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Theoretical Study and Case Analysis for a Pre-dried Pyrolysis Coupled Lignite-Fired Power System

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Abstract
Lignite, a kind of low rank coal, has the characteristics of high moisture, high volatile, high ash and low heat value. The low-temperature pyrolysis technology is potential to improve the utilization efficiency of lignite. Therefore, a lignite-based energy system integrated with pre-drying and low-temperature pyrolysis was proposed in this paper. To assess the influence of pre-drying process, theoretical models were developed based on thermodynamics, and a case analysis was then performed to get the quantitative effect of pre-drying on efficiency of energy utilization. Results show that pre-drying on PPPS theoretical model can significantly improve the utilization of lignite by 1.46%.

Keywords: *Lignite; Pre-drying; Low-temperature pyrolysis; Energy efficiency; Case analysis.*

1. Introduction

Lignite is worldwidely considered as inferior fuel with abundant supply.[1] It is mainly used in power plants. However, the conventional lignite-fired power system (CLPS) is costly, not efficient and with high pollutant emissions. Lignite upgrading technologies, including pre-drying and pyrolysis, are effectively to improve lignite utilization efficiency. Therefore, many researches were conducted for the lignite pre-drying[2, 3, 4] and pyrolysis[5, 6] technologies. However, these two technologies are isolatedly used. The integration of the lignite pre-drying and pyrolysis may realize the energy cascade utilization and then increase the utilization of lignite. Therefore, a pre-dried pyrolysis coupled lignite-fired power system (PPPS) was proposed in this paper.

The proposal of PPPS aims to overcome the disadvantages of the pyrolysis process by the integration of pre-drying. However, the research on influences of pre-drying process on pyrolysis system is not deepgoing and unambiguous. In this paper, theoretical models were developed based on thermodynamics, and a case analysis was then performed to get the quantitative effects of pre-drying. Moreover, the energy and exergy analysis were carried out to uncover the energy saving mechanism.

2. System proposal

The schematic of a PPPS is schematically presented in Fig.1 Raw lignite (point 1) is fed into the steam dryer and pre-dried primarily. The primary pre-dried lignite (point 2) is then fed into the drying unit and pre-dried ultimately. Afterwards, the ultimate pre-dried lignite (point 3) is led to the pyrolysis unit, heated by the elevated temperature flue gas, pyrolyzed and separated into char (point 4), tar (point 13), pyrolysis gas (point 21) and water (point 12) in pyrolysis furnace. The tar and pyrolysis gas are recycled as products. Nevertheless, the char is converted by a series of energy forms and transformed into electricity (point 20), eventually. Waste steams (point 5, 6, and 12) generated in the process are exhausted to environments. The heat source of pyrolysis furnace is the elevated temperature flue gas (point 11) extracted from the boiler unit and led to the inlet of the burner. The heat source of the drying unit in the pyrolysis system is the flue gas (point 10) exhausted from the pyrolysis chamber. The flue gas (point 9) is extracted to the boiler unit by the pump after releasing heat in the drying unit, the waste heat of which is recycled by the regenerative air preheaters. The heat source of the steam pre-drying unit is the 5# low-pressure extraction steam (point 7) from the turbine unit. The steam is led to the steam dryer, condensed after releasing heat, and recovered in the de-aerator. The steam dryer makes full use of the low grade energy contained by the extraction steam from regenerative system, and reduces the heat load in the pyrolysis system.

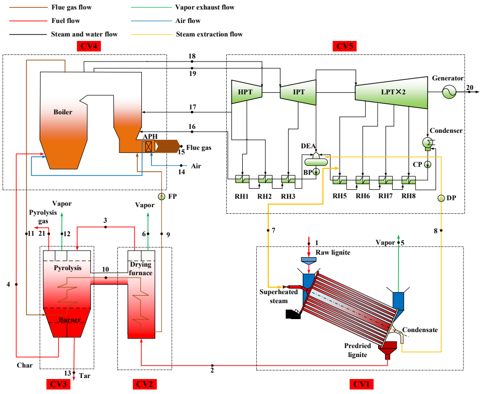


Fig.1 The pre-dried pyrolysis coupled lignite-fired power system. Note: APH, air preheater; HPT, high-pressure turbine; IPT, intermediate-pressure turbine; LPT, low-pressure turbine; DEA, de-aerator; RH, regenerative heater; CP, condensate pump; BP, boiler feed-water pump exchangers; DP, drain water pump; FP, flue gas backflow pump; CV1, steam pre-drying unit; CV2, drying furnace unit; CV3, pyrolysis unit; CV4, boiler unit; CV5, steam turbine unit.

3. Model development

In this paper, the reference pressure and the temperature are given, as follows;

$$p_0=0.1013 \text{ MPa} \tag{1}$$

$$T_0=298.15 \text{ K} \tag{2}$$

The calculations of enthalpy, higher heating value, and exergy are all based on this condition. In this part, the belt pyrolysis furnace is selected as pyrolysis model. The following pyrolysis reaction occurs when the temperature and pressure of the pyrolysis furnace remains constant.

$$\text{predried lignite(s)} \rightarrow \text{char(s)} + \text{tar(l)} + \text{gas(g)} + \text{water(g)} \tag{3}$$

The parameters in pyrolysis process are shown in Table 1, where HHV_* is higher heating value;h_* is the specific enthalpy at $kJ\cdot kg^{-1}$;t_* is the temperature at ˚C;λ_* is pyrolysis production rate defined as the (*) mass rate produced from unit mass of feed for pyrolysis furnace, $kg\cdot kg^{-1}$. μ (γ) is the degree of pre-drying defined as the moisture mass released from unit mass of raw lignite (primary predried lignite), $kg\cdot kg^{-1}$.

Table 1. The parameters of pyrolysis process.

Predried lignite	Char	Tar	Gas	Water
P_0	P_0	P_0	P_0	P_0
h_{ul}	h_c	h_t	h_g	h_{wa}
HHV_{ul}	HHV_c	HHV_t	HHV_g	–
t_{ul}	t_p	t_p	t_p	t_p
□–	λ_c	λ_t	λ_g	λ_{wa}
$B(1-\mu)(1-\gamma)$	$\lambda_c \cdot B(1-\mu)(1-\gamma)$	$\lambda_t \cdot B(1-\mu)(1-\gamma)$	$\lambda_g \cdot B(1-\mu)(1-\gamma)$	$\lambda_{wa} \cdot B(1-\mu)(1-\gamma)$

By applying an enthalpy balance for the overall pyrolysis, the flue gas mass flow (D'_f) needed in the pyrolysis can be obtained:

$$D'_f = \frac{\lambda_c\left(\mathrm{HHV_c} + h_c\right) + \lambda_t\left(\mathrm{HHV_t} + h_t\right) + \lambda_g\left(\mathrm{HHV_g} + h_g\right) + \lambda_{wa}h_{wa} - \left(\mathrm{HHV_{ul}} + h_{ul}\right)}{\left(h_{pin} - h_{fin}\right)\cdot\eta_p} \cdot B\left(1-\mu\right)\left(1-\gamma\right) \quad (4)$$

where η_p is the thermal utilization efficiency of the pyrolysis furnace; and h_{pin} is the specific enthalpy of flue gas in pyrolysis furnace inlet. Pyrolysis gases products are obtained as mixture, containing CO, H_2, CO_2 and hydrocarbons (CH_4, C_2H_4, C_2H_6, C_3H_6 and C_3H_8). The HHV_g is calculated as follow;

$$\mathrm{HHV_g} = \sum w_i \cdot \mathrm{HHV_i} \quad (5)$$

where HHV_i is the higher heating value of constituent (i) in pyrolysis gas calculated by CoolProp and w_i is the mass fraction of constituent (i). D_f and D'_f are equal by adjusting t_{fin} in MATLAB. D_f is the flue gas mass flow needed in the drying furnace unit. The energy and exergy flow ratios of each control volume and the power system to the input energy or exergy are defined as follows;

$$\varepsilon_L^{en} = \frac{Q}{B \cdot \mathrm{LHV_{raw}}} \times 100\% \quad (6)$$

$$\varepsilon_H^{en} = \frac{Q}{B \cdot \mathrm{HHV_{raw}}} \times 100\% \quad (7)$$

$$\varepsilon^{ex} = \frac{E}{B \cdot \mathrm{HHV_{raw}}} \times 100\% \quad (8)$$

where LHV is the lower heating value at $kJ \cdot kg^{-1}$; Q is the energy flow based on LHV in equation (6) and based on HHV in equation (7) at kW; E is the exergy flow at kW; and ε is the efficiency.

4. Results and discussion

4.1.Results of calculation

4.1.1Reference case

The lignite pyrolysis power system (LPPS, only involving CV2, CV3, CV4 and CV5 in Fig.1) is derived from a conventional lignite-fired power system (CLPS)[7] with the pyrolysis system integrated, the parameters of which are set with reference to the CLPS. The parameters of live steam and reheat steam, including temperature, pressure and mass flow rate of LPPS are assumed similar to those of the CLPS. The temperature of boiler flue gas before the air preheater is assumed to be the same as the CLPS. The boiler exhaust temperature decreases to 126˚C in the LPPS. The performances of the LPPS are calculated, and the thermodynamic properties of the state points of the LPPS are shown in Table 2.

Table 2. Thermodynamic properties of the state points of LPPS.

Point	Substance	Temperature ˚C	Pressure MPa	Mass flow rate,$kg\cdot s^{-1}$	Exergy $kJ\cdot kg^{-1}$	Exergy flow,kW
2	Raw lignite	25	0.1013	187.9878	13080	2458900
3	Predried lignite	300	0.1013	122.9542	20111	2472700
4	Char	550	0.1013	84.7154	23913	2025800
6	Steam	200	0.1013	65.0336	520.16	33828
9	Flue gas	350	0.1013	526.1187	119.11	62665
10	Flue gas	752.2	0.1013	526.1187	409.53	215460
11	Flue gas	1200	0.1013	526.1187	823.43	433220
12	Steam	550	0.1013	8.6068	927.96	7986.8
13	Tar	550	0.1013	6.4797	34652	224530
14	Air	25	0.1013	799.1080	0	0
15	Flue gas	126	0.1013	863.3152	18.178	15693
16	Water	284	30.400	527.7806	348.08	183710
17	Steam	323.3	4.8310	448.2778	810.70	363420
18	Steam	566	24.200	527.7806	1533.3	809260
19	Steam	566	4.3480	448.2778	1125.3	504460
20	Electricity	–	–	–	–	600000
21	Pyrolysis gas	550	0.1013	19.8079	17956	355670

By calculation, the thermal efficiency of the LPPS is 52.886% based on LHV, and 47.997% based on HHV. The exergy efficiency of the LPPS is approximately 48.00%.

4.1.2 Pre-dried pyrolysis coupled lignite-fired power system

The PPPS is put forward in previous part as shown in Fig.1.The parameters are assumed similar to those of the LPPS. The performances of the PPPS are calculated, and the thermodynamic properties of the state points are shown in Table 3.

Table 3. Thermodynamic properties of the state points of PPPS.

Point	Substance	Temperature ˚C	Pressure MPa	Mass flow rate,kg·s^{-1}	Exergy kJ·kg^{-1}	Exergy flow,kW
1	Raw lignite	25	0.1013	168.4627	13080	2203492
2	Predried lignite	99.6	0.1013	126.6086	17417	2205200
3	Predried lignite	300	0.1013	110.1837	20111	2215900
4	Char	550	0.1013	75.9166	23913	1815400
5	Steam	99.6	0.1013	41.8541	485.45	20318
6	Steam	200	0.1013	16.4249	545.46	8959.2
7	Steam	258.1	0.4232	53.4036	783.17	41824
8	Water	145.7	0.4232	53.4036	82.178	4388.6
9	Flue gas	420.96	0.1013	356.1046	162.25	57778
10	Flue gas	600	0.1013	356.1046	287.78	102480
11	Flue gas	1200	0.1013	356.1046	823.44	293230
12	Steam	550	0.1013	7.7129	927.96	7157.3
13	Tar	550	0.1013	5.8067	34652	201210
14	Air	25	0.1013	716.1097	0	0
15	Flue gas	126	0.1013	773.6530	18.177	14063
16	Water	284	30.400	527.7806	348.08	183710
17	Steam	323.3	4.8310	448.2778	810.70	363420
18	Steam	566	24.200	527.7806	1533.3	809260
19	Steam	566	4.3480	448.2778	1125.3	504460
20	Electricity	–	–	–	–	569870
21	Pyrolysis gas	550	0.1013	17.7506	17956	318730

By calculation, the thermal efficiency of the PPPS is 54.507% based on LHV, and 49.458% based on HHV. The exergy efficiency of the PPPS is approximately 49.46%. Obviously, due to the steam pre-drying process, the PPPS theoretical model can evidently increase the efficiency of the LPPS by approximately 1.46% based on the HHV, and by 1.62% based on the LHV at the calculation condition.

4.2. Energy and exergy analysis

4.2.1Energy analysis

The energy flows and losses of the LPPS and PPPS are illustrated in Fig.2a and Fig.2b respectively. The energy input to the system is expressed by the HHV of raw lignite in order to avoid the phenomenon of "Non-conservation of energy"[8]. The energy outputs involve 14.46% in the pyrolysis gas, 9.13% in the tar and 24.40% in electricity. The highest amount of energy loss is from the turbine unit, followed by the drying furnace in the LPPS. 29.63% energy is extracted from the boiler unit and only 56.83% energy is transferred to the steam. Comparatively, the electricity output in the PPPS is improved by 1.46%. However, the pyrolysis gas and tar outputs are invariable because of the constant yield for the pyrolysis unit. Only 22.38% energy is extracted from the boiler unit and 63.42% energy is transferred to the steam. Using the energy analysis, the reason for the improved efficiency of the PPPS can be explained. The energy mostly discharged from the turbine is recycled by pre-drying lignite, and this energy is mainly transferred to the available energy in lignite.

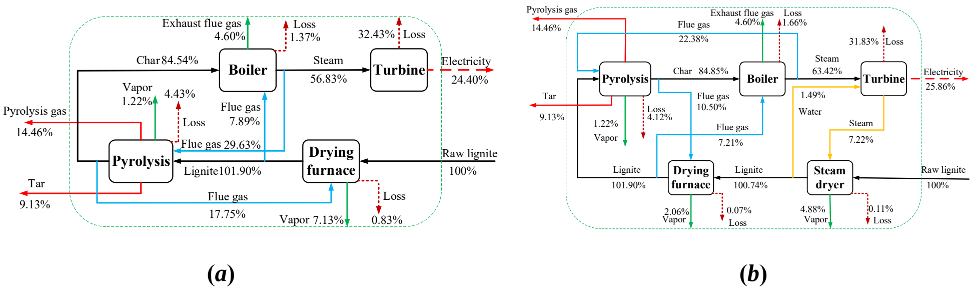
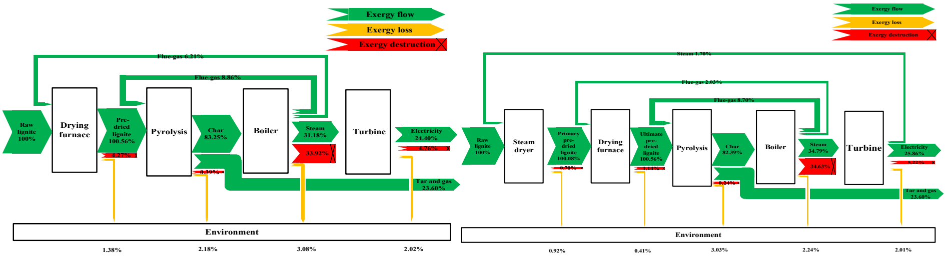


Fig.2 Energy flow and loss charts:(a)LPPS and (b) PPPS.

4.2.2 Exergy analysis

On the basis of the Table 2 and Table 3, the exergy flow, loss and destruction charts between the units of the LPPS and PPPS are illustrated in Fig. 3a and Fig. 3b, the data of which represent the exergy ratio to the input exergy of the system. The maximal loss and destruction in LPPS are the combustion process in the boiler unit, followed by the drying furnace unit. The low grade steam is firstly used to pre-dry the lignite, and then, the flue gas at the low temperature is used as the pre-drying heat source. In the whole drying process, the heat transfer temperature difference of PPPS is much lower than that of LPPS. Therefore, the exergy lost during the pre-drying is decreased significantly. Meanwhile, the lesser exergy extracting from the boiler also decreases the exergy lost in the boiler unit. Because of the exergy extracting, the lost in turbine is increased slightly. The exergy analysis suggests that the low heat transfer temperature difference and low grade energy recycling make the exergy efficiency increased.



(*a*) **(*b*)**

Fig.3 Exergy flow, loss and destruction charts:(a)LPPS and (b) PPPS.

5. Conclusions

A novel lignite-based energy system integrated with PPPS was proposed and thermodynamically analyzed in this paper. The thermal efficiency of the power system could be significantly increased by 1.62% (1.46%) based on the LHV (HHV). The energy mostly discharged from the turbine is recycled by pre-drying lignite, and this energy is mainly transferred to the available energy in lignite. The exergy analysis suggests that the low heat transfer temperature difference and low grade energy recycling make the exergy efficiency increased.

6. References

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