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The consumption of exergy for lignite drying with different technologies: a comparative theoretical study

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Abstract

Pre-drying is an effective method to upgrade lignite and broaden its utilization areas. Various drying technologies could be applied to pre-dry lignite. The drying temperature in these drying technologies are different, which means that energy at different grades is used in these dryers. To analyze the irreversibilities of drying process, the exergetic analysis models are developed in this study. The exergy feeding and consumption rates are defined as the indicators. Various lignite drying technologies are calculated and quantitatively compared. Results show that exergy consumption rate for steam fluid-bed dryer is the smallest, which is 432.6 kJ (kg H_2O)$^{-1}$.

Keywords: *lignite; drying technologies; exergy analysis; thermodynamics*

1. Introduction

Lignite, a kind of low rank coal, is widely used as feeding fuel for power plants. However, power plants directly using raw lignite always have low efficiency and high pollutant emissions. Pre-drying is a proved method to improve the utilization efficiency of lignite[1]. Many types of dryers could be applied to dry lignite. The heat consumption rate is usually used to evaluate the performance of dryers, which is defined as the amount of energy consumed to evaporate 1 kg water with the unit of kJ (kg H_2O)$^{-1}$. However, energies used to dry lignite are in different grades. The heat consumption rate could not perfectly reflect performances of dryers based on the second law of thermodynamics. Exergy is a concept of thermodynamics expressing the maximum useful work possible contained in energy[2]. It is widely used to evaluate energy grades and the performance of energy processes.

Exergetic analyses were conducted on various lignite dryers in this study. Lignite drying technologies were reviewed firstly and thermodynamic analysis models were then developed. The exergy feeding and consumption rates are defined to evaluate the performance of dryers in the viewpoint of exergetic analysis and are compared quantitatively for various lignite dryers.

2. Materials and Methods

2.1. Lignite drying technologies

Drying of lignite could be classified to evaporative drying and mechanical-thermal dewatering. In this paper, we focus on the evaporative drying technologies. The evaporative drying is an energy intensive process, because water in lignite needs to absorb a lot of heat to evaporate. For the evaporative drying technologies, flue-gas or steam could be applied as the drying heat sources. Dryers uses steam as heating source are classified as steam dryers, including rotary-tube dryer and steam fluid-bed dryer. Characteristics and working parameters of steam dryers are listed in Table 1. When flue-gas is used to pre-dry lignite, the dryers are classified as flue-gas dryers. Characteristics and working conditions of flue-gas dryers are listed in Table 2.

Table 1 Operation parameters of steam dryers[3]

Dryer type	Characteristics	Heating medium parameters	
		Inlet	Outlet
Rotary-tube dryers	Using air as carrier as evaporative moisture; consisted of a drum equipped with tubes.	~180°C/0.4~0.5MPa	~Saturated water
Steam fluid-bed dryers	Lignite drying in slightly superheated steam; steam fluid-bed with internal heaters.	~140°C /0.32MPa	~Saturated water

Table 2 Operation parameters of flue-gas dryers[4]

Dryer type	**Characteristics**	**Heating medium temperature /°C**	
		Inlet	**Outlet**
Rotary	Drying along with disintegration; cocurrent mode.	750	120
Pneumatic	Short drying time; Lignite lifted by drying gas during pneumatic transport drying.	600	100
Fluid-bed	Easy to control; High drying intensity due to good mixing and high temperature heating medium.	450	75
moving bed	Possibility of full automation; compact construction and simple design.	175	80

2.2. Thermodynamic analysis models

2.2.1 Dryer model

The dryer model is indicated in Fig.1. As shown in Fig.1, 1 kg raw lignite is fed into the dryer, and λ kg water contained in lignite is dried out. m_a kg air is leaked into or used as carrier gas for drying 1 kg raw lignite. m_h kg heating medium (flue-gas or steam) releases heat in the dryer to dry lignite. In some types of dryers the heating medium directly contacts with lignite and leaves the dryer as dryer exhaust. While in some indirect dryers (rotary-tube dryer, etc.), the heating medium only exchanges heat in the dryer.

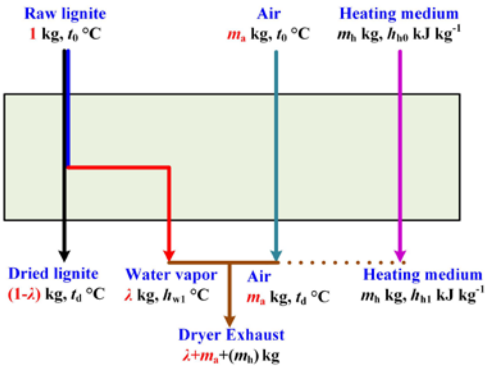

Fig. 1 Schematic diagram of Dryer.

The degree of pre-drying, λ, is defined to express the mass of water removed from per unit mass of raw lignite as

$$\lambda = \frac{M_{raw} - M_{upg}}{1 - M_{upg}} \tag{1}$$

where M_{raw} and M_{upg} are the mass of water contained in per unit mass of raw and dried lignite, respectively.

The minimum energy consumption, which is only absorbed by lignite to increase temperature and water to evaporate, for drying 1 kg lignite could be evaluated with

$$q_{d0} = \lambda \cdot (h_{dw} - h_{w0}) + (1-\lambda) \cdot (h_{c1} - h_{c0}) \quad (2)$$

where h_{dw} and h_{w0} are enthalpies of the water contained in dryer exhaust and raw lignite respectively, kJ kg^{-1}; h_{c1} and h_{c0} are enthalpies of dried lignite at the outlet and inlet temperatures respectively, kJ kg^{-1}.

The energy absorbed by possible in-leaking or carrier air is

$$q_{da} = m_a \cdot Cp_a (t_d - t_0) \quad (3)$$

where Cp_a is the specific heat capacity of air, kJ kg^{-1} K^{-1}; t_{d1} and t_{a0} are temperatures of dryer exhaust and ambient respectively, °C.

Based on the energy balance in the dryer, the mass of heating medium is

$$m_h = \frac{q_{d0} + q_{da}}{\eta_d \cdot (h_{h0} - h_{h1})} \quad (4)$$

where h_{h0} and h_{h1} are enthalpies of heat medium led into and output from the dryer, kJ kg^{-1}; η_d is the thermal efficiency of dryer, kJ kg^{-1}.

To evaluate the mass flow rate of drying heat source, the rate of drying medium to dry out 1 kg water is defined as

$$K_h = \frac{m_h}{\lambda} \quad (5)$$

2.2.2 Exergetic analysis model

The dead point is the benchmark for the exergetic analysis. When the exergy carried by the dryer exhaust is recovered by cooling, the dryer exhaust could be cooled to the ambient temperature and becomes saturated moist gas. Therefore, the compositions of saturated moist gas is defined as the deadpoint compositions. The deadpoint pressure and temperature for the exergetic analysis are

$$p_0 = 0.1\text{MPa} \quad (6)$$

$$T_0 = 293.15\text{K} \tag{7}$$

In the drying process, substances include lignite, gas (flue-gas and air), water (liquid and steam) and dryer exhaust. Assumptions of ideal gas mixture for the dryer exhaust are used. The exergy of water component is calculated with

$$E_w = h_w - h_{w0} - T_0(s_w - s_{w0}) + \bar{R}_w T_0 \ln \frac{y_w}{y_{w0}} \tag{8}$$

where h_w and h_{w0} are the enthalpies of water at calculation and deadpoint conditions respectively, kJ kg^{-1}; s_w and s_{w0} and are the entropies at calculation and deadpoint conditions respectively, kJ kg^{-1} K^{-1}; $\bar{R}_W$ is gas constant of water vapor, kJ kg^{-1} K^{-1}; y_w and y_{w0} are volume fractions of water vapor at calculation and deadpoint conditions.

It is assumed that the flue-gas or air component has constant specific heat (average specific heat Cp_g, kJ kg^{-1} K^{-1}). Then the exergy of gas component is

$$E_g = Cp_g(T_g - T_0 - T_0 \ln \frac{T_g}{T_0}) + R_g T_0 \ln \frac{y_g}{y_{g0}} \tag{9}$$

where T_g is temperature at calculation condition, K; $\bar{R}_g$ is gas constant of gas, kJ kg^{-1} K^{-1}; y_g and y_{g0} are volume fractions of gas at calculation and deadpoint conditions.

The physic exergy carried by the dried lignite is

$$E_l = Cp_l(T_d - T_0 - T_0 \ln \frac{T_d}{T_0}) \tag{10}$$

where Cp_l is the constant specific heat of lignite, kJ kg^{-1} K^{-1}; T_d is the temperature of lignite at the outlet of dryer, K.

To quantitatively compare the thermodynamic performance of various dryers, the exergy feeding rate is defined as

$$e_f = \frac{E_h}{\lambda} \tag{11}$$

where E_h is the exergy fed into the dryer by drying heat source, kJ.

The exergy carried by the dried lignite or dryer exhaust can be recovered by heat recovered, whereas the internal exergy loss (exergy destruction) in the dryer and external exergy loss along with heat loss of the dryer could not be recovered. The exergy consumption rate is defined as

$$e_c = \frac{E_h - E_l - E_e}{\lambda} \tag{12}$$

The exergy feeding rate e_f (kJ (kg H_20)$^{-1}$) expresses the exergy feeding amount to dry 1 kg water out from raw lignite, and the exergy consumption rate e_c (kJ (kg H_20)$^{-1}$) expresses the irreversibilities and heat loss of lignite dryers.

3. Results and discussions

We use Yimin lignite as the reference coal to carry out quantitative analysis[5]. Moisture contents of raw lignite is 39.5% and it is assumed to be dried to 15% in the dried lignite. The constant specific heat of lignite is 1.3 kJ kg^{-1}.

3.1. Heat balance of lignite dryers

The heat balance of lignite dryers listed in Tables 1 and 2 is calculated. The mass flow rate of heat source for drying 1 kg water out from lignite is compared in Fig.2. As shown in Fig.2, the mass flow rate of heat source varies greatly. The heat released by per unit flue-gas is significantly lower than that released by per unit steam. Therefore, K_h for flue-gas dryers is bigger than that for steam dryers. The K_h is above 29 for the moving bed dryer, because the temperature drop of flue-gas for the moving bed dryer is only 95 °C. For the steam fluid-bed dryer and rotary-tube dryer, the rates of drying medium are 1.38 and 1.49, respectively.

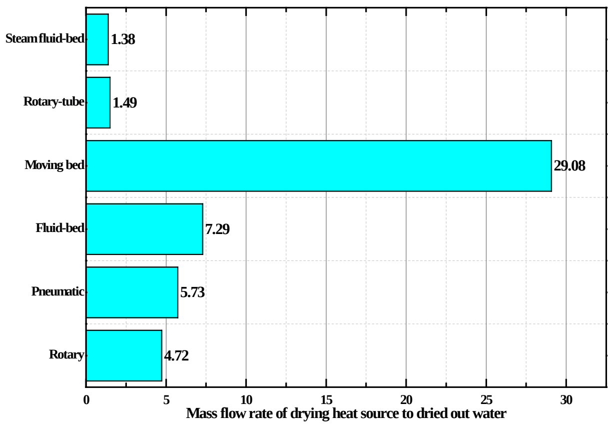

Fig. 1 Schematic diagram of Dryer.

3.2. Comparison of exergy feeding and consumption rates

Based on the heat balance of lignite dryers, exergetic analyses were conducted. The exergy feeding and consumption rates for lignite dryers were compared in Fig.3. As shown in Fig.3, the exergy feeding rate and exergy consumption rate for dryers vary greatly. The flue-gas of 750 °C is used to dry lignite in the rotary dryer, so the exergy feeding rate is as big as 1837.9 kJ (kg H_2O)$^{-1}$. If the exergy contained in dryer exhaust and dried lignite could be recovered, the exergy consumption rate could be decreased to 1424.8 kJ (kg H_2O)$^{-1}$. The low temperature heat source is used to dry lignite for the steam dryers. The exergy feeding rates for rotary-tube dryer and steam fluid-bed dryer are 1131.7 and 955.2 kJ (kg H_2O)$^{-1}$, respectively. In the steam fluid-bed dryer, no air is used as carrier gas, so more exergy could be recovered from dryer exhaust. The exergy consumption rate for steam fluid-bed dryer is only 432.6 kJ (kg H_2O)$^{-1}$.

Air is always used as carrier gas for the rotary-tube dryer. In Fig.3, the mass flow rate of air for drying 1 kg water is assumed as 3 kg. The mass flow rate of carrier gas for rotary-tube dryer will indeedly influence the exergy feeding rate and exergy consumption rate, which is shown in Fig.4. As shown in Fig.4, the exergy feeding rate increases linearly with mass flow rate of carrier air. For more exergy can be recovered in dryer exhaust when less air is used as the carrier gas, the exergy rate reduction of exergy consumption rate compared with exergy feeding rate decreases with the increase of mass flow rate of carrier gas.

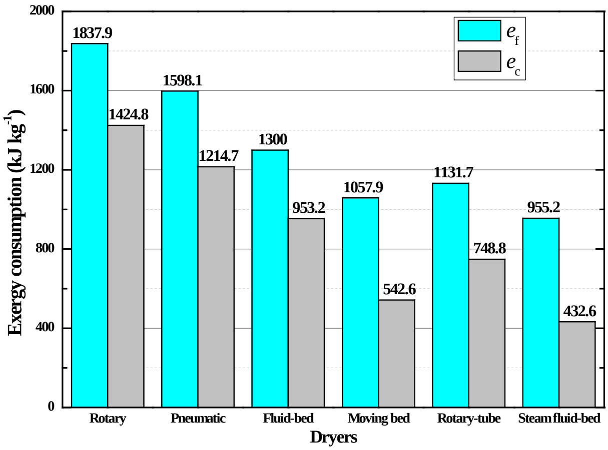

Fig. 3 Comparison of exergy consumption rate.

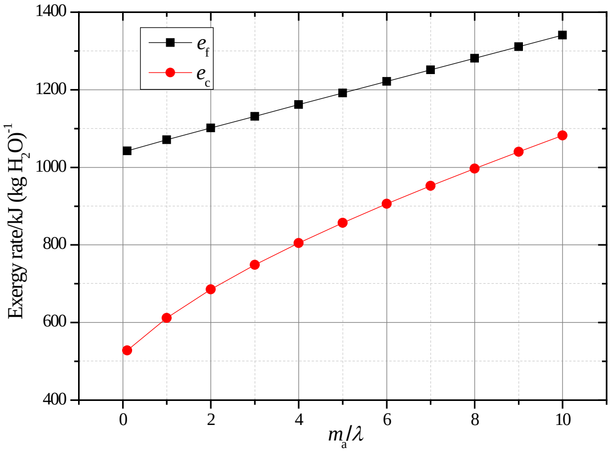

Fig. 4 Influence or carrier air on exergy feeding and consumption rates for rotary-tube dryer.

4. Conclusions

The heat consumption rate for lignite drying is a conventional indicator to evaluate the performance of lignite dryers. However, the drying temperature for various drying technologies are different, which means that energy at different grades is used in these drying technologies. The heat consumption rate could not evaluate the irreversibilities in drying process. Therefore, the exergetic analysis models are developed in this paper, and the exergy feeding rate and exergy consumption rate are defined as indicators for exergy analysis. Quantitative analyses on lignite dryers reveal that irreversitbilities vary greatly for lignite drying technologies. Dryers using low temperature heat as dryer heat source consume less exergy in the drying process. The exergy consumption rate for steam fluid-bed dryer is the smallest, which is 432.6 kJ (kg H_2O)$^{-1}$.The aim of this paper is to provide a guidance for the development and study of lignite drying technologies in the viewpoint of reduction for exergy consumption.

5. References

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