



Energy quality factor and exergy destruction processes analysis for a proposed polygeneration system coproducing semicoke, coal gas, tar and power



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ABSTRACT

A new polygeneration system was established by combining coal pyrolysis with semicoke combustion, semicoke gasification and a steam Rankine cycle, and calculation approaches were developed to analyze the system. The energy and exergy efficiencies of the system were 68.3% and 76.8%, respectively. The standard energy quality factor α^0 values of the 17 components and the energy quality factor α of each system stream were obtained based on the benchmark of the selected environmental reference state. The features of the energy grade of the components were elucidated according to their energy quality factors. And the exergy destruction processes in system blocks were exhibited and analyzed in combination with the concept of the energy quality factor. In the DRYER and PYRO, the majority of exergy destructions were used to pay the thermodynamic penalty of the increased energy grade of the coal. In the BUR and GASIF, the energy grade difference between the semicoke and output gas was the main cause of exergy destruction. Especially in the BUR, the energy grade difference was enormous and the exergy destruction was large. In HEX2, the average energy grade difference between Q_{ED} and Q_{EA} was the main cause of the exergy destruction. Finally, from the perspective of the energy quality factor, some potential improvements were analyzed to reduce the exergy destruction in the blocks.

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1. Introduction

China is rich in coal, but not oil and gas, therefore, coal will continue to be the major energy source for a long time, making thermal conversion technologies that can convert coal into syngas, liquid fuel, coke and other value-added chemicals attractive [1]. Coal pyrolysis has attracted the attention of many researchers [2–4]. In general, the heat carriers for coal pyrolysis can be categorized as a gas or solid. The representative techniques of solid heat carrier pyrolysis include Lurgi-Ruifgas, Toscoal and DG [5,6], while those of gas heat carrier pyrolysis include LFC, Lurgi-Spuelgas and COED [7,8]. Gas heat carriers may dilute the volatiles, but the heat transfer efficiency and uniformity of gas carriers are higher than those of solid carriers [9].

After extracting the valuable chemicals, e.g., fuel oils, from the coal through pyrolysis, the semicoke can be used for gasification, combustion or other applications; therefore coal pyrolysis technology can be coupled with other technologies to form polygeneration systems. Zhang et al. proposed a dual-bed pyrolysis gasification

process that combines a coal pyrolyzer and a pneumatic char gasifier to produce pyrolysis oil and gasification gas [10]. In their study, the gasification agent used in the gasifier could be air or air and steam, and the heat carrier for coal pyrolysis was a mixture of char and quartz sand. Yi et al. proposed a system for lignite pyrolysis through solid heat carrier coupled gasification [11]. In their work, the gasification process was relatively independent of the pyrolysis process, and the optional gasification technology was not limited. The heat carrier was quartz sand, and the energy consumed by the system was supplied by char and pyrolysis gas combustion. Guo et al. presented a polygeneration system by integrating a circulating fluidized bed and an atmospheric pressure pyrolyzer [12,13]. In their system, the pyrolyzed volatiles were utilized for the cogeneration of methanol, oil, and electricity, while the char residues were fired in boilers. Dai et al. introduced a process for the integration of pyrolysis and entrained-flow gasification to utilize high moisture low rank coal [14]. In this work, a new polygeneration system for coproducing semicoke, coal gas, tar and power is introduced in Section 2.

The energy grade of a material was initially proposed by Rant in 1961 [15]. After estimating the exergies of many homogeneous organic fuels, Rank determined the exergy ratios of gas fuel and

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Nomenclature

A	ash	TUR	turbine
BUR	burner	W	work duty, kJ h^{-1}
CON	condenser	x	mass fraction
CW	cooling water	V	valve
DRYER	drying reactor		
FLA	flash tank	<i>Subscripts</i>	
GCHC	gas circulating heat carrier	ar	as received
GASIF	gasification reactor	d	dry basis
H	specific enthalpy, kJ kg^{-1}	gr	gross
HEX	heat exchanger	I	the first law of thermodynamics
I	exergy destruction and loss, kJ h^{-1}	II	the second law of thermodynamics
M	mixer	θ	standard state
m	mass flow rate, kg h^{-1}	i	number of the material stream or energy stream
p	pressure, bar		
P	pump	<i>Greek letters</i>	
PYRO	pyrolysis reactor	η	efficiency
Q	heat duty, kJ h^{-1}	α	energy quality factor
REB	reboiler	ε	specific exergy, kJ kg^{-1}
s	specific entropy, $\text{kJ K}^{-1} \text{kg}^{-1}$		
S	splitter		
T	temperature, K		

liquid fuel as 0.95 and 0.975, respectively. Szargut and Styrylska [16] attempted to correct Rant's formulas by considering the chemical composition of fuels, and the mass ratios of H/C, O/C, N/C and S/C were used to describe the chemical compositions. Stepanov investigated several methods for estimating the energies and exergies of fuels and compared the results [17]. In 2009, Zheng and Hou [18] developed the concept of the energy quality factor, i.e., the ratio of exergy to enthalpy, to evaluate the energy grade of a substance. And they calculated the standard exergy data for 81 elements based on the environmental reference state proposed by Kameyama et al. [19]. Furthermore, in 2017, as the benchmark for calculating the standard exergy value of a substance, the environmental reference state was improved by Zheng et al., and the standard enthalpy and standard exergy data for 81 elements were recalculated [20].

Exergy is considered as the energy that can be converted into work. The energy grade of mechanical work is 1; the energy grade of heat flux is measured by the Carnot coefficient, and the concept of energy quality factor provides a reasonable index of a substance's energy grade. The basis of exergy analysis is that energy has an inherent quality. Hebecker and Bittrich developed a similar concept for the exergetic evaluation of material fluxes; they used the concept to analyze technology in a brewery [21]. By analyzing the energy grade, i.e., the exergy rate, changes between the heat flux and a type of pseudo-work, Zheng and Jing established a system analysis method to reveal the heat conversion mechanism of heat conversion cycles without material conversion, e.g., heat pumps [22]. Then, Jing and Zheng used the proposed energy grade analysis method to elucidate the energy efficiency boosting mechanism of a power/cooling cogeneration cycle [23]. From the perspective of the energy quality factor, Chen et al. investigated the energy performance of a low-rank coal pyrolysis system and suggested several potential improvements [24]. Unfortunately, the values of the energy quality factor calculated in Chen's work may not be accurate because they cited outdated basic data published by Zheng and Hou in 2009 [18].

Based on the second law of thermodynamics, exergy analysis has been extensively conducted to evaluate the performance of coal-based systems [25–28], and the conventional expressed tools

used for exergy analysis include pie charts, Sankey diagrams and Grassmann diagrams. Analogous to the Carnot coefficient, which is used to measure the quality of heat under different temperatures, the energy quality factor provides a reasonable index of a substance's energy grade. Therefore, exergy analysis of coal-based systems can be performed in combination with the concept of the energy quality factor.

In this study, a polygeneration system based on coal pyrolysis was proposed and simulated. Based on the selected benchmark of the environmental reference state, the enthalpy and exergy values of the streams were calculated using the introduced calculation approach. Then, the standard energy quality factors of the involved components, the actual energy quality factor of the system streams, and the exergy destruction of the system blocks were calculated. Based on the calculation results, the exergy destruction processes were analyzed in combination with the concept of the energy quality factor.

2. Description of the proposed polygeneration system

Atmospheric semicoke gasification gas has not only a high temperature but also a high calorific value, and the gas is suitable as a heat carrier for coal pyrolysis to avoid dilution of the pyrolysis gas. Atmospheric semicoke gasification was coupled with coal pyrolysis in this work. The coal drying process also requires energy; however, the quality of the gas heat carrier for coal pyrolysis is high, and it is wasteful to use it as the heat carrier for coal drying. On the other hand, the steam Rankine cycle is usually driven by the high-temperature flue gas of coal combustion, and the middle-temperature waste exhaust could be recovered to dry the input coal before pyrolysis. Therefore, semicoke combustion and a steam Rankine cycle were added to the coal pyrolysis, and a new polygeneration system was established by combining coal pyrolysis with semicoke gasification, semicoke combustion, and a steam Rankine cycle to co-produce semicoke, coal gas, tar and power.

The configuration of the polygeneration system is shown in Fig. 1. The raw materials of the system are wet coal, water vapor, oxygen and air, and the products are coal gas, tar, semicoke and

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