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High-efficiency power generation system with integrated supercritical water gasification of coal

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ABSTRACT

A novel power generation system with integrated supercritical water gasification (SCWG) of coal is proposed in this article. The gasification product directly enters the supercritical turbine to generate electricity. After pressure relief, the syngas separated from the unreacted water is transferred to the combined cycle. The influences of coal-water-slurry concentration (CWSC) and the outlet pressure (P_h) of the supercritical turbine on the system performances are studied. The results show that the thermal efficiency increases with increasing CWSC or decreasing P_h. The ultimate thermal efficiency of the system can be obtained when the CWSC is 25 wt% and P_h is 1 bar, which can approach 54.68%. The thermal efficiency of the novel system is higher than that of the power generation system with integrated SCWG of coal and parallel chemical heat recovery.

1. Introduction

Coal is the second source of primary energy (approximately 30%), and contributes over 40% of the worldwide electricity production [1]. The large consumption of coal causes severe environmental pollution, such as acid rain, greenhouse effect. Meanwhile, direct combustion of coal is not an efficient way to use the high-level energy stored in the coal. The thermal efficiencies of conventional coal-fired supercritical power plants are usually between 41.0 and 45.0% [2–5]. And the thermal efficiencies of the major coal-based Integrated Gasification Combine Cycle (IGCC) projects worldwide are approximately within the range of 35.0–43.0% [6,7]. It is urgent to develop more efficient coal utilization technologies to meet the growing energy demand.

Supercritical water (SCW) can efficiently and cleanly convert coal into hydrogen-rich syngas for further utilization. SCWG of coal has some characteristics as follows [8–14]: (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 (approximately 500–700 °C) compared to conventional coal gasification technology (about 1200 °C); (3) in conventional coal gasification technology, pure oxygen is worked as gasification agent to improve the coal gasification efficiency. Thus, large amount of energy should be provided to the air separation unit to produce pure oxygen. And in the supercritical water gasification of coal process, pure oxygen is instead by the supercritical water. Thus, the air separation unit can be omitted, which may lead to better thermal performance.

The gasification product consists of the produced syngas and unreacted SCW, and the syngas partially dissolves in the unreacted SCW. There is large amount of chemical energy and sensible heat exists in the gasification product. When integrating power generation cycles, the integration schemes should be considered for efficient utilization of the energy. In the aspects of power generation systems integration, there are two main integration schemes in the literature: firstly, as can be seen in Fig. 1, coal direct combustion with integrated self-heating and supercritical turbine scheme, i.e., the coal is combusted with SCW and pure oxygen to produce high-temperature mixed working medium (only consists of CO_2 and H_2O), and then the mixed working medium goes through a supercritical turbine to generate electricity. After the expansion in the supercritical turbine, the CO_2 can be separated from the H_2O, and

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Nomenclature

SCW	Supercritical Water
SCWG	Supercritical Water Gasification
CWSC	Coal-water-slurry concentration
CGE	Cold Gas Efficiency
W	Work output
LHV	Lower Heating Value

be captured for further use.

In this integration scheme, the pressure energy and sensible heat is reasonably used in the supercritical turbine. However, due to the relative low turbine inlet temperature (approximately 620 °C), this integration scheme is not efficient enough from the viewpoint of thermal efficiency.

Secondly, as can be seen in Fig. 2, coal gasification with integrated external-heating and synags combustion in combined cycle scheme, i.e., the coal is gasified by the SCW with the heat from the external energy sources. According to the principle of cascade utilization of energy [15], the produced syngas is transferred to the combine cycle for efficient power generation, and the sensible heat of the gasification product can be recovered or transferred to a Rankine cycle for power generation. In this integration scheme, the syngas should be firstly separated from the unreacted SCW. In the separation process, the pressure and temperature of the gasification product would be lowered down to atmospheric values. Thus, the pressure energy of the gasification product is released in a pressure relief, and is not reasonably used. However, due to the high power generation efficiency of the combined cycle, this integration scheme could be more efficient than scheme A.

Briola et al. proposed a supercritical water oxidation (SCWO) power plant for coal combustion, which used scheme A. The coal reacted with pure oxygen and supercritical water in the SCWO reactor. The thermal power produced by the reaction was transferred to the feed water of a reheat Rankine cycle to generate electricity. The pure oxygen was produced by the air separation unit. The maximum net thermal efficiency of the system was 27.9% [16]. Bermejo et al. proposed SCWO power plants with or without a reheating cycle. Coal reacted with water and air in the SCWO reactor. The reaction product expanded in a supercritical turbine until atmospheric pressure to generate electricity. In the system with a reheating cycle, the heat removed from the expanded reaction product was used to preheat partially the air stream and water stream. The net thermal efficiencies of the SCWO power plants with and without the reheating cycle reached 37.8% and 41.17%, respectively [17].

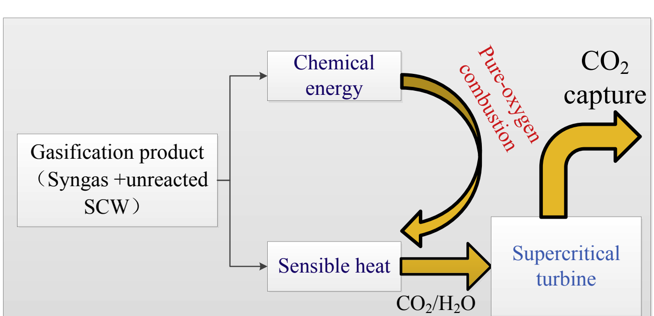

Fig. 1. Efficient power generation integration principles for the supercritical water gasification of coal: *Scheme A*.

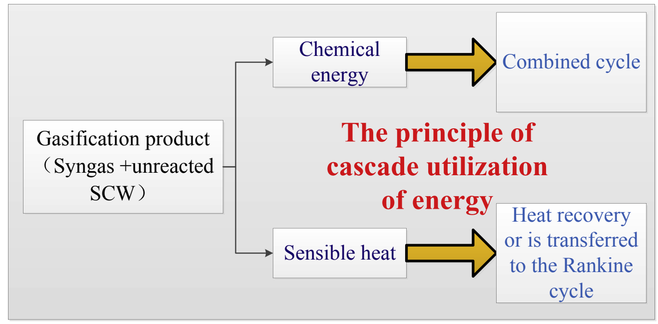

Fig. 2. Efficient power generation integration principles for the supercritical water gasification of coal: Scheme B.

According to scheme B, Chen et al. proposed the power generation systems integrated SCWG of coal with tandem [18] and parallel [19] chemical heat recovery. The heat for the gasification reaction was provided by the coal combustion in an external combustor. The sensible heat of the gasification product was used to heat the feed water of a Rankine cycle or preheat the SCW. The syngas produced by the gasification reactions was firstly separated from the unreacted water, and then was transferred into the combined cycle for power generation. The net thermal efficiencies of the power generation systems integrated SCWG of coal with tandem and parallel chemical heat recovery are 42.2% and 46.6%, respectively.

From the literature researches mentioned above, benefiting from the more efficient energy use in the combined cycle than in the supercritical turbine, Scheme B have advantages over Scheme A. However, the pressure energy of the gasification product is not fully used in Scheme B. Due to the high-pressure characteristic of SCWG of coal, the gasification product can be directly transferred into a supercritical turbine for power generation. And then the syngas can be separated from the unreacted water and transported to the combined cycle. This kind of integration scheme may further improve the thermal efficiencies of the power generation systems with integrated SCWG of coal.

2. Proposal of the novel system

The temperature and pressure of SCWG technology 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 SCWG reaction is part of endothermal. For simple and clear understanding of the SCWG technology, coal is instead by carbon for analyses. The main gasification reaction during SCWG technology is listed as follows:

$$C+2H_2O \rightarrow 2H_2+CO_2 \quad \text{(R1)}$$

The heat needed for the gasification reaction is supplied by the carbon combustion in the air:

$$C + O_2 \rightarrow CO_2 \quad \text{(R2)}$$

The flow sheet of the novel power generation system with integrated SCWG of coal and direct expansion of the gasification product in the supercritical turbine is illustrated in Fig. 3. The carbon is gasified by SCW in the gasifier where the temperature and pressure are 650 °C and 25 MPa, respectively. The gasification product, which consists of H_2O, CO_2 and H_2, flows out of the gasifier, and enters the supercritical turbine. In the supercritical turbine, the gasification product expands to 1 bar for power generation. Then,