary-tube dryer

INTRODUCTION

Lignite is a type of low-rank coal, and it has high moisture content (20%–50%), high ash content (6%–25%), lower heating value (10,000–21,000 kJ/kg on an as-received basis), and high volatile content (40%–50% on a dry and ash-free basis).[1] Lignite is considered undesirable because its high moisture content entails high transportation costs, potential safety hazards during transportation and storage, and low thermal efficiency during combustion. However, lignite is a competitive primary energy source for power generation. Lignite is cheaper than bituminous coal because the price of coal depends on heating value and the demand for bituminous coal is increasing because a number of coal-fired power plants are being constructed, especially in China.[2]

Chinese lignite has vast reserves that exceed 130 billion tons, accounting for more than 13% of the total national coal in China, which is distributed mainly in Inner Mongolia and Northeast China. Chinese lignite is primarily used to generate electricity near the mining origin; however, a lignite-fired power plant unfortunately has very low efficiency. Because of high moisture content in lignite, the energy consumed in pulverizing lignite is higher than that in pulverizing bituminous coal; boiler fans also use up more energy since more flue gases must be transported. The efficiency of a lignite-fired boiler is generally lower than 91%, and the boiler always costs more than a bituminous-fired boiler because it is larger for a greater amount of flue gases.

A number of attempts have been undertaken to fire lignite effectively and meet the increasing requirements in efficiency and environmental protection. Reduced moisture content of coal increases the efficiency of power plants, decreases transportation costs, decreases ash disposal requirements, and decreases power plant emissions.[3] Lignite pre-drying before combustion is considered an effective way to increase power system efficiency, which will offer large economic benefits for the power plant.

Several studies aiming at lignite drying have been conducted by previous researchers. Much research has been conducted on coal drying methods, such as rotary drying, fluid bed drying, mechanical-thermal dewatering, and so on. Some researchers studied dried lignite characteristics, e.g., moisture re-absorption,[4] mesopore structure,[5,6] combustion behavior,[7,8] and so on. In addition, analysis of PLPS always uses a computer simulation method.[9] However, a comprehensive model approach for studying the influence of PLPS parameters on power generation

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efficiency, which is very important in designing an effective dryer and an efficient lignite-fired power system, has not been located in the literature.

In the present study, a simplified theoretical model for studying the incorporation of a rotary-tube dryer in a conventional lignite-fired power plant was established, which allows for a comprehensive investigation of the operation and the structure parameters of the power plant in relation to the impact of lignite pre-drying to the overall electricity generation efficiency. It is a simple but effective tool for the feasibility study of a conventional lignite-fired power plant revamp or of a novel, pre-dried, lignite-fired, power plant design. A case calculation was also involved in the current paper, and the influence of the dryer parameters on generation efficiency was analyzed. Inevitably, the calculation results can provide strong guidance on dryer and pre-dried lignite-fired power plant designs.

PRE-DRIED LIGNITE-FIRED POWER SYSTEM

Rotary-Tube Dryer

Indirect and direct dryers can all be used in lignite drying. Indirect dryers are those in which the heating medium does not come in contact with the product being dried, whereas the heating medium in direct dryers directly comes in contact with the product being dried. Steam, hot gas, and thermal fluid can all be used as the heating medium. However, dryers used in lignite-fired power plants have to be safe, dependable, and efficient because lignite is combustible during the drying progress, the dryer should run continuously in power plants, and the incorporation of a dryer in lignite-fired power plants should have high thermal economics.

A rotary dryer is a mature type of direct dryer, and the drying medium used is hot air or combustion gases. Residence time and drying temperature are the most important factors influencing drying progress. Hatzilyberis et al. studied the residence time distribution (RTD) in rotary dryers to investigate the flow of lignite particles both in a bare drum[10] and in a flighted drum;[11] moreover, they provided the design aspects of rotary dryers.[12] Mean residence time, space-time, and solid hold-up were correlated with the operating conditions of the drum in their research, which is a basic theory in designing rotary dryers; temperature profiles along the dryer length, the amount of evaporation (moisture conversion), and the solids residence time distribution were measured in their research, too. Fluidized bed dryers using steam or hot gas as the heating (and fluidizing) medium are widely applicable for lignite drying and have attracted a number of researchers. The basic principles of lignite drying in a fluidized bed are currently being studied[13–19] through theoretical and experimental methods. The steam equilibrium moisture content of coals is related to the degree of superheat by a simple equation by Bongers et al.[13]; they also investigated the shrinkage of brown coal during high pressure steam drying and the physical structure of the product.[14] Chen et al.[15,16] developed a single-particle model and the operation of a fluidized bed drying unit model for steam fluidized bed drying of coal. Calban et al.[17] investigated the drying of a Turkish lignite in a batch fluidized bed, and observed that the drying rate increased with the decrease in bed height. In addition, the equilibrium moisture content, and the time it took to reach the equilibrium moisture content, decreased with decreasing initial moisture concentration.[18] Hoehne et al.[19] studied the basic principles of lignite drying in a pressurized steam fluidized bed. They found that dewatering by mechanical thermal expression (MTE) is effective for drying lignite,[20–22] which has low heat consumption because the water is not evaporated during the drying progress. Different kinds of lignite were dried using the MTE method, and the dewatering kinetics was investigated.

Rotary dryers are widely used in industrial drying; however, they are restricted to lignite drying to avoid possible ignition. Fluidized bed dryers are not dependable enough because they have not been successfully and maturely used in lignite-fired power plants. MTE was also studied only in a laboratory scale. Rotary-tube dryers are indirect dryers heated by steam at pressures of 0.15–0.55 MPa.[23] As mature dryers utilized in industries, rotary-tube dryers have low drying temperatures not exceeding 150°C, which avoids spontaneous lignite combustion. They also have lower heat consumption than rotary dryers.

Rotary-tube dryers were used in the PLPS examined in the current paper. The rotary-tube dryer consist of a drum,

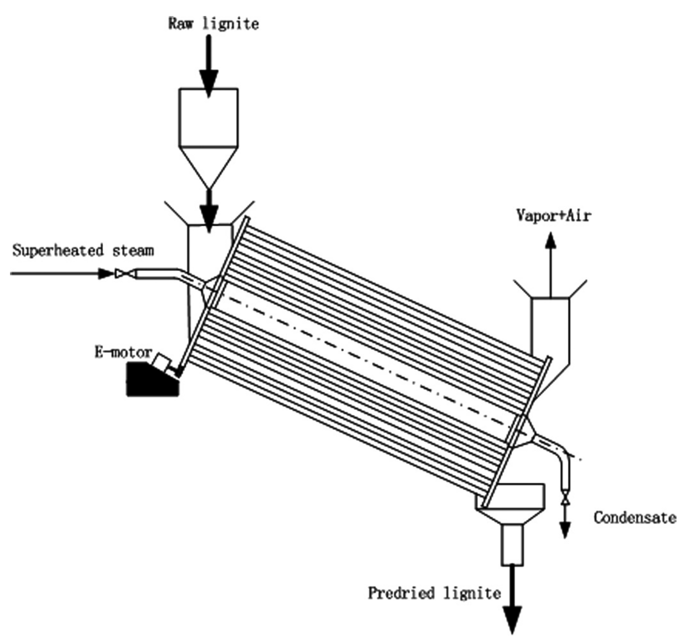

FIG. 1. Schematic of rotary-tube dryer.

TABLE 1
Some technical data for the rotary-tube dryers[23]

Diameter	2500, 2800, 3130, 3350, 3750, and 4000 mm
Drum length	7~8 m
Angle of inclination of drum	about 8°C
Speed of rotation	5~9 rpm
Drying rate per unit exposed surface	5.4~8 kg/(m^2 · h)
Temperature of vapor	90°C
Coal temperature at outlet	80°C
Heat consumption:	2950~3100 kJ/kg H_2O
Dust content in vapor in drying of brown coal	about 25 g/m^3

formed by a slightly inclined rotary system, which rotates during the drying process (Figure 1). Raw lignite is continually fed into the dryer tubes and transported to the exit by the rotary motion. The energy required for the moisture to evaporate out of lignite is provided by steam extraction of the regenerative system. The steam extraction enters the dryer along the axis, transfers heat on the tube surfaces, and leaves the rotary-tube dryer as condensate. The evaporated moisture is carried by air, going through the dryer in the same direction as the lignite. Some technical data regarding the rotary-tube dryers are shown in Table 1.

Pre-Dried Lignite-Fired Power System

A schematic graph of PLPS is shown in Figure 2, which adds a steam extraction lignite pre-drying system in CLPS. Raw lignite is fed into the dryer, where a portion of water in the lignite is evaporated after absorbing the heat of steam extraction of the regenerative system. Pre-dried lignite is then fed into the boiler. Hot steam releases heat in the dryer and produces water condensate, which is recovered in the de-aerator or in the condenser.

The system is based on a conventional power plant; thus, the design and revamp of the PLPS can be easily executed. With this system, the moisture content of lignite was reduced to 10%–20%, and its energy density increased to more than 40%. Boiler efficiency was improved because less moisture was evaporated in the boiler. Meanwhile, the reduction in power consumption in some auxiliary mechanical equipment of the boiler, such as pulverizers and boiler fans, added further improvement to system efficiency.

MODEL DEVELOPMENT

In this section, a theoretical model for the thermal economic analysis of the PLPS system was developed. CLPS, which directly fires lignite, was used as the comparison benchmark for PLPS economic analysis. The aim of the model is to calculate the generation efficiency improvement of PLPS and compare it with that of the CLPS. For the convenience of theoretical analysis, the following assumptions between CLPS and PLPS were made:

1. The flow rate and parameters of new steam (steam from the boiler to the high-pressure turbine) remain unchanged.
2. Boiler heat losses are the same except for the heat loss from the boiler exhaust.
3. The efficiency of the steam turbines remains unchanged.
4. The terminal temperature difference of the heaters remains unchanged.

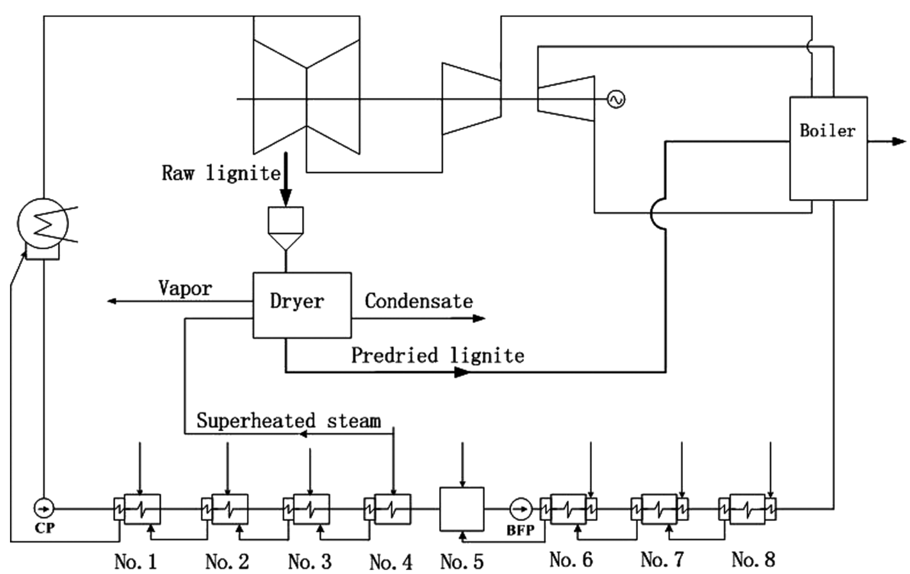

FIG. 2. Schematic of PLPS.

In this section, the dryer model was first established and was later used in the system thermal economic analysis model; an overall theoretical model was then developed.

Dryer Model

The purpose of establishing a dryer model is to determine the ratio $f(m)$, i.e., the steam extraction flow rate needed to dry out 1 kg moisture from lignite (kg/kg). The rotary-tube dryer model used in this system is shown in Figure 3. The energy required for the drying process is the steam extraction of the regenerative system. The superheated steam passes through the dryer, releases heat, and leaves the dryer as condensate, while the raw lignite is fed into the dryer where some of the moisture is evaporated. The heat absorbed by the raw lignite is divided into two parts: the heat absorbed by evaporated moisture from the lignite, and the heat absorbed by the other part of the lignite (pre-dried lignite). The thermal utilization efficiency of the dryer, which considers the influence of dryer heat dissipation and non-condensable in steam, is assumed as η_d. The parameters of the steam and lignite are also shown in Figure 3, where

$P*$ is pressure (MPa);
$t*$ is temperature (°C);
$h*$ is the specific enthalpy (kJ/kg), referred to as "enthalpy" in the rest of the paper;
B is the lignite feeding rate, in PLPS(kg/s);
M is the degree of pre-drying, i.e., the moisture mass released from 1 kg raw lignite (kg/kg); and
$D_{f(m)}$ is the steam extraction flow rate for lignite pre-drying (kg/s).

Thus, the mass flow rate of vapor is $B \cdot m$, and the mass flow of pre-dried lignite is $B \cdot (1-m)$. The heat absorbed by air, which goes through the dryer and removes moisture, is not taken into account. By applying an enthalpy balance for the overall dryer, the following equation can be obtained:

$$D_{f(m)} \cdot (h_j - h_{do}) \cdot \eta_d = B \cdot m \cdot (h_v - h_{w0}) + B \cdot (1-m) \cdot (h_{pl} - h_{pl0}) \quad (1)$$

where h_{w0} is the specific enthalpy of moisture contained in raw lignite (kJ/kg), and h_{pl0} is the specific enthalpy of pre-dried lignite at the inlet temperature (t_l) (kJ/kg).

The steam extraction mass flow rate needed for lignite drying ($D_{f(m)}$) is determined by the following equation:

$$D_{f(m)} = B \cdot m \cdot f(m) \quad (2)$$

The increase in enthalpy in pre-dried lignite is calculated by the following formula:

$$h_{pl} - h_{pl0} = C_{coal} \cdot (t_{pl} - t_l) \quad (3)$$

where C_{coal} is the specific heat capacity of this part of lignite [kJ/(kg · K)], which is determined by the following formula:[1]

$$C_{coal} = C_{dr} \frac{100 - M}{100} + 4.187 \frac{M}{100} \quad (4)$$

where M is the average moisture content of pre-dried lignite along the dryer, in wet basis (%); and C_{dr} is the specific heat capacity of lignite, in dry basis (kJ/kg).

Using the equations above, the following equation for $f(m)$ can be obtained:

$$f(m) = \frac{h_v - h_{w0}}{(h_j - h_{do}) \cdot \eta_d} + \frac{(1-m) \cdot (h_{pl} - h_{pl0})}{m \cdot (h_j - h_{do}) \cdot \eta_d} \quad (5)$$

Using the equations above, $f(m)$ can be calculated when the parameters of the steam extraction and lignite are given.

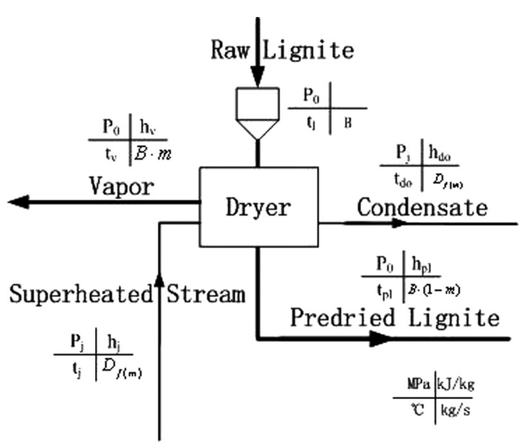

FIG. 3. Dryer model.

Thermal Economic Analysis Model of PLPS

The power system efficiency influenced by performing steam extraction of the regenerative system to pre-dry lignite can be divided into two parts: the system input heat reduction and the system output electric power reduction. The system input heat reduction results from lignite pre-drying, which reduces the moisture content in lignite and lowers the boiler exhaust temperature. On the other hand, the power plant output electric power reduction is caused by the steam extraction and condensate recovery. After using steam extraction to pre-dry lignite, the system input heat changes to $Q + \Delta Q$, and power plant output electric power changes to $W_e + \Delta W_e$, where

W_e is the power plant output electric power of CPLS(kW);
Q is the power plant input heat of CPLS (kW);

ΔW_e is the power plant output electric power variation (kW); and
ΔQ is the input heat variation (kW).

In this section, the system input heat reduction model and the output electric power reduction model were developed, and the system efficiency influenced by lignite pre-drying was modeled.

System Input Heat Reduction Model

The system input heat reduction of PLPS can be calculated from the following equation:

$$\Delta Q = (B_0 - B) \cdot Cal \tag{6}$$

where B_0 is the lignite feeding rate in CLPS(kg/s), and *Cal* is the lower heat value of raw lignite (kJ/kg).

The mathematical model to compute for B in Equation (6) was developed with the assumption that the new steam remains unchanged, and thus the heat carried by the steam from the boiler is the same both in PLPS and CLPS. However, with less moisture content of the feed lignite and a lower boiler exhaust temperature, the amount of heat taken away by PLPS boiler emissions is reduced. Instead, this portion of heat is also carried by the steam. In CLPS, the heat carried by the steam from the boiler to the turbines is$B_0 \cdot \eta_b \cdot Cal$. In PLPS, the lignite feeding rate is reduced to B. If the PLPS feed lignite is fired in CLPS, the heat carried by the steam from the boiler to the turbines is$B \cdot \eta_b \cdot Cal$; however, the heat taken away by the boiler emissions in PLPS is reduced into two parts: (i) the heat for the reduced moisture evaporation ΔQ_w; and (ii) an extra-sensible heat for the lower exhaust temperature ΔQ_{py}, ich is also carried by the steam to the turbines. Thus, the following equation can be obtained:

$$B \cdot \eta_b \cdot Cal + \Delta Q_w + \Delta Q_{py} = B_0 \cdot \eta_b \cdot Cal \tag{7}$$

1. Heat for the reduced moisture evaporation (ΔQ_w)
   If an amount of water is not removed from lignite, it will absorb heat in the boiler, evaporate, and leave the stack at the vapor state. This amount of heat can be expressed as

$$\Delta Q_w = B \cdot m \cdot (h_{w10} - h_{w0}) \tag{8}$$

   where h_{w0} and h_{w10} are the enthalpies of the entrance of water contained in the raw lignite and of the vapor contained in the CLPS boiler exhaust, respectively. After drying, this amount of heat ΔQ_w is not taken away by the boiler emissions.
2. Heat for the lower exhaust temperature (ΔQ_{py})

Due to the reduction in boiler exhaust moisture content, the exhaust temperature can be reduced. This amount of heat taken away by the boiler exhaust without lignite pre-drying can be expressed as

$$\Delta Q_{py} = B \cdot Q(\alpha, ar) \cdot (t_{10} - t_1) \tag{9}$$

where $Q(\alpha, ar)$ is the specific heat of flue gas at the boiler exhaust, expressed as per kg of raw lignite fired in the PLPS [kJ/(kg · K)];
t_{10} is the boiler exhaust temperature of CPLS (°C); and
t_1 is the boiler exhaust temperature of PPLS (°C).

$Q(\alpha, ar)$ in Equation (7) can be calculated from the following equation:

$$Q(\alpha, ar) = m_{N_2} \cdot Cp_{N_2} + m_{O_2} \cdot Cp_{O_2} + m_{CO_2} \cdot Cp_{CO_2} + m_{H_2O} \cdot Cp_{H_2O} + m_{SO_2} \cdot Cp_{SO_2} \tag{10}$$

where m_* is the mass of the (*) flue gas component at the boiler exhaust per 1 kg of raw lignite fired in PLPS (kg/kg), and Cp_* is the specific heat of the (*) flue gas at constant pressure [kJ/(kg · K)].

The theoretical (stoichiometric) air mass (m^0_{air}) needed for firing 1 kg raw lignite is calculated from the following equation:

$$m^0_{air} = 0.115(C_{ar} + 0.375 S_{ar}) + 0.342 H_{ar} - 0.043 O_{ar} \tag{11}$$

Where

C_{ar} is the organic carbon content on an as-received basis (%);
S_{ar} is the organic sulfur content on an as-received basis (%);
H_{ar} is the organic hydrogen content on an as-received basis (%); and
O_{ar} is the organic oxygen content on an as-received basis (%).

The actual air mass (m_{air}) needed for firing 1 kg raw lignite is calculated from the following:

$$m_{air} = m^0_{air} \cdot \alpha \tag{12}$$

where α is the excess air coefficient.

Thus, $m*$ can be calculated from the following equations:

$$m_{CO_2} = 0.0367 \cdot C_{ar} \tag{13}$$

$$m_{SO_2} = 0.02 \cdot S_{ar} \tag{14}$$

$$m_{H_2O} = 0.0100 \cdot (M_t - 100m + 9H_{ar}) \tag{15}$$

$$m_{N_2} = 0.767 m_{air} + 0.0100 \cdot N_{ar} \tag{16}$$

$$m_{O_2} = 0.233\frac{(\alpha - 1)}{\alpha} m_{air} \tag{17}$$

where M_t is the moisture content on an as-received basis (%).

Thus, $Q(\alpha, ar)$ can be calculated from Equations (10)–(17), and ar represents the lignite elemental composition on an as-received basis.

With equation (7)-(9), the boiler feed lignite mass flow rate with lignite pre-drying can be determined as follows:

$$B = \frac{Cal \cdot \eta_b}{Q(\alpha, ar) \cdot (t_{10} - t_1) + m \cdot (h_{w10} - h_{w0}) + Cal \cdot \eta_b} B_0 \tag{18}$$

Given that $Q(\alpha, ar)$ is a function of the PLPS lignite feeding rate *(B)*, B can be obtained through an iteration of Equation (18).

System Output Electric Power Reduction

PLPS uses steam extraction of a heat regenerative system to pre-dry lignite so that more steam is extracted from the steam turbine, which results in an output electric power reduction. The condensate from the dryer is sent to the de-aerator or the condenser, which are usually used in condensation steam recovery.

(1) The condensate is sent to the condenser.
Owing to the assumption that the steam flow rate from the boiler to the turbines remains constant, the feed water of all the heaters are kept unchanged, and the steam extraction for the heaters are kept constant. The system output electric power reduction can then be expressed as follows:

$$\Delta W = D_{f(m)} \cdot (h_f - h_n) \tag{19}$$

where h_f is the steam extraction enthalpy (kJ/kg), and h_n is the turbine exhaust steam enthalpy (kJ/kg).

(2) The condensate is sent to the de-aerator.
Owing to the assumption that the new steam mass flow rate remains constant, the boiler feed water flow rate is also constant. Therefore the flow rate of water flowing out from the de-aerator is kept constant compared with that of CLPS when the condensate from the dryer is sent to the de-aerator. Thus, the water flow rate entering the de-aerator and the heaters before the de-aerator reduces $D_{f(m)}$.

For the de-aerator (the *No.k* heater) shown in Figure 4, the following equation can be obtained by applying an enthalpy balance for the de-aerator:

$$D_{f(m)} \cdot (h_{wk} - h_{w(k-1)}) + D_{f(m)} \cdot (h_{do} - h_{wk}) = \Delta D_k (h_k - h_{wk}) \tag{20}$$

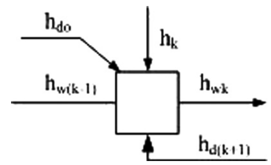

FIG. 4. No. k deaerator.

where ΔD_k expresses the steam variation in the de-aerators of PLPS and CLPS.

Through the conversion of Equation (20), the steam extraction variation in the de-aerator ΔD_k can be obtained from the following equation:

$$\Delta D_k = \frac{D_{f(m)} \cdot (h_{do} - h_{w(k-1)})}{h_k - h_{wk}} \tag{21}$$

The heaters before the de-aerator are always surface heaters in a modern power plant. The parameters of the *No.j* heater are shown in Figure 5, including the feeding water enthalpy $h_{w(j-1)}$, export water enthalpy h_{wj}, steam extraction enthalpy h_j,drain water enthalpy h_{dj}, and drain water from the previous higher-pressure heater $(No.(j+1))$ enthalpy $h_{d(j+1)}$. Compared with the CLPS heat regenerative system, the steam extraction variation is ΔD_j, and the drain water from the previous higher-pressure heater $(No.(j+1))$ variation is $\Delta D_{d(j+1)}$ for the No. j heater.

The terminal temperature difference of heaters is assumed unchanged; thus, by using the parameters of the CLPS heat regenerative system, the steam extraction variation ΔD_j can be calculated from the following equation:

$$\Delta D_j = \frac{D_{f(m)} \cdot (h_{wj} - h_{w(j-1)}) - \Delta D_{d(j+1)} \cdot (h_{d(j+1)} - h_{dj})}{h_j - h_{dj}} \tag{22}$$

The drain water of the No. (j + 1) heater variation $\Delta D_{d(j+1)}$ can be calculated from the following equation:

$$\Delta D_{d(j+1)} = \sum_{i=j+1}^{k-1} \Delta D_i \tag{23}$$

The steam extraction of the No. j heater changes ΔD_j, and if this amount of steam had expanded in the turbines, it could produce an extra work ΔW_j, which can be expressed

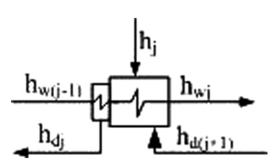

FIG. 5. No. j heater.

as follows:

$$\Delta W_j = \Delta D_j \cdot (h_j - h_n) \tag{24}$$

Thus, the work reduction of steam ΔW between CPLS and PPLS can be expressed as follows:

$$\Delta W = D_{f(m)} \cdot (h_f - h_n) - \sum_{j=1}^{k} \Delta W_j \tag{25}$$

The system output electric power reduction can be expressed in the following equation:

$$\Delta W_e = \Delta W \cdot \eta_m \cdot \eta_e \tag{26}$$

where η_m is the mechanical efficiency of steam turbine; and η_e is the generator efficiency.

Model of the Power Plant Efficiency Variation

The absolute variation in generation efficiency $\Delta\eta_c$ and the relative variation in generation efficiency $\delta\eta_c$ expressing the variation in the power plant efficiency are always used. The absolute variation in generation efficiency $\Delta\eta_c$ can be calculated from the following equation:

$$\Delta\eta_c = \eta_c' - \eta_c \tag{27}$$

where η_c' is the PLPS power plant generation efficiency, and η_c is the CLPS power plant generation efficiency.

η_c can be calculated from $\eta_c = \frac{W_e}{Q}$; thus, η_c' can be expressed as

$$\eta_c' = \frac{W_e + \Delta W_e}{Q + \Delta Q} \tag{28}$$

The relative variation in generation efficiency $\delta\eta_c$ can be calculated from the following equation:

$$\delta\eta_c = \frac{\Delta\eta_c}{\eta_c'} \times 100 = \frac{\eta_c' - \eta_c}{\eta_c'} [\%] \tag{29}$$

The power plant efficiency variation can thus be expressed as

$$\delta\eta_c = \frac{\eta_c' - \eta_c}{\eta_c'} \times 100 = \frac{\frac{W_e+\Delta W_e}{Q+\Delta Q} - \frac{W_e}{Q}}{\frac{W_e+\Delta W_e}{Q+\Delta Q}} \times 100 = \frac{\Delta W_e - \Delta Q \cdot \eta_c}{W_e + \Delta W_e} \tag{30}$$

$$\Delta\eta_c = \frac{\eta_c \cdot \delta\eta_c}{1 - \delta\eta_c} \tag{31}$$

Using the equations above, the influence of lignite drying on the power plant generation efficiency can be calculated. The aim of the model developed above is to calculate the generation efficiency improvement of PLPS and compare it with that of CLPS. It should be emphasized that the calculation results of the efficiency improvement is influenced by the use of CLPS parameters as contrast, the pre-drying parameters, and so on. Thus, the calculation benchmark condition (CBC) is always required in the analysis of efficiency improvements and of the influence of parameters. The CBC parameters consist of the CLPS parameters as contrast, the lignite pre-drying parameters, and the dryer parameters.

MODEL APPLICATION AND ANALYSIS FOR AN EXISTING CLPS CASE

A case was examined and analyzed in this section. The purpose of this section is to check the model and analyze the influence of parameters on the efficiency improvement of PLPS and compare the results with that of CLPS.

The existing CLPS analyzed here was a 600 MW supercritical condensing power plant, and the calculation condition used was the turbine heat acceptance (THA) condition. The parameters of the THA heat regenerative system condition are shown in Table 2. The lignite fired in the boiler was YIMIN lignite of Chinese origin; its composition, which affects dryer performance as well as the quality of output, is shown in Table 3.

TABLE 2
Heat regenerative system parameters of THA condition

Heater No.	Steam extraction enthalpy (kJ/kg)	Drain water enthalpy (kJ/kg)	Feed water enthalpy (kJ/kg)	Heater export water enthalpy (kJ/kg)
1	2486.4	163.3	140	246.5
2	2622.2	268.4	246.5	344
3	2739.4	366.1	344	425.5
4	2979.2	447.7	425.5	594.4
8	3199.4		594.4	764.9
6	3410.3	811.5	801.6	927.27
7	2980	943.9	927.27	1098.6
8	3059.6	1124.5	1098.6	1207.6

TABLE 3
Composition of YIMIN lignite

C(wt%)	H(wt%)	S(wt%)	O(wt%)	N(wt%)	Ash(wt%)	H_2O(wt%)	LHV(MJ)
34.59	2.03	0.14	11.3	0.35	12.09	39.5	11.79

Results of Calculation Benchmark Condition (CBC)

The parameters of CBC are shown in Table 4. The moisture content was dried to 19.5%, i.e., the moisture mass dried from 1 kg lignite (m) was 0.2484 kg/kg. The boiler exhaust temperature decreased to 131 C in PLPS. The power system efficiency improvement was calculated using the previously developed model, the results of which are shown in Table 5. The plant generation efficiency improved by 1.87% when the dryer condensate was sent to the de-aerator, and by 1.72% when the condensate was sent to the condenser; this is a significant efficiency improvement for PLPS.

Influence of Parameters

With this model, the influence of parameters (such as dryer thermal efficiency, drying degree, boiler exhaust temperature, etc.) on power plant efficiency was analyzed in this section. A parameter was changed in each small section, whereas the other parameters were kept unchanged with CBC. The results can be used on system design and thermodynamic system optimization.

TABLE 4
Parameters of calculation benchmark condition

Existing CLPS	Operation condition: THA condition Generating power: 600 MW. Enthalpy of turbine exhaust: 2318.6 kJ/kg Steam turbines unit efficiency: 47.81% Boiler efficiency: 91% Heat-supply pipe efficiency: 99% Mechanical efficiency: 99.5% Generator efficiency: 99% Excess air coefficient: 1.2 Boiler exhaust temperature: 148°C Lignite fired: YIMIN lignite Feed lignite: 20°C
Rotary-tube dryer	Raw lignite: 20°C Pre-dried lignite: 80°C Steam extraction: No. 4 heater Condensate: saturated water Vapor: 90°C, 2100 kJ/kg Thermal efficiency of dryer: 98% Drying degree: 0.2484 kg/kg
PLPS	Boiler exhaust temperature: 131°C

Influence of Dryer Thermal Efficiency η_d

The influence of the dryer thermal efficiency η_d was calculated, the results of which are shown in Figure 6. Power plant thermal efficiency improved with dryer thermal efficiency. With the dryer thermal efficiency between 70% and 100%, power efficiency improved from 1.38% to 1.90% when the condensate was sent to the de-aerator, and from 1.17% to 1.75% when the condensate was sent to the condenser. The difference in power plant efficiency improvements with different condensate recovery locations changed from 0.21% to 0.15% along with the improvement in dryer thermal efficiency.

Influence of m (The Degree of Pre-Drying)

The influence of *m* (the degree of pre-drying) was calculated, the results of which are shown in Figure 7. The improvement quantity in terms of plant generation efficiency linearly increased with the dry degree. A 0.1 increase in pre-drying degree improved plant generation efficiency by more than 0.65%. The difference in power plant efficiency improvement with different condensate recovery locations improved with dry degree, with 0.08% at 0.1 pre-drying degree and 0.17% at 0.3 degree.

Influence of the Boiler Exhaust Temperature

The influence of the boiler exhaust temperature was calculated, the results of which are shown in Figure 8. Other parameters were kept unchanged within the calculation. The boiler exhaust temperature difference Δt between PLPS and CLPS was changed in the calculation. As shown in Figure 8, the improvement quantity in terms of plant generation efficiency linearly increased with the temperature difference Δt. A 10°C increase in Δt improved plant generation efficiency by approximately 0.24%. The difference in power plant efficiency improvement quantity with different condensate recovery locations remained

TABLE 5
Calculation results for CBC

	ΔW_e(kW)	ΔQ(kW)	$\delta\eta_c$(%)	$\Delta\eta_c$(%)
Condensate to de-aerator	−16053.1	93176.4	4.16	1.87
Condensate to condenser	−18323.1	93176.4	3.84	1.72

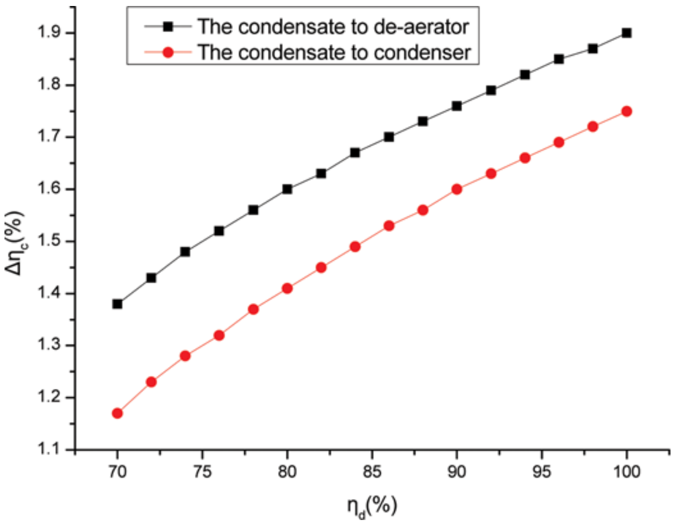

FIG. 6. Influence of η_d on the plant generating efficiency.

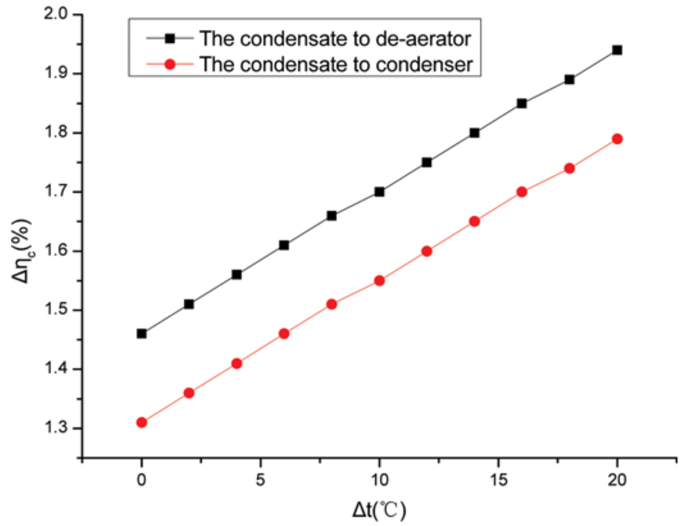

FIG. 8. Influence of flue gas temperature on the plant generating efficiency.

unchanged with the increase in Δt, which was approximately 0.15% more for the condensate compared with the de-aerator.

Influence of the Condensate Temperature

The influence of the dryer condensate temperature was calculated, the results of which are shown in Figure 9. The plant generation efficiency remained unchanged with the condensate temperature when the condensed steam was sent to the de-aerator. The improvement quantity in terms of plant generation efficiency linearly decreased with the exit temperature of the dryer when the condensation was sent to the condenser. A 10 C increase in condensate temperature reduced plant generation efficiency by approximately 0.02%.

Influence of the Dryer Export Vapor Enthalpy

The influence of the dryer export vapor enthalpy was calculated, the results of which are shown in Figure 10. Plant generation efficiency decreased by approximately 0.05% with a 100 kJ/kg increase in dryer export vapor enthalpy. The difference in power plant efficiency improvement quantity with different condensate recovery locations remained unchanged with the increase in vapor enthalpy, which was approximately 0.14%.

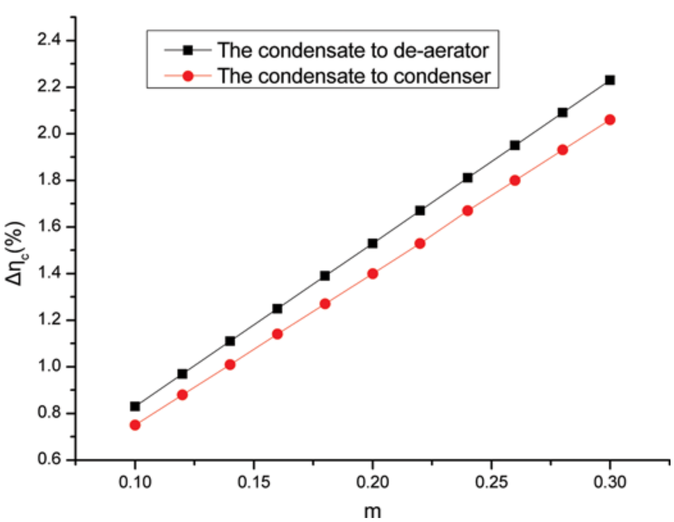

FIG. 7. Influence of m on the plant generating efficiency.

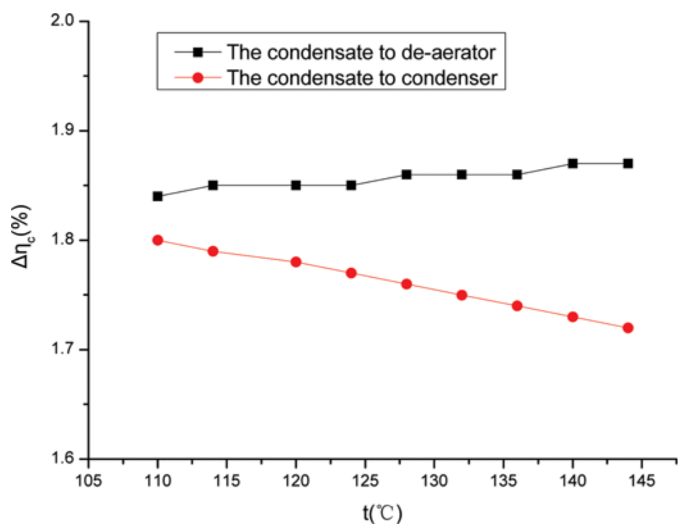

FIG. 9. Influence of condensate temperature on the plant generating efficiency.

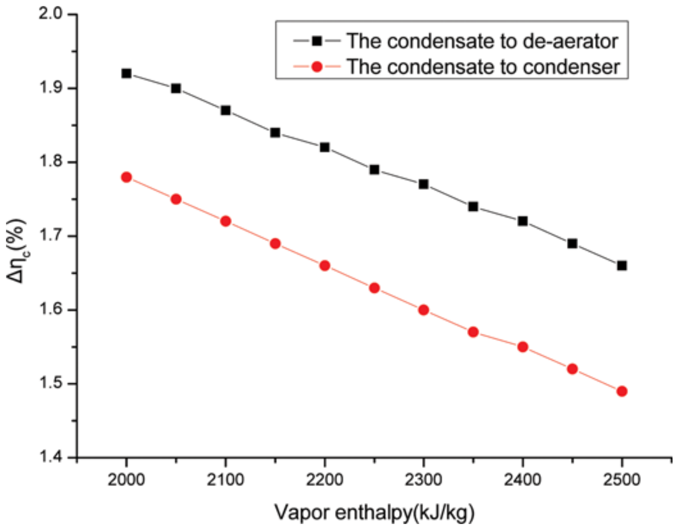

FIG. 10. Influence dryer export vapor enthalpy on the plant generating efficiency.

CONCLUSIONS

In the present study, a theoretical model for PLPS was established based on basic thermal principles. A systematic quantitative analysis and optimization was conducted using this model as a theoretical foundation. A 600 MW supercritical condensing power system was used as an example. The results of the calculations show that this model can be used to calculate the influence of lignite pre-drying on generation efficiency using steam extraction. In addition, the influence of parameters was calculated with this model.

Calculation results show that the system using steam extraction to pre-dry lignite increased power generation efficiency. This system improved power efficiency by 1.87% when the condensate was sent to the de-aerator, and by 1.72% when the condensate was sent to the condenser at the rated condition listed in this paper. Thus, from the case analysis, the following can be concluded:

1. The dryer thermal efficiency greatly influences the PLPS efficiency improvement. With dryer thermal efficiency between 70% and 100%, the power efficiency improvement quantity changed from 1.38% to 1.90% when the condensate was sent to the de-aerator.
2. Plant power generation efficiency linearly improved with dry degree. A 0.1 increase in dry degree improved plant generation efficiency by more than 0.65%.
3. Plant generation efficiency linearly improved with boiler exhaust temperature difference (Δt) between CLPS and PLPS. An increase of 10°C improved plant generation efficiency by approximately 0.24% for PLPS.
4. A 10 C increase in condensate temperature reduced plant generation efficiency by approximately 0.02% when the condensate was sent to the condenser; however, generation efficiency almost did not change when the condensate was sent to the de-aerator.
5. Plant generation efficiency decreased by approximately 0.05% with a 100 kJ/kg improvement in dryer export vapor enthalpy.
6. Recovering the condensate in the de-aerator instead of in the condenser is more efficient when the operating condition of the dryer changed.

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