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Thermo-economic analysis of an efficient lignite-fired power system integrated with flue gas fan mill pre-drying

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Abstract

Lignite is a domestic strategic reserve of low rank coals in many countries for its abundant resource and competitive price. Combustion for power generation is still an important approach to its utilization. However, the high moisture content always results in low efficiencies of lignite-direct-fired power plants. Lignite pre-drying is thus proposed as an effective method to improve the energy efficiency. The present work focuses on the flue gas pre-dried lignite-fired power system (FPLPS), which is integrated with fan mill pulverizing system and waste heat recovery. The thermo-economic analysis model was developed to predict its energy saving potential at design conditions. The pre-drying upgrade factor was defined to express the coupling of pre-drying system with boiler system and the efficiency improvement effect. The energy saving potential of the FPLPS, when applied in a 600 MW supercritical power unit, was determined to be 1.48 %-pts. It was concluded that the improvement of boiler efficiency mainly resulted from the lowered boiler exhaust temperature after firing pre-dried low moisture content lignite and the lowered dryer exhaust gas temperature after pre-heating the boiler air supply.

Keywords: *lignite; pre-drying; thermodynamic analysis; thermo-economics.*

1. Introduction

Lignite is still considered as a domestic and abundant energy source for many countries. [1] Power generation is an important approach to utilization of lignite resources. However, the high moisture content always results in low efficiencies of lignite-direct-fired power plants. Pre-drying is an effective method to improve the energy efficiency because it removes the redundant moisture and increases the heating value of the lignite entering the furnace. [2,3]

Many works have been performed concerning the performance analysis of the pre-dried lignite-fired power systems (PLPSs) based on energy and exergy criteria and/or economic and environmental indicators. In China, Liu et al. [4] conducted process modeling of the steam pre-drying power system using Aspen Plus, and investigated the exergy destruction distributions of a 600 MW unit under nominal and partial loads. Moreover, biomass pre-drying [5] and solar pre-drying [6] were studied, respectively, to further demonstrate the energy saving potential of pre-drying. Zhu et al. [7] carried out an energy analysis of a lignite steam pre-drying power system with an efficient waste heat recovery system. Xu et al. [8] modeled a lignite power system integrated with boiler exhaust gas pre-drying, and analyzed the energy saving potentials with different lignite types and pre-drying degrees. Recently, different configurations of solar pre-drying were proposed by Xu et al. [9] The selection of drying heat source is gradually extended to renewable energy sources, which aims to further improve the energy efficiency of low rank coals. In Greece, Atsonios et al. [10] examined various scenarios of lignite drying and utilization depending on power load variation of the plant during certain periods of the day, in order to simultaneously increase the plant efficiency and reduce the electricity cost. Rakopoulos et al. [11] assessed different lignite-fired plant configurations for combined heat and power production for use in district heating networks, in terms of environmental, technical, and economic criteria. Avagianos et al. [12] presented a thermodynamic methodology for the prediction of lignite fired boilers at low power loads; even below the current technical minimum, when pre-dried lignite is employed. Drosatos et al. [13] conducted numerical simulation of a lignite-fired boiler using pre-dried lignite as supporting fuel for flexible operation. As summarized by Agraniotis et al. [14], state-of-the-art lignite pre-drying technologies can not only improve the energy efficiency but also operation flexibility. Energy saving of lignite pre-drying also attracts other researchers worldwide lately. For example, Fushimi et al. [15] developed drying process based on self-heat recuperation technology and evaluated the thermal efficiency penalty and costs. Kambara et al. [16] compared the thermal efficiencies for an existing 316 MWe power plant with and without steam tube dryers (STDs), and found that the improvement can be up to 4.2 %-pts. Giuffrida et al. [17] presented a detailed analyses based on mass and energy balances of lignite-fired air-blown gasification-based combined cycles with CO_2 pre-combustion capture. Akkoyunlu et al. [18] carried out an economic assessment of drying prior to grinding mill process in lignite-fired thermal power plants. It was indicated that the growth in the boiler efficiency ranged between 3.9-12.6% when there was a 10% decrease in moisture content. Moon et al [19] developed a combination of low rank coal drying with power generation, and investigated the influences of steam extraction point and amount of drying coal on the thermal efficiency. In brief, an agreement has reached that pre-drying can improve the efficiency of lignite power generation, but system optimization still requires specifications and methodologies.

The authors have reported earlier predicted energetic performance of the FPLPS at off-design conditions [20] and suggested possible performance improvement through the energy matching in the drying process [21]. It is necessary to provide a comprehensive idea of technical and economic feasibility of lignite pre-dying. The major objective of this study is thereby to be a demonstration of a detailed thermo-economic analysis of flue gas mill pre-drying concept. It is continuation of works associated with lignite pre-drying power systems.

2. Materials and Methods

2.1. System Layouts

A conceptual schematic of the FPLPS system is depicted in Fig. 1. The common features of the FPLPS include the use of flue gas as drying agent in the drying tubes and fan mills, the integration of an open pulverizing system with the boiler, the concentration of water vapor in the dryer exhaust gas, and the air pre-heating by the dryer exhaust gas. More specifically, the flue gas dryer exhaust gas, containing a large amount of water vapor, is not recycled to the furnace but led to the heat recovery system, in which the waste heat is utilized to pre-heat the air supply of the boiler.

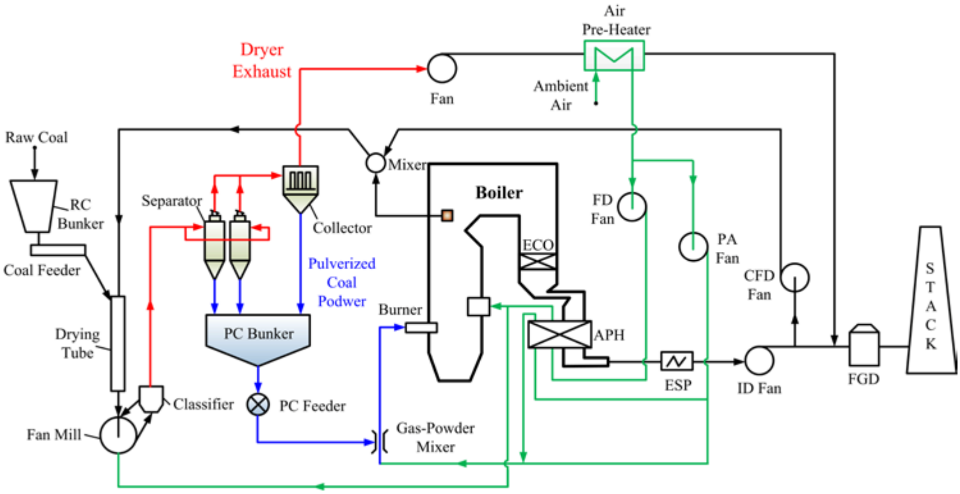

Fig. 1. System layout of the FPLPS.

2.2. Thermo-economic analysis model

Raw lignite is fed into the dryer, in which a part of the moisture content is removed and the heat supply is basically conserved with the latent heat of moisture evaporation $\Delta M \cdot h_{\mathrm{v}}$. Accordingly, the LHV of the pre-dried lignite is derived as:

$$\mathrm{LHV_{pc}} = (\mathrm{LHV_{ar}} + \mathit{\Delta M} \cdot h_{\mathrm{v}}) / (1 - \mathit{\Delta M}) \tag{1}$$

where $\mathit{\Delta M}$ is the mass of evaporated moisture per kg raw lignite (kg·kg^{-1}), also defined as **pre-drying degree**, and h_{v} is the water latent heat of vaporization.

$$\mathit{\Delta M} = (M_{\mathrm{ar}} - M_{\mathrm{pc}}) / (100 - M_{\mathrm{pc}}) \tag{2}$$

where M_{ar} and M_{pc} are the moisture contents in the raw and pre-dried lignite, respectively. The moisture content of pre-dried lignite can be calculated as:

$$M_{\mathrm{pc}} = 0.048 \cdot M_{\mathrm{ar}} \cdot R_{90} \cdot t_{\mathrm{de}}{}^{-0.46} \tag{3}$$

In the present work, a dimensionless **pre-drying upgrade factor** is defiend as:

$$k_{\mathrm{pd}} = 1 + \Delta M \cdot h_{\mathrm{v}} / \mathrm{LHV_{ar}} \tag{4}$$

In this way, boiler efficiencies on different basis can be derived as:

$$\eta_{\mathrm{b},t_{\mathrm{ref}}=t_0} = k_{\mathrm{pd}} \cdot \eta_{\mathrm{b},t_{\mathrm{ref}}=t_{\mathrm{ap}}} \tag{5}$$

The plant thermal efficiency, η_{tot}, can be calculated by the combined product of the efficiencies of the main components, and is expressed as follows:

$$\eta_{\mathrm{tot}} = \eta_{\mathrm{b}} \eta_{\mathrm{p}} \eta_{\mathrm{sc}} \eta_{\mathrm{m}} \eta_{\mathrm{g}} \tag{6}$$

where η_{b} is the boiler efficiency (t_0 basis), η_{p} the heat supply pipe efficiency, η_{sc} the steam cycle efficiency, η_{m} the mechanical efficiency, and η_{g} the electric generator efficiency.
The plant thermal efficiency improvement, $\mathit{\Delta}\eta_{\mathrm{tot}}$, is calculated as:

$$\mathit{\Delta}\eta_{\mathrm{tot}} = \eta_{\mathrm{tot,FPLPS}} - \eta_{\mathrm{tot,CLPS}} \tag{7}$$

3. Results and Discussion

3.1. Case Study

3.1.1. Benchmark parameters

To evaluate the energy saving potential of the FPLPS comprehensively, simulation calculations on a 600 MW water-cooled supercritical unit were carried out based on the simulation algorithm introduced above. Detailed specifications in simulation and calculation, such as the thermal parameters of the heat regenerative system, can be found in Ref.[21]. The properties of the Chinese Yimin lignite, with 39.5% moisture content are given in Table 1.

Table 1. Properties of Chinese Yimin lignite

M_{ar}, %	A_{ar}, %	C_{ar}, %	H_{ar}, %	O_{ar}, %	N_{ar}, %	S_{ar}, %	LHV, MJ·kg^{-1}
39.50	12.09	34.59	2.03	11.30	0.35	0.14	11.79

To conduct thermodynamic analysis, it is firstly necessary to determine the moisture content of pre-dried lignite with given parameters. According to the empirical correlation (Eq.1), the moisture content after grinding and milling can be obtained, as a function of pre-drying degree and R_{90} (Fig. 2). M_{pc} is calculated as 9.82% when t_{de} equals 110 °C. The heating value can also be calculated, as shown in Fig. 3. The HHV and LHV are elevated by 49.1% and 59.5%, respectively. Obviously, with higher pre-drying degree, the rank of the lignite is improved. The plant efficiency benefit is expected. As summarized in Table 2, compared with conventional lignite-fired power system (CLPS), the plant thermal efficiency can be improved by 1.48 %-pts.

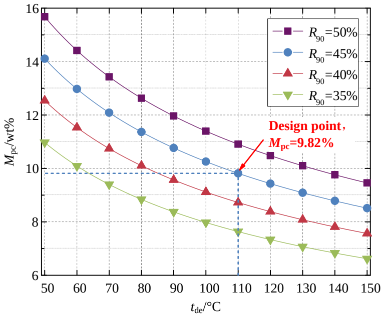

Fig. 2. M_{pc} in terms of R_{90} and t_{de}.

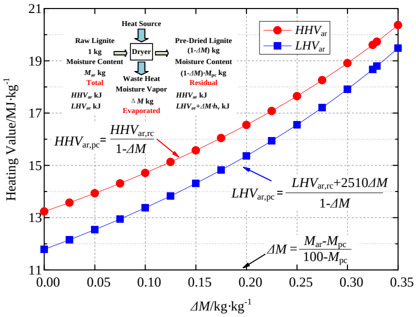

Fig. 3. Heating value in terms of ΔM.

Table 2. Comparison of the parameters and thermo-economics of the CLPS and FPLPS

Items	**Unit**	**CLPS**	**FPLPS**
Boiler exhaust temperature, t_{be}	°C	144	110
Air pre-heating temperature, t_{ap}	°C	-	55
Dryer exhaust temperature, t_{de}	°C	150	110
Boiler efficiency on t_{ap} basis, $\eta_{b,t_{ref}=t_{ap}}$	%	-	89.49
Pre-drying upgrade factor, k_{pd}	-	-	1.07
Boiler efficiency on t_0 basis, $\eta_{b,t_{ref}=t_0}$	%	92.59	95.76
Steam cycle efficiency, η_i	%	47.67	47.67
Plant thermal efficiency, η_{tot}	%	43.26	44.74

3.1.2. Thermodynamic analysis

The joint influences of boiler exhaust temperature (t_{be}), dryer exhaust temperature (t_{de}), air pre-heating temperature (t_{ap}) on the energy efficiency improvements are depicted in Fig. 4. It can be seen in Fig. 5 that the plant efficiency improvement varies with t_{be}, t_{de}, and t_{ap} linearly. The $\Delta\eta_{tot}$ increases by 0.09 %-pts when t_{de} decreases by 10 °C, 0.18 %-pts when t_{be} decreases by 10 °C, and 0.16 %-pts when t_{ap} increases by 10 °C. To sum up, the decrease of t_{de}, t_{be} and increase in t_{ap} contribute to the total $\Delta\eta_{tot}$ by 0.38 %-pts, 0.62 %-pts, and 0.48 %-pts, respectively.

The pre-drying upgrade factor (k_{pd}) is defined in the present work to demonstrate the energy saving mechanism of pre-drying from energy analysis perspective. It is shown in Fig. 6 that the k_{pd} increases linearly with the pre-drying degree (ΔM) with given lignite properties. It is calculated as 1.07 for Yimin lignite, which means that the boiler efficiency is increased by 7%. The k_{pd} increases by 0.02 with 0.1 kg·kg^{-1} increase in ΔM. As a result, the boiler efficiency increases with the pre-drying degree (Fig. 7).

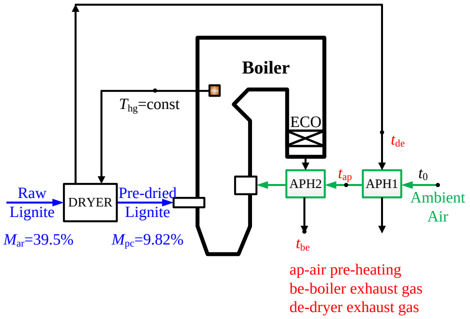

Fig. 4. *Schematic of the key temperatures in FPLPS.*

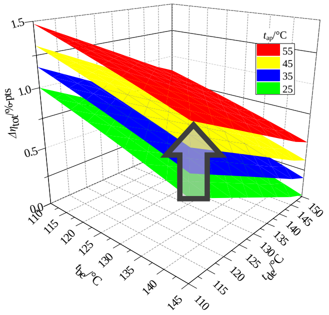

Fig. 5. *Influence of t_{be}, t_{de}, and t_{ap} on $\Delta\eta_{tot}$*

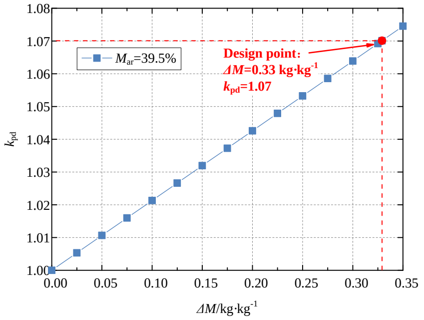

Fig. 6. *k_{pd} as a function of ΔM.*

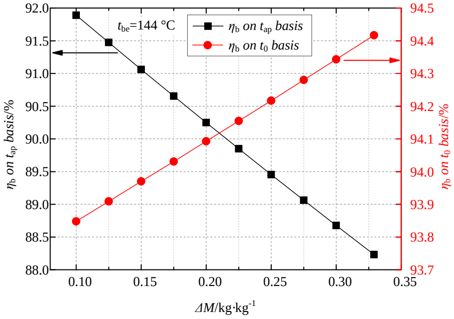

Fig. 7. *Boiler efficiencies in terms of ΔM.*

3.2. Parametric analysis

Apart from the key temperatures above, the plant efficiency improvement also depends on drying process parameters. Pre-drying degree and dryer efficiency are the parameters, from the perspectives of moisture removal and thermal conversion, respectively. The uncertainty in the calculation of the moisture content should be taken into consideration, as well as the dryer efficiency. Therefore, it is necessary to investigate the variations of the improvement.

3.2.1. Influence of pre-drying degrees

It is shown in Fig. 8 that the $\Delta\eta_{tot}$ increases ΔM linearly. Moreover, the slope increases with t_{be}. It means that for lignite-fired boilers with high exhaust temperature, the energy saving potential is remarkable. For example, when t_{be} is equal to 144 °C and 110 °C, respectively, the $\Delta\eta_{tot}$ increases by 0.12 %-pts and 0.05 %-pts, with 0.1 kg·kg^{-1} increase in ΔM.

3.2.2. Influence of dryer efficiency

The dryer efficiency influences the energy saving potential significantly, as shown in Fig. 9. When the dryer efficiency drops below the design value, the $\Delta\eta_{tot}$ decreases sharply. Especially, there exit critical dryer efficiencies with given boiler exhaust temperature. For example, when t_{be} is equal to 144 °C, the $\eta_{d,cri}$ is approximately 80%. When the dryer efficiency gets lower than that, the FPLPS does not save coal any more. It can be attributed to the fact that although kpd does not change with dryer efficiency, the heat load of the dryer increases with decreasing dryer efficiency and the boiler efficiency drops.

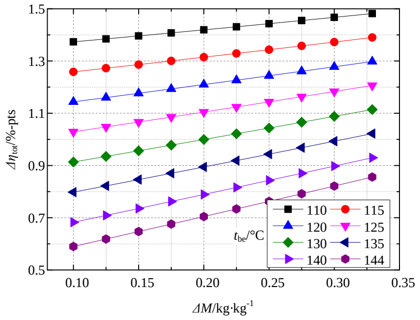

Fig. 8. $\Delta\eta_{tot}$ as a function of ΔM.

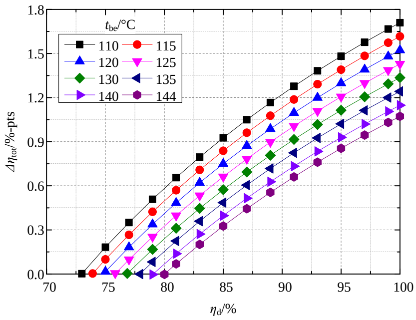

Fig. 9. $\Delta\eta_{tot}$ as a function of η_d.

4. Conclusions

A theoretical framework of modeling and thermo-economics on lignite pre-drying is presented in the present work, which offers a comprehensive idea of economic feasibility of lignite utilization integrated with flue gas fan mill pre-drying. The main conclusions are:

1) A pre-drying upgrade factor was defined to decouple the drying and boiler systems. When the moisture content decreased from 39.5% to 9.82%, the pre-drying degree was 0.33 kg·kg^{-1}, and pre-drying upgrade factor was calculated to be 1.07. As a result, the plant thermal efficiency improvement of the FPLPS compared with CLPS can be up to 1.48 %-pts, when the boiler exhaust gas temperature, the dryer exhaust gas temperature and the air pre-heating temperature were set as 110 °C, 110 °C, and 55 °C, respectively.

2) Through parametric analyses, the contributions of key design temperatures and pre-drying conditions to the energy saving potential of the FPLPS were analyzed. Results showed that the plant efficiency improvement resulted from pre-drying and air supply pre-heating increased by 0.09 %-pts, 0.16 %-pts, and 0.18 %-pts with 10 °C increase in the dryer exhaust temperature, 10 °C decrease in the air pre-heating temperature, and 10 °C decrease in the boiler exhaust temperature, respectively.

5. Acknowledgments

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