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Research Paper

Exergy analysis on the process with integrated supercritical water gasification of coal and syngas separation

Zhewen Chen, Xiaosong Zhang *, Wei Han, Lin Gao, Sheng Li

Institute of Engineering Thermophysics, CAS, China
University of Chinese Academy of Sciences, Beijing 100190, China

HIGHLIGHTS

- Exergy analysis of a process with supercritical water gasification of coal is conducted.
- The exergy conversion mechanism of the process is obtained.
- The exergy destruction and distribution of the process is analyzed.
- A maximum exergy efficiency of 89.18% is obtained.

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ABSTRACT

Supercritical water gasification (SCWG) is a promising technology for clean and efficient coal utilization. The exergy analyses on the processes with integrated SCWG of coal and syngas separation are conducted for clear understanding about the exergy distributions in the processes. The energy level of the heat provided for the gasifier is upgraded to the energy level of the syngas, which is driven by the decrease of energy levels from the coal to the syngas. The minimum temperatures of the heat provided for the gasifier are obtained in different coal-water-slurry concentrations (CWSCs). The total exergy destruction firstly increases, and then decreases with increasing CWSC. The maximum total exergy destruction of the process is obtained when the CWSC is approximately 10%. The exergy efficiency of the process has a converse trend with the total exergy destruction. When the CWSC is in the range of 6% and 20%, the maximum exergy efficiency is 89.18%. The origins for the production of the exergy destruction are also studied.

1. Introduction

Coal is the second source of primary energy (approximately 30%), and over 40% of the worldwide electricity is produced from coal [1]. The large consumption of coal causes severe environmental pollutions, such as acid rain, greenhouse effect and so on. Meanwhile, direct combustion of coal is not an efficient way to use the high-level energy stored in the coal.

There have been mature or immature coal utilization technologies such as gasification, liquefaction, poly-generation, and chemical looping, which are environmental friendly and efficient. Supercritical water gasification is another technology which can efficiently and cleanly convert coal into hydrogen-rich syngas for further utilization. SCWG of coal has some characteristics as follows [2–4]: (1) elements such as N, S, P, As and Hg deposit as inorganic salts in the supercritical water (SCW). After separating the syngas from (SCW; $T > 374\,°C$ and $P > 22.1$ MPa), there is no need to clean the syngas before further use; (2) complete gasification can be achieved at a lower temperature (about 500–700 °C) compared to conventional coal gasification technology (about 1200 °C); (3) SCWG of coal produces hydrogen-rich syngas; (4) some water participates in the gasification reactions to improve the calorific value of the syngas.

Supercritical water gasification has been proposed for decades. In 1978, Modell firstly found that unexpectedly high conversion to high BTU gas compositions from organic materials without accompanying formation of undesired char or coke can be obtained when reacting the organic materials with water at a temperature and pressure equal to or more severe than the critical condition for water [5]. In the 1980s and 1990s, researchers mainly focused on extracting low-rank coals, biomass, and lignin in supercritical water to obtain synthetic fuels [6–9]. From the beginning of this century, main attention was paid to producing hydrogen-rich

* Corresponding author at: Hainan University, China.
E-mail address: zhang.xiaosong@foxmail.com (X. Zhang).

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Nomenclature

SCW	supercritical water	η	thermal efficiency
SCWG	supercritical water gasification	α, β, γ, π	dimensionless parameters
Q	heat resource	*s*	entropy
ΔH, *h*	enthalpy	*w*	mass fraction
ΔE, *e*	exergy	*x*	mole fraction
ΔEXL	exergy destruction	*R*	universal gas constant
W	work output	*A*	energy level
LHV	lower heating value		

syngas through gasifying biomass, coal or other organic materials in supercritical water. Many works in the literature were carried out to study the influences of different parameters, such as gasification temperature, pressure, coal-water-slurry concentration (CWSC), catalyst, residence time, oxidation ratio and coal type on the product distributions and yields [10–14]. Other works were concentrated on thermodynamic and kinetics model for gasification reactions [2,15,16], transformation of elements such as sulfur [17], heavy metal [18], and potassium [19] during gasification reactions, numerical investigations on reactors of heat and mass transfer performances [20,21], and power generation models integration [22,23].

Coal reacts with SCW in a gasifier where the temperature and pressure are usually 500–700 °C and over 22.1 MPa, respectively. The gasification product consists of produced syngas and unreacted SCW. The gasification product has a large amount of sensible heat. When the CWSC is between 2% and 20%, the ratio of the sensible heat of the gasification product and the lower heating value (LHV) of the coal is in the range of 0.275–5.519. The ratio is higher in lower CWSC. The produced syngas is partially dissolved in the unreacted SCW. Thus, the syngas should be separated from the unreacted SCW for further utilization. The simplest way for the separation is lowering the temperature and pressure of the gasification product because the solubility of the syngas in the water is very small. To reasonably use the sensible heat of the gasification product, the parallel heat recovery method [23] is implemented.

As can be seen in the literature review, few articles considered the exergy conversion in the SCWG processes. Yan et al. [24] proposed the exergy release mechanism and conducted exergy analysis for coal oxidation in supercritical water. The analysis is based on the comparison between coal oxidation in SCW and in air. And the molar ratio of the coal and SCW is 1:1, i.e., the CWSC is assumed to be 20%. However, the SCW is excess in practical SCWG processes. The relationship between the total exergy destructions and CWSCs are not discussed. In the other hand, the natures or origins for the production of exergy destruction in the SCWG process are not studied.

In this study, a process with integrated SCWG of coal and syngas separation is proposed and analyzed. The sensible heat of the gasification product is used to simultaneously preheat the water before being heated to supercritical state and heat the feed water of a Rankine cycle. The syngas is separated from the unreacted water after being decompressed to atmospheric pressure. The influence of CWSC on the destructions in the process is discussed, and the origins for the production of the exergy destructions are studied. The exergy efficiencies of the process in different CWSCs are obtained.

2. Proposal of the process

The temperature and pressure of SCWG process are usually 500–700 °C and over 22.1 MPa, respectively. The gasification product mainly consists of H_2, CO_2, CH_4, CO, and C_2H_6. The yields of H_2, CO_2, and CH_4 account for more than 50%, approximately 30–40%, and approximately 10–20% of the total gas yield, respectively. Approximately 10% of the SCW is consumed in the gasification reactions. The produced syngas partially dissolves in the unreacted SCW under high-temperature and -pressure. For simple and clear understanding of the process with integrated SCWG of coal and syngas separation, coal is instead by carbon for analysis. The gasification reaction is listed as follows:

$$C + 2H_2O \rightarrow 2H_2 + CO_2 \tag{R1}$$

2.1. Detailed description

The flow sheet of the process with integrated SCWG of coal and syngas separation is illustrated in Fig. 1. Coal is gasified by SCW in the gasifier where the temperature and pressure are 650 °C and 25 MPa, respectively. Q from the heat resources (solar energy or organic material combustion) is provided for the gasification processes, and the minimum temperature of Q is T_{min}.

After the gasification process, the gasification product flows out of the gasifier, and enters the heat exchanger (HE) to release most of its sensible heat. In the HE, the water is pre-heated, and the feed water of the Rankine cycle is heated to 510.1 °C. The water is preheated to $T_{back\text{-}heating}$ in the HE. The temperature of the gasification product is lowered down to approximately 30 °C after the heat exchange process. And then the pressure of the gasification product is decompressed to atmospheric pressure in the pressure relief. The syngas can be separated from the water in a separator.

2.2. Methodology

For simple analysis, the work consumptions of the pumps for the compressions of the water and feed water are neglected.

The energy balance of the gasifier can be expressed as:

$$\Delta H_c + Q + \Delta H_w = \Delta H_m \tag{1}$$

The exergy balance of the gasifier is:

$$\Delta E_c + \Delta E_q + \Delta E_w = \Delta E_m + \Delta EXL1 \tag{2}$$

The energy balance of the HE is:

$$\Delta H_m = \Delta H_h + \Delta H_{m1} + \Delta H_w \tag{3}$$

The exergy balance of the HE is:

$$\Delta E_m = \Delta E_h + \Delta E_{m1} + \Delta E_w + \Delta EXL2 \tag{4}$$

The work output of the Rankine cycle is:

$$W = \Delta H_h \cdot \eta_r \tag{5}$$

The exergy balance of the Rankine cycle is:

$$\Delta E_h = W + \Delta EXL3 \tag{6}$$