Exergy destruction calculation and analysis for a Coal drying system

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Abstract. A coal drying system was modelled and the calculation methodology was developed to calculate the system. Then the system performance was obtained and the exergy destruction and loss in the system is 70.5 kW. The reasons of exergy destruction were tried to be explained from the perspective of energy grade. In DRY-REAC, the wet coal was dried to dry coal, the process of which is irreversible, and the main exergy destructions are used to pay the thermodynamic penalty of the increased energy grade of the wet coal.

1. Introduction

Coal is the most abundant and widely distributed non-renewable energy in China, and some of the coal have high water content, such as lignite. When the water content of coal is more than 10%, the boiler efficiency will decrease by 0.07% for every 1% increase of water content [1]. The existence of water in coal also has a direct impact on the design and operation of coal handling and pulverizing systems. Therefore, dehydration of low rank coal with high moisture content is one of the important ways to improve the energy utilization efficiency of coal. The drying process of low rank coal involves many factors such as the temperature, humidity and flow rate of the drying medium. It takes a lot of manpower and material resources to carry out this research through experiments. Therefore, it is necessary to solve the relevant problems with the help of simulation calculation [2-3].

Aspen Plus is general chemical engineering software, which has been used by some researchers to simulate the drying process of lignite. Li Zheng et al. made technical and economic analysis on integrated gasification combined cycle system of bituminous coal and lignite respectively, and Aspen Plus was used to simulate the drying process of lignite [4]. Liu Na simulated the coal drying process by Aspen Plus software, and studied the relationship among different drying media, different media temperature flow and dry coal outlet temperature [5].

From the perspective of the second law of thermodynamics, energy analysis is widely used to measure the performance of coal-based systems [6–7]. Li and Lin calculated the exergy destruction distributions of the liquid from coal (LFC) system, and found that the overall exergy efficiency can be increased by reducing moisture in lignite and making full use of physical exergy of pyrolysates [8]. He et al. have made exergy analysis for an industrial-scale pressurized Lurgi fixed-bed coal gasifier, and the results show that the exergetic efficiency of the fixed-bed gasifier is mainly determined by the oxygen/coal ratio [9]. However, the studies of exergy analysis on coal drying systems are short. In this study, a coal drying system was simulated and then the exergy destruction for the system was performed.
2. Modelling and calculation methods

2.1 Description of the coal drying process

The configuration of the coal drying system is schematically shown in Figure 1. The coal drying system consists of two major components, drying reactor (DRY-REAC) and gas-solid separation unit (SEP). The wet coal with 25 wt% of initial moisture (1) is heated by the hot gas (2) in DRY-REAC, and the moisture in the wet coal is reduced to 5 wt%, all the logistics leaving DRY-REAC are sent to SEP. The gas phase (3) leaving SEP comprises low temperature drying gas and removed water vapor, while the solid phase (4) leaving PYRO is the product dry coal.

![Figure 1. Schematic description of coal drying](image)

The coal drying system is shown in Figure 1 was calculated using Aspen Plus. In the simulation process, the block RSTOIC reactor was employed to simulate the drying unit by inputting the reaction coal (wet) → coal (dry) + 0.055H2O and embedding a calculation block to realize the drying process [10]. And the block FLASH was used to simulate the separation process of exhaust gas and dry coal.

2.2 Calculation methods

The basic equations obtained from the conservation law for mass, energy and exergy in the components are written as Eqs. (1), (2) and (3), respectively. For calculating energy, exergy and other properties, the Peng-Robinson equation of state is used as the global property method.

\[
\sum m_i = 0
\]

\[
\sum m_i \cdot H_i + \sum Q_j + \sum W_k = 0
\]

\[
\sum m_i \cdot \varepsilon_i + \sum \left[ \int_0^1 \left( 1 - \frac{T_0}{T} \right) \delta Q \right]_j + \sum W_k - m \cdot I = 0
\]

where \( m_i \), \( H_i \) and \( \varepsilon_i \) denote the mass flow, enthalpy and exergy of stream i, respectively; \( Q_j \) is the heat of unit j exchanged with environment; \( W_k \) is the work input or output; and I stands for the exergy destruction and loss in the process.

The proximate and ultimate analyses of the wet coal is listed in Table 1. The drying medium for the wet coal consists of nitrogen and oxygen, and the volume fractions of nitrogen and oxygen are 99% and 1%, respectively. The temperature of the drying medium is 473 K. The moisture content of coal after drying is 5%.

| Proximate (wt %) | Ultimate analysis (wt %) | Calorific value/KJ kg\(^{-1}\) |
|------------------|--------------------------|-------------------------------|
| FC\(_d\) | V\(_d\) | A\(_d\) | M\(_ar\) | C\(_d\) | H\(_d\) | O\(_d\) | N\(_d\) | S\(_d\) | A\(_d\) | Q\(_ar\),net |
| 56.97 | 32.83 | 10.2 | 25 | 72.14 | 4.58 | 12.60 | 1.06 | 0.28 | 4.10 | 23420 |
2.3 Exergy calculation of coal

Compared with conventional substances such as water, nitrogen and oxygen, the coal is non-conventional substance, which doesn’t have determined molecular formulas, and the exergy of coal cannot be calculated by the software of Aspen Plus. In this study, the enthalpies and exergies for conventional substances and the enthalpy of coal were calculated by Aspen Plus; while the exergy of coal was calculated by Eqs. (4) and (5) [11].

The standard exergy of coal was calculated by Eq. (4)

$$\varepsilon^0(T_0, p^0) = \left[ 1.0401 + 0.1728 \frac{H}{C} + 0.0432 \frac{O}{C} + 0.2169 \frac{N}{C} \left( 1 - 2.0628 \frac{S}{C} \right) \right] \cdot Q_{ar,net}$$

(4)

The term $\varepsilon^0(T_0, p^0)$ stands for the standard exergy of coal, and the C, H, O, N and S represent carbon, hydrogen, oxygen, nitrogen and sulphur contents of the coal, in wt% (dry basis). $Q_{ar,net}$ is the net heat value of coal.

The exergy of coal at any state can be calculated by Eq. (5).

$$\varepsilon(T, p) = \varepsilon^0(T_0, p^0) + \int_{T_0}^{T} C_p dT - T_0 \int_{T_0}^{T} \frac{C_p}{T} dT - R \ln \left( \frac{P}{p^0} \right)$$

(5)

where the term $\varepsilon^0(T_0, p^0)$ is calculated by Eq. (4), and thermodynamic features $C_p$, $T$, $p$ are the heat capacity, temperature and pressure, respectively. The values of the temperature and pressure at the environmental state are $T_0 = 298.15$ K and $p^0 = 100$ kpa.

2.4 General assumptions

The coal drying system was calculated under the following assumptions.

(1) The cycle runs in steady-state, and the changes in the potential energy and the kinetic energy of the components are negligible.

(2) The process of coal drying is treated as a chemical reaction.

(3) The mass flow rate of the feed coal is 1000.00 kg h$^{-1}$, and the outlet temperature of dry coal is 323 K.

3. Results and discussion

Based on the above conditions, the coal drying system was calculated. The results showed that the mass flow rates of the input wet-coal (1), the hot-gas (2), the exhaust gas (3) and the output dry-coal (4) are 1000.0 kg h$^{-1}$, 3500 kg h$^{-1}$, 3710.52 kg h$^{-1}$, and 789.48 kg h$^{-1}$, respectively. Specially, according to the calculation methods mentioned in section 2, the enthalpies and exergies for the streams were calculated, and the data are listed in Table 2. Furthermore, according to the Eqs. (2) and (3) and the exergy data listed in Table 2, the system performance was obtained and showed in Table 3. The exergy destruction and loss in the drying process can be obtained and the value is 70.5 kW.

| State no.(j) | $T_j$/K | $p_j$/bar | $m_j$/kg h$^{-1}$ | $H$/kJ kg$^{-1}$ | $\varepsilon$/kJ kg$^{-1}$ |
|-------------|---------|-----------|-----------------|----------------|-----------------|
| 1           | 298.15  | 1         | 1000            | 11973289.32    | 24866.83        |
| 2           | 473.15  | 1         | 3500            | 182.63         | 37.14           |
| 3           | 322.69  | 1         | 3710.52         | -735.3         | -747.5          |
| 4           | 322.69  | 1         | 789.48          | 15170310.08    | 34854.10        |
Table 3. Performance of the system

| State no.\((j)\) | Input to the cycle | Substance | Outputs from the cycle |
|------------------|--------------------|-----------|------------------------|
|                  | Energy, kW | Exergy, kW |                       | Energy, kW | Exergy, kW |
| 1                | 332591.7   | 6907.4    | 3                      | -757.9     | -770.45    |
| 2                | 177.56     | 36.11     | 4                      | 3326849    | 7643.50    |
| Total            | 3326091.3  | 6943.56   | Total                  | 3326091.1  | 6873.05    |

In Table 3, it can be obtained that the total enthalpy input is equal to the total output; while the total exergy destruction is 70.5 kW. In DRY-REAC, the temperature of the hot gas (2) is decreased and heat is released to dry the wet coal (1). The detailed internal processes are that, with the temperature decrease of the hot gas (2), the energy grade of stream (2) drops down; while the wet-coal (1) becomes the dry coal (4), its energy grade increased. The cost of coal grade increasing is the decreasing of the energy grade of the hot gas. The energy grade increase of coal is represented by the decrease of water content, and the process of water evaporation and separation from coal is irreversibility, which caused the main exergy destruction in DRY-REAC.

4. Conclusion
A coal drying system was modelled and the system is mainly composed of drying reactor and gas-solid separation unit. Then the calculation methodology was developed to calculate the system. The enthalpies and exergies of conventional substances were calculated with the help of Aspen plus, while the exergy of coal was calculated by formulas. The exergy destruction and loss in the system blocks were calculated and the value is 70.5 kW. The reasons of exergy destruction were tried to be explained from the perspective of energy grade. In DRY-REAC, the wet coal was dried to dry coal, the process of which is irreversible, and the main exergy destructions are used to pay the thermodynamic penalty of the increased energy grade of the wet coal.

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