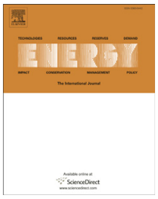
Energy 134 (2017) 933–942

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy



Novel power generation models integrated supercritical water gasification of coal and parallel partial chemical heat recovery

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ARTICLE INFO

Article history:
Received 17 December 2016
Received in revised form
5 June 2017
Accepted 6 June 2017
Available online 17 June 2017

Keywords:
Supercritical water gasification
Model integration
Process optimization
Parallel chemical heat recovery

ABSTRACT

Supercritical water gasification (SCWG) of coal is a promising clean coal technology. Supercritical water can effectively and cleanly convert coal to hydrogen-rich syngas. Three power generation models integrated SCWG of coal are proposed and compared in this article. The gasification products have a large amount of sensible heat. Efficient use of the sensible heat can improve the model performance. Compared to the models with total and without chemical heat recovery, the model with partial chemical heat recovery has the advantages of much less exhausted energy and relative small amount of fuel coal used to heat the water to the supercritical state. The efficiency of the model with partial chemical heat recovery is higher than that of other models, and increases with increasing coal-water slurry concentration (CWSC). The efficiencies of the models with partial chemical heat recovery, without chemical heat recovery, and with total chemical heat recovery are 46.60%, 37.56%, and 42.17% when CWSC is 11.3%, respectively. The thermal efficiency of the PCHR model is higher than most conventional coal-fired power plants and coal-based IGCC projects.

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1. Introduction

Coal plays a crucial role in the development of China's economy and society. China's coal production and consumption have continuously increased over the past decade. In 2013, the coal production and consumption account for 75.6% of total energy production and 66.0% of total energy consumption, respectively [1]. However, current coal utilization in China faces problems including low energy efficiency and severe environmental issues. Hu conducted data envelopment analysis for APEC economies, and found that China had the lowest energy efficiency [2]. The heat rate of power supply in 2014 was 318 g coal equivalent per kWh, thus the power efficiency was 38.67% after conversion [3]. In the other aspect, the CO_2 emission of China approached 8.2 billion in 2012, which was accounted for approximately 26% of the world's total CO_2 emissions. Approximately half of the CO_2 emissions came from coal combustion [4]. Besides CO_2 emissions, serious haze, 90% of the SO_2 emissions, 70% of the dust emissions, and 67% of the NO_x emissions were the results of coal combustion [5,6]. So there are great demands of more cleaner and efficient ways of using coal for China's sustainable development.

The properties such as low viscosity, low dielectric constant and high diffusivity make supercritical water (SCW) ($T > 374$ °C, $P > 22.1$ MPa) an ideal solvent for biomass or coal to take homogenous reactions [7]. Compared to conventional gasification technologies, supercritical water gasification (SCWG) has advantages such as: (1) lower gasification temperature (usually 500–700 °C, and more than 1200 °C for conventional gasification technologies); (2) faster reaction rate due to lower heat and mass transfer resistance in SCW; (3) cleaner gasification products: elements such as N, P, S, Hg deposits as inorganic salts in SCW [8]. Thus, there is no need for further cleaning of the gasification products. While in conventional gasification, cleaning units such as dust-extraction unit, SO_x separation unit are needed to clean the syngas for further using; (4) higher carbon conversion benefit from the inhibiting effect of SCW and catalyst to preventing tar and char formation [9,12]; (5) hydrogen-rich syngas production. The hydrogen yield accounts for almost 50–70% of total syngas yield [10]. Thus, SCWG may be a promising technology for clean and efficient utilization of coal.

Currently, studies on SCWG mainly focus on the influences of gasification temperature, pressure, catalyst, oxidation ratio, reactor types, feed concentration, and residence time on the product distribution, numerical investigation of reactors for visualization to

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http://dx.doi.org/10.1016/j.energy.2017.06.027
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Nomenclature

T	Temperature
h	Enthalpy
Q	Heat
W	Work
σ, τ, λ	Energy ratio
η	Thermal efficiency
HE	Heat Exchanger
PCHR	Model with Partial Chemical Heat Recovery
NCHR	Model without Chemical Heat Recovery
TCHR	Model with Total Chemical Heat Recovery

find out the heat and mass transfer performance in the reactor, thermodynamic and kinetics model developing. Molino et al. [11] conducted continuous gasification of glucose in SCW with a bench scale plant under condition of 250 bar and 550 °C, and obtained the product distribution in different glucose concentrations. Zhu et al. [12] studied SCWG of glucose in quartz reactors with temperature of 500 °C, glucose concentration of 5 wt%, and reaction time between 10 and 1800s. The influences of reaction time and Ru/Al_2O_3 catalyst on the product distribution were investigated. The gas yields increased with increasing reaction time, and the Ru/Al_2O_3 catalyst promoted the degradation of intermediates to gaseous products. Giuseppe et al. [13] carried out computational fluid dynamics simulations about a continuous flow reactor to understand the complex fluid dynamics inside the reactor, and found that the top section of the reactor behaved like a mixed reactor and the bottom section behaved like a plug flow reactor. Yan et al. [14] developed a non-stoichiometric thermodynamic model based on minimum free energy to predict the hydrogen production from SCWG of biomass. The prediction results were in good agreement with the experimental data.

In SCWG processes, approximately 10% of the SCW takes part in the gasification reactions. Thus, the mixture flowing out of the reactor consists of the syngas produced by the gasification reaction and the unreacted SCW, which has a large amount of sensible heat. The ratio of the sensible heat and enthalpy of the coal lies between 1 and 7, when the CWSC (coal-water slurry concentration) is between 2 and 10%, and the ratio is higher in lower coal-water slurry concentration. When integrating SCWG of coal with power generation cycles, methods of using the sensible heat have a great influence on the generation efficiency. One way to use the heat is heating the feed water of a Rankine cycle to obtain high-temperature and high-pressure steam (510.1 °C, and 87.21 bar) for power generation. The other way is recovering the heat to preheat water before being heated to the supercritical state. The methods of using the sensible heat can be separately or jointly implemented. If the sensible heat is only used to heat the feed water of a Rankine cycle for power generation, the model is integrated without chemical heat recovery. If the sensible heat is only recovered to preheat water before being heated to the supercritical state, the model is integrated with total chemical heat recovery. If the sensible heat within high-temperature range is used to heat feed water of a Rankine cycle, and the sensible heat within low-temperature range is recovered to preheat water before being heated to the supercritical state, the model is integrated with tandem partial chemical heat recovery. If the sensible heat is simultaneously used to heat the feed water of a Rankine cycle and recovered to preheat water before being heated to the supercritical state, the model is integrated with parallel partial chemical heat recovery. Different implementation ways lead to different performances.

Chen et al. proposed and analyzed a power generation model integrated SCWG of coal with tandem partial chemical heat recovery. The maximum thermal efficiency of the model is 42.18% [15]. In this work, models with different chemical heat recovery methods are compared with each other. The energy distributions of different models have great influences on the thermal efficiencies. The energy at the outlet of these models is consisted of three parts: energy being transported into a combined cycle for power generation, energy being converted to a Rankine cycle for power generation, and energy being discharged into the atmosphere. The relative values of these three parts energy greatly affect the model performances. The optimal model structure is confirmed through analyses on the energy distributions of different models with different chemical heat recovery methods.

2. Proposal of the novel models

The temperature and pressure of supercritical water gasification reactions are usually 500–700 °C, and over 22.1 MPa, respectively. The produced syngas 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. The yields of CO and C_2H_6 are small. The gasification reaction is endothermal. Thus, some heat (approximately 700–1000 °C) should be provided for the processing of the gasification reaction. The ratio of the provided heat and the LHV of the gasified-coal is approximately 4–15%. The heat can be provided by coal combustion or solar energy. Some heat is converted to chemical energy stored in the syngas through the gasification reactions, and can be released in a combined cycle (approximately 1300–1700 °C) with a higher energy level. Thus, the energy level of the provided heat is upgraded through the gasification reactions.

Three power generation models integrated with supercritical water gasification of coal are proposed in this section. The main difference of the models is the utilization methods of the sensible heat of the mixture. In the model with partial chemical heat recovery (PCHR), the sensible heat of the mixture is simultaneously transferred to a Rankine cycle for power generation and used to preheat the feed water of the SCW. While in the model with total chemical heat recovery (TCHR), the sensible heat of the mixture is only used to preheat the feed water of the SCW. And in the model without chemical heat recovery (NCHR), the sensible heat of the mixture is only used to heat the feed water of a Rankine cycle for power generation.

2.1. Detailed model description

Coal undergoes complex gasification reactions with supercritical water in a gasifier. The main reactions include the carbon-steam reaction, and water-gas shift reaction. After the gasification reactions, most produced syngas is dissolved in the unreacted SCW.

As seen in Fig. 1, the flowchart of PCHR is illustrated. HE is the heat exchanger for heat exchange between the mixture and the feed water of the rankine cycle and the water to be preheated. CC is the combine cycle where the syngas is combusted for power generation.

The parameter $h_{gasified\text{-}coal}$ is the enthalpy of the gasified coal; h_1 is the enthalpy of the SCW; h_2 is the enthalpy of the mixture consisted of produced syngas and unreacted SCW; h_4 is the enthalpy of the mixture that flows out of HE; h_5 is the enthalpy of unreacted SCW after decompression, cooling, and separation processes; $h_{5'}$ is the enthalpy of the mixed water; h_6 is the enthalpy of the preheated water; $h_{fuel\text{-}coal}$ is the enthalpy of the fuel coal; h_{eg} is the enthalpy of

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