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Advanced exergy analysis of an oil shale retorting process

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HIGHLIGHTS

- Advanced exergy analysis was conducted to the FsOSR process for the first time.
- Real potential for exergy destruction reduction of the FsOSR process is 54.60%.
- Interactions between the components of the FsOSR process are identified.
- Some efficient improvement strategies are proposed to reduce exergy destruction.

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ABSTRACT

Fushun-type process is the most common method of oil shale retorting used in China. The process is, however, characterized by poor thermodynamic performance. While conventional exergy analysis is able to quantitatively determine exergy destruction in a system, identification of the sources of the exergy destruction, and thus identification of areas with the greatest potential for efficiency improvement, requires advanced exergy analysis. In this paper, an advanced exergy analysis is applied to evaluate the performance of a Fushun-type oil shale retorting process.

The results indicate that, the simulation results are consistent with industrial data. The process can produce 21.90 t/h of shale oil from 500 t/h oil shale. The exergy efficiency of the Fushun-type oil shale retorting process studied in this work is 34.17% and the total exergy destruction is 442.62 MW. The analysis shows that 45.40% of the exergy destruction cannot be reduced. The retort is found to be the element of the Fushun-type oil shale retorting process having the greatest potential for decrease in exergy destruction. Improvement strategies are proposed to minimize exergy destruction in the retort.

1. Introduction

Finite world oil supplies are one of the major drivers of increasing attention to the exploitation of alternative, non-traditional energy sources [1]. One such alternative, oil shale is found worldwide and is regarded as a most promising alternative to crude oil [2]. The extractable amount of shale oil is estimated as 6.89×10^{11} t, three times the world's crude oil reserves [3], and shale oil reserves in China total 4.76×10^{10} t, double the country's crude oil reserves [4]. Effective exploitation of oil shale could relieve shortages of crude oil, reduce dependence on imported oil, and enhance the structure of energy resources in China and many other countries.

Several oil shale retorting processes are in industrial use, e.g. the Brazilian Petrosix [5], Estonian Kiviter and Galoter [6] and Chinese Fushun-type [7] processes. Fushun-type oil shale retorting technology has many advantages, such as simplicity, considerable adaptability and reliable operation. It has been widely used in China. In 2014, there were about 605 sets of retorts running in China [8], of which 546 were Fushun-type [1]. A block diagram of the Fushun-type oil shale retorting (FsOSR) process is shown in Fig. 1. In this process, oil shale is converted into shale oil, retorting gas and char. Despite its advantages, the Fushun-type oil shale retorting process is, however, characterized by the significant drawbacks of low oil yield and poor energy efficiency [9,10]. These drawbacks motivate the current research on the FsOSR process. Better understanding of the physical and chemical processes involved and improved mathematical modeling and simulation can contribute to endeavors to reduce energy loss of the FsOSR process.

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Nomenclature

E	exergy, MW
e^{θ}_{os}	standard exergy of oil shale, kJ/kg
e^{θ}_{so}	standard exergy of shale oil, kJ/kg
FsOSR	Fushun-type oil shale retorting
h	enthalpy, kJ/mol
Δh^{θ}_{L}	standard low heating value of oil shale, kJ/kg
Δh^{θ}_{H}	standard high heating value of shale oil, kJ/kg
k	reaction rate constants, s^{-1}
R	gas constant, 8.314 kJ/kmol K
s	entropy, kJ mol^{-1} K^{-1}
T	temperature, K
A	pre-exponential factor
t	time, s
x	the concentration at a time t, kg/m^3
y	exergy destruction ratio, %
Subscripts	
F	fuel
P	product
D	destruction
L	loss
C	collecting tube
W	washing tower
I	indirect cooling tower
E	electric oil separator
H	heating furnace
k	kth component
tot	total
ph	physical
ch	physical
0	reference condition
Superscripts	
AV	avoidable
EN	endogenous
EX	exogenous
UN	unavoidable
Greek letters	
ε	exergy efficiency, %
ω	mass fraction of water in oil shale, %

In recent years, intensive studies have been conducted on modeling and simulation of oil shale retorting process. For example, Bai et al. [11] simulated a Huadian-type oil shale process. Wang et al. [12] studied an oil shale retorting process with a gas-heat carrier. Wang et al. [13] investigated utilization options of Chinese oil shale resources. Bai et al. [14] and Qian et al. [9] researched Fushun-type oil shale retorting process. These studies, focusing on building of the retort model, validated the feasibility of Aspen plus software for simulation of the oil shale retorting process. However, little work has been done to model and simulate the complete FsOSR process, and there is a lack of research analyzing the thermodynamic performance of the whole FsOSR process. Li et al. [15] used conventional exergy analysis to analyze and compare three typical retorting technologies: the FsOSR, the gas full-circulation retorting process, and the Dagong retorting method. The obtained results showed that the FsOSR technology had the biggest exergy destruction ratio, 65.7%. It is 1.70 times higher than that of the Dagong retorting process and 1.27 times higher than that of the gas full-circulation retorting process. This result indicates the urgency of research on improvement of the thermodynamic performance of the FsOSR process.

The inefficiency of the FsOSR process can be quantitatively determined by conventional exergy analysis. However, conventional exergy analysis cannot identify the share of inefficiencies that can be avoided [16]. Moreover, conventional exergy analysis cannot assess the interactions between the components of the system or the improvement potential of each component [17,18].

In this paper, advanced exergy analysis is used to address this issue. The approach divides exergy destruction into two main groups: endogenous/exogenous exergy destruction and avoidable/unavoidable exergy destruction. Advanced exergy analysis is able to determine the share of the inefficiency caused by the interactions of the systems' components and what inefficiency could be avoided by technological improvement [19]. The method has been applied previously to analyze natural gas liquefaction [18,20], an LNG-based cogeneration system [21], a supercritical coal-fired power plant [22,23], a combined cycle power plant [19,24], an absorption refrigeration machine [25–27], and a food drying process [28]. To date, however, no works have been published on the application of advanced exergy analysis to the oil shale retorting process.

The main objectives of this work are: (1) For the first time, to apply the advanced exergy analysis to the oil shale retorting process; (2) to investigate the interactions between system components and their improvement potential; (3) to propose a four-step method for application of the advanced exergy analysis to the FsOSR process; and (4) to suggest possible improvement strategies to increase the thermodynamic performance of the FsOSR process.

2. Process description

A flowsheet of the studied Fushun-type oil shale retorting process is shown in Fig. 2. The process consists of two stages: retorting and gasification. The oil shale, with a diameter of 10–75 mm, enters the retorting stage. In this stage, oil shale is converted into shale oil, retorting gas, and semi-coke at 0.1 MPa and 525 °C [29].

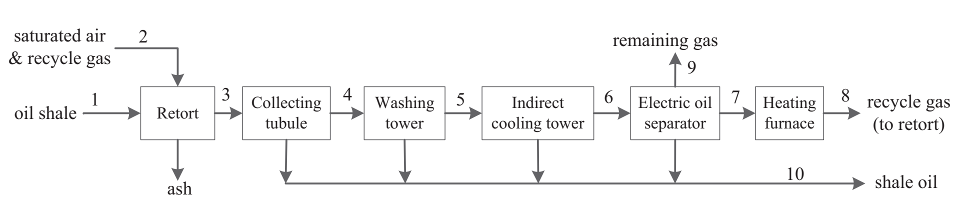

Fig. 1. Block diagram of the FsOSR process.