Advanced Exergy Analysis of an Oil Shale Retorting Process

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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.

Key words: oil shale retorting; conventional exergy analysis; advanced exergy analysis; process simulation; improvement strategy

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.

Fig. 1. Block diagram of the FsOSR process

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

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

22 In this paper, advanced exergy analysis is used to address this issue. The
23 approach divides exergy destruction into two main groups: endogenous/exogenous
24 exergy destruction and avoidable/unavoidable exergy destruction. Advanced exergy
25 analysis is able to determine the share of the inefficiency caused by the interactions of
26 the systems' components and what inefficiency could be avoided by technological
27 improvement [19]. The method has been applied previously to analyze natural gas
28 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]. The semi-coke is fed to the gasification stage, where it reacts with carbon dioxide and steam at 950°C. The fixed carbon in the semi-coke is converted into CO, CO₂, H₂, and CH₄. As the semi-coke enters the last part of the gasification stage, it is burnt with air. The oil-gas mixture from the retort is fed to a collecting tube to separate the shale oil. In the collecting tube, the oil-gas mixture is cooled by water to a temperature of about 85°C. The mixture is then cooled in the washing and indirect cooling towers to recover more shale oil. The outlet stream from the indirect cooling tower reaches about 40°C. The stream is next fed into an electric oil separator in order to improve the separation of the shale oil. The retorting gas exiting from the electric oil separator is divided into three streams: (1) recycle gas, to be re-fed into the retort; (2) burning gas, to heat the recycle gas; and (3) byproduct gas, to be eventually used for power generation or the production of chemical products.

Fig. 2. Flowsheet of the FsOSR process

3. Methodology of the process analysis

The advanced exergy analysis method applied to the FsOSR process is summarized in the flow diagram shown in Fig. 3. It comprises four steps:

1. Process modeling and simulation. Mathematical models of the FsOSR process are built, simulation is conducted, and the results are validated.

2. Conventional exergy analysis. The key thermodynamic parameters (such as enthalpy, entropy, temperature, and stream compositions) obtained in Step 1 are used to perform conventional exergy analysis. The exergy destruction is determined by calculating the exergy balance for each component. The performance of each component is determined by calculation of the exergy efficiency and exergy destruction ratio.

3. Advanced exergy analysis. The operating conditions of the system are adjusted on the basis of technological and economical limitations. The new mass and the exergy balances of the system are formulated with respect to theoretically optimal operating conditions and practically optimal operating conditions.

The practical conditions are used for conventional exergy analysis. The endogenous/exogenous exergy destruction is calculated with the theoretically optimal conditions. Unavoidable/avoidable exergy destruction is calculated using the defined

maximum permissible values, i.e. theoretically optimal and practically feasible operating conditions. The exergetic product for whole system is assumed to be constant. Using the information obtained from conventional and advanced exergy analysis, the endogenous/exogenous and unavoidable/avoidable exergy destructions are calculated. Four terms are defined: unavoidable-endogenous exergy destruction ($E_{D,k}^{UN,EN}$), unavoidable-exogenous exergy destruction ($E_{D,k}^{UN,EX}$), avoidable-endogenous exergy destruction ($E_{D,k}^{AV,EN}$) and avoidable-exogenous exergy destruction ($E_{D,k}^{AV,EX}$) [30]. Detailed definitions and equations are given in the next section.

4. Improvement strategy. In this step, the first objective is to find the component that has the greatest impact on the total avoidable exergy destruction of the whole system. Priority is then given to this component when searching for the utilization possibilities for the avoidable exergy destruction ($E_{D,k}^{AV,EN}$ and $E_{D,k}^{AV,EX}$). Efficient improvement priorities are then proposed for reduction of the endogenous and exogenous exergy destruction.

Fig. 3. Flow diagram of advanced exergy analysis of the FsOSR process

3.1 Process modeling and simulation

Process modeling and simulation are widely used for analysis of chemical processes. In this paper, Aspen Plus (Version 8.4) is used to simulate mass and exergy balances of the FsOSR process. Redlich-Kwong-Soave method (RK-SOAVE) is selected as the property model because the components of the retorting gas are mainly non-polar or weak-polar hydrocarbons, light gas, and shale oil [8, 31]. The oil shale sample was obtained from the Fushun oil shale plant located in Fushun City, Liaoning Province, China. Its proximate and elemental analyses are shown in Table 1. The key operating parameters required for the simulation are given in Table 2.

Table 1 Proximate and element analysis of samples

	proximate analysis (wt. %, ar) ^a				element analysis (wt. %, ar) ^a				
	M	FC	V	A	C	H	O	N	S
oil shale	5.00	3.69	18.56	72.79	79.07	9.93	7.02	2.12	1.86
semi-coke	0.44	82.13	14.34	4.09	11.42	0.81	3.18	0.76	1.26
shale oil					85.39	12.09	0.71	1.27	0.54

^a received basis.

Table 2 Key operating parameters required for the simulation

Key parameter	Value	Key parameter	Value
Retorting temperature	500°C	Collecting tube temperature	86°C
Gasification temperature	950°C	Washing tower temperature	76°C
Operating pressure	0.1 MPa	Indirect cooling tower temperature	42°C
Saturated air temperature	83°C	Electric oil separator temperature	40°C
Recycle gas temperature	650°C	Heating furnace temperature	1500°C

The following assumptions were made in modelling of the FsOSR process: (1) the whole system operates in steady state; (2) oil shale particles do not flow back to the retorting reactor; (3) organic material in the oil shale is completely reacted; (4) ash in the oil shale is considered as an inert material and does not take part in the retorting reaction; (5) hydrocarbons are represented by CH₄, C₂H₄, C₂H₆, C₃H₆ and C₃H₈, as the amount of other components is negligible; and (6) there is no pressure drop across

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$$\frac{dx}{dt} = k(1-x)^n = A \exp\left(-\frac{E_a}{RT}\right)(1-x)^n \quad (2)$$

where x is concentration at a time t , k is the specific rate constant, n is the order of the reaction, A is the apparent frequency factor, E_a is the apparent activation energy, and R is the gas constant equal to 8.314 J/(mol K). For Fushun oil shale, the specific rate constant k is given as follows [33]:

$$k = 2.81 \times 10^{13} \exp\left(-\frac{26390}{T}\right) \quad (3)$$

Equations (2) and (3) give:

$$\frac{dx}{dt} = k(1-x)^n = 2.81 \times 10^{13} \exp\left(-\frac{26390}{T}\right)(1-x)^n \quad (4)$$

The semi-coke produced in the retorting process is fed into the gasification stage. The semi-coke is reacted with saturated air at 0.1 MPa and 950°C. The following reactions take place at this point: reduction, represented by Eqs. (5)-(7), and oxidation, illustrated by Eqs (8)-(10).

The outlet stream goes into a gas-solid separator to remove ash. The gasified gas is recycled back to the retorting stage to supply heat for the retorting reaction. The oil-gas mixture from the retort enters the collecting tube, washing tower, indirect cooling tower and electric oil separator to separate shale oil and retorting gas. The reactions taking place in the collecting tube and the washing tower are given by Eqs. (11)-(19). The outlet stream is directed to the indirect cooling tower and the electric oil separator in order to recover the remaining share of shale oil.

A part of the purified retorting gas, called recycle gas, is sent to the retort after being heated to 650°C by the burning gas. The combustion reactions are modeled applying the model of a stoichiometric reactor (RStoic model). With a sufficient amount of air, CO, H₂, CH₄ and C_nH_m (C₂H₄, C₂H₆, C₃H₆, and C₃H₈) contained in the retorting gas are oxidized into CO₂ and H₂O, as shown by Eqs. (20)-(24). The high temperature flue gas is discharged after exchanging heat with the recycled gas.

3.2 Conventional exergy analysis

The concept of exergy is based on the second law of thermodynamics and is defined as the maximum possible work potential of a system [34]. For a steady-state system, exergy of a stream (E) includes physical exergy (E_{ph}), chemical exergy (E_{ch}),

and mixing exergy ($\Delta_{\text{mix}} E$). They can be calculated as follows [35, 36]:

$$E = E_{\text{ph}} + E_{\text{ch}} + \Delta_{\text{mix}} E \quad (25)$$

$$E_{p, \bar{h}} = \Delta_{(T, P) \rightarrow (T_0, P_0)} \left[L \left(\sum_i x_i h_i^l - T_0 \sum_i x_i s_i^l \right) + V \left(\sum_i y_i h_i^v - T_0 \sum_i y_i s_i^v \right) \right] \quad (26)$$

$$E_{\text{ch}} = L_0 \sum_i x_{0,i} E_{\text{ch}_i}^{\text{ol}} + V_0 \sum_i y_{0,i} E_{\text{ch}_i}^{\text{ov}} \quad (27)$$

$$E_{\text{mix}} = \Delta_{\text{mix}} h - T_0 \Delta_{\text{mix}} s \quad (28)$$

where L and V are the liquid and gas mole flow rates; x_i and y_i are the mole fraction of each substance i ; h_i^l and h_i^v are the enthalpy of each substance i in the liquid and gas phases; s_i^l and s_i^v are the entropy of each substance i in the liquid and gas phases; $Ex_{\text{ch}, i}^{\text{ol}}$ and $Ex_{\text{ch}, i}^{\text{ov}}$ are the standard molar chemical exergy of substance i in the liquid and gas phases; $\Delta_{\text{mix}} h$ and $\Delta_{\text{mix}} s$ are the mixing enthalpy and entropy, respectively; and 0 is the reference thermodynamic environment.

The exergy balance is used to calculate exergy destruction and to determine its distribution [37]. The exergy balance for the k^{th} component can be written as follows [38]:

$$E_{F,k} = E_{P,k} + E_{D,k} \quad (29)$$

where $E_{F,k}$ is the exergy of the fuel; $E_{P,k}$ is the exergy of the product; and $E_{D,k}$ is the exergy destruction within the k^{th} component.

There is no exergy loss associated with the k^{th} component based on an assumption that the system boundaries, used for analysis of exergy balances, are at the reference temperature T_0 [39]. Therefore, the exergy losses, E_L , are considered only at the level of the overall system, and the exergy balance for the overall FsOSR system can be written as [40]:

$$E_{F,\text{tot}} = E_{P,\text{tot}} + E_{D,\text{tot}} + E_{L,\text{tot}} = E_{P,\text{tot}} + \sum_k E_{D,k} + E_{L,\text{tot}} \quad (30)$$

where the subscript *tot* means overall system.

In conventional exergy analysis, two variables are defined to evaluate system performance:

1) Exergy efficiency (ε): the ratio of the exergy of the product and fuel. The k^{th} component ε_k and the overall system ε_{tot} are defined as [41]:

$$\varepsilon_k = \frac{E_{P,k}}{E_{F,k}} \times 100\% \quad (31)$$

$$\varepsilon_k = \frac{E_{P,\text{tot}}}{E_{F,\text{tot}}} \times 100\% \quad (32)$$

2) Exergy destruction ratio (y). For the k^{th} component, y_k is the ratio of the exergy destruction within the k^{th} component to the total exergy of the fuel; y_k^* is the ratio of the exergy destruction within the k^{th} component to the total exergy destruction of the system [42]. For the overall system, y_{tot} is the ratio of the total system exergy destruction to the total exergy of the fuel of the overall system. The ratios can be calculated as [43]:

$$y_k = \frac{E_{D,k}}{E_{F,\text{tot}}} \times 100\% \quad (33)$$

$$y_k^* = \frac{E_{D,k}}{E_{D,\text{tot}}} \times 100\% \quad (34)$$

$$y_{\text{tot}} = \frac{E_{D,\text{tot}}}{E_{F,\text{tot}}} \times 100\% \quad (35)$$

3.3 Advanced exergy analysis

Conventional exergy analysis does not provide results for interactions between components nor provide information about the improvement potential of each component of the system [16]. Advanced exergy analysis, however, evaluates the interactions between the components, and reveals the potential for improving the system component/the overall system within the given technological and economic

constraints [20]. Advanced exergy analysis involves splitting the exergy destruction of the system components into endogenous/exogenous and avoidable/unavoidable parts [20]. By combining the two splitting options, exergy destruction can be separated into four parts: unavoidable-endogenous, unavoidable-exogenous, avoidable-endogenous and avoidable-exogenous exergy destruction.

Endogenous/exogenous exergy destruction: The exergy destruction within the k^{th} component is the sum of the endogenous and exogenous exergy destruction, as shown in Eq. (36) [25].

$$E_{D,k} = E_{D,k}^{EN} + E_{D,k}^{EX} \quad (36)$$

Endogenous exergy destruction ($E_{D,k}^{EN}$) is the part of the exergy destruction within the k^{th} component obtained when all other components operate in ideal/reversible conditions and the k^{th} component under consideration operates with its currently efficiency. The exogenous part of the variable ($E_{D,k}^{EX}$) is the share of exergy destruction within the k^{th} component reduced by a structural upgrading of the overall system or by increasing the efficiency of the remaining elements or by improving the efficiency of the k^{th} component [26].

Unavoidable/avoidable exergy destruction: The unavoidable exergy destruction ($E_{D,k}^{UN}$) is the amount of exergy destruction that cannot be reduced because of technical or economical limitations such as the availability and cost of materials or the manufacturing methods used [26]. The avoidable exergy destruction ($E_{D,k}^{AV}$) is the difference between the total exergy destruction and the unavoidable exergy destruction [23]. Thus, the division of the exergy destruction into unavoidable and avoidable parts in the k^{th} component can be expressed by Eq (37). The separation of the exergy destruction into avoidable and unavoidable parts provides a realistic measure of the potential for improving the thermodynamic efficiency of the components involved. Namely, for any component, the avoidable exergy destruction is the part that should be considered during the improvement procedure [44].

$$E_{D,k} = E_{D,k}^{UN} + E_{D,k}^{AV} \quad (37)$$

Combination of the splitting: After division of the exergy destruction into the different parts; namely, endogenous, exogenous, unavoidable and avoidable parts, the next task is to evaluate how the different categories of exergy destruction can be combined to provide meaningful information [45]. Thus four different parts of exergy destruction can be presented as follows [26]:

- 1) Unavoidable endogenous exergy destruction ($E_{D,k}^{UN,EN}$) - cannot be reduced because of technical or economical limitations of the k^{th} component.
- 2) Avoidable endogenous exergy destruction ($E_{D,k}^{AV,EN}$) - can be reduced by improving the efficiency of the k^{th} component.
- 3) Unavoidable exogenous exergy destruction ($E_{D,k}^{UN,EX}$) - cannot be reduced because of technical or economical limitations of the other components of the overall system.
- 4) Avoidable exogenous exergy destruction ($E_{D,k}^{AV,EX}$) - can be reduced by a structural improvement of the overall system or by improving the efficiency of the remaining components or by improving the efficiency in the k^{th} component.

All options of splitting the exergy destruction within the k^{th} component are explicitly described in Fig. 5. The four splitting combinations can be calculated based on the product exergy of the k^{th} component ($E_{P,k}^R$) [23]:

$$E_{D,k} = E_{D,k}^{AV,EN} + E_{D,k}^{UN,EN} + E_{D,k}^{AV,EX} + E_{D,k}^{UN,EX} \quad (38)$$

$$E_{D,k}^{UN} = E_{P,k}^R \times \left(\frac{E_D}{E_P} \right)_k^{UN} \quad (39)$$

$$E_{D,k}^{AV} = E_{D,k} - E_{D,k}^{UN} \quad (40)$$

$$E_{D,k}^{UN,EN} = E_{P,k}^{EN} \times \left(\frac{E_D}{E_P} \right)_k^{UN} \quad (41)$$

$$E_{D,k}^{UN,EX} = E_{D,k}^{UN} - E_{D,k}^{UN,EN} \quad (42)$$

$$E_{D,k}^{AV,EN} = E_{D,k}^{EN} - E_{D,k}^{UN,EN} \quad (43)$$

$$E_{D,k}^{AV,EX} = E_{D,k}^{EX} - E_{D,k}^{UN,EX} \quad (44)$$

Fig. 5. Division of the exergy destruction in an advanced exergy analysis [43]

4. Results and discussion

Detailed conventional and advanced exergy analyses of FsOSR process were performed using the above-presented four-step method.

4.1 Process simulation

The simulation of the FsOSR process gives values for the key parameters of the main streams as shown in Table 3. The results show that about 21.90 t/h of shale oil can be produced from 500 t/h oil shale. The results of the simulation show that the shale oil recovery ratio is 74.97%. This could be considered a quite satisfactory result when compared to industrial data, where the recovery ratios are in the range of 65-75% [1]. The composition of the retorting gas, as well as mass and energy balance results were compared with industrial data from the Fushun retorting plant in order to validate the accuracy of the model, shown in Tables 4-6.

Table 3 Key parameters of the main streams of the FsOSR process

NO. ^a	1	2 ^b	3	4	5	6	7	8	9	10
T (°C)	25	-	100	86	76	40	40	650	40	25
mass (t/h)	500.00	460.10	501.00	483.95	410.60	331.40	238.38	161.90	63.72	21.90
exergy (MW)	773.61	239.22	749.28	591.86	488.70	458.04	286.72	217.45	104.25	241.81
mass fraction (%)										
N ₂	0.00	52.26	34.29	35.50	41.84	51.83	52.80	52.80	52.80	0.00
O ₂	0.00	7.94	0.29	0.30	0.35	0.43	0.44	0.44	0.44	0.00
H ₂	0.00	0.42	0.53	0.55	0.65	0.80	0.82	0.82	0.82	0.00
CO	0.00	2.25	2.84	2.94	3.47	4.29	4.37	4.37	4.37	0.00
CO ₂	0.00	16.14	20.40	21.11	24.89	30.83	31.41	31.41	31.41	0.00
CH ₄	0.00	1.89	2.39	2.47	2.92	3.61	3.68	3.68	3.68	0.00
C ₂ H ₆	0.00	0.35	0.45	0.46	0.55	0.68	0.69	0.69	0.69	0.00
C ₃ H ₈	0.00	0.51	0.65	0.67	0.79	0.98	1.00	1.00	1.00	0.00
H ₂ O	0.00	18.23	31.68	32.69	22.76	4.66	4.75	4.75	4.75	0.00
NH ₃	0.00	0.00	0.49	0.09	0.00	0.00	0.00	0.00	0.00	0.00
H ₂ S	0.00	0.00	0.15	0.05	0.00	0.00	0.00	0.00	0.00	0.00
shale oil	0.00	0.00	5.86	3.16	1.80	1.87	0.05	0.03	0.05	100.0
oil shale	100.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

a: The stream numbers of the FsOSR process are shown in Figures 1, 2, 4.

b: No. 2 stream is mixed with retorting gas, air and water.

The simulation results show that the mole fractions of the components in the retorting gas are close to the industrial data, as can be seen in Table 4. The results of the mass and energy balances, Table 5 and Table 6, show that the majority of the simulation results are in good agreement with the industrial data. However, the relative error of some parameters, such as production of shale oil and system losses, is greater than 5%. A likely cause for this result is that the simulation is conducted for a steady state of the system. Leakage and residuals in the industrial equipment are likely to be bigger than those assumed in the simulation, resulting in a smaller production yield and greater mass and energy losses. Additionally, for the sake of the model simplicity, assumptions and simplifications have been made, as listed in Section 3.1.

Table 4 Simulation and industrial data of the composition of the retorting gas

	Mole fraction ^a (%)						
	N ₂	O ₂	H ₂	CO	CO ₂	CH ₄	C _n H _m ^b
Simulation data	54.92	0.40	11.91	4.55	20.79	6.70	0.73
Industrial data ^[14]	54.91	0.40	11.90	4.43	20.84	6.77	0.75

a: ignore the component with the fraction less than 1 PPM, such as H₂S and NO.

b: C_nH_m includes C₂H₄, C₂H₆, C₃H₈, C₄H₁₀, etc.

Table 5 Simulation and industrial data of the mass balance of the FsOSR process

		Simulation data		Industrial data ^[9,14]		<i>RE</i> (%) ^a
		Mass (t/h)	Ratio (%)	Mass (t/h)	Ratio (%)	
Input	Oil shale	500.00	52.08	500.00	52.02	0.00
	Air	110.05	11.46	111.50	11.60	1.30
	Water in air	52.25	5.44	51.57	5.37	1.32
	Recycle gas	161.90	16.86	157.35	16.37	2.89
	Water in recycle gas	8.10	0.84	7.78	0.81	4.13
	Water	127.80	13.31	132.94	13.83	3.86
	total	960.10	100.00	961.14	100.00	0.11
Output	Output gas of retort	146.97	15.31	145.87	15.18	0.75
	Water in output gas	158.70	16.53	160.92	16.74	1.38
	Shale oil	21.90	2.28	20.64	2.15	6.10
	Dry ash	402.67	41.94	405.78	42.22	0.77
	Water in ash	50.50	5.26	52.83	5.50	4.41
	Recycle gas	161.90	16.86	157.35	16.37	2.89
	Water in recycle gas	8.10	0.84	7.78	0.81	4.13
	Other/loss	9.36	0.97	9.97	1.04	6.12
	Total	960.10	100.00	961.14	100.00	0.11

a: *RE* (%) = (simulation data - industrial data) / industrial data * 100%

Table 6 Simulation and industrial data of the energy balance of the FsOSR process

		Simulation data		Industrial data ^[9,14]		<i>RE</i> (%) ^a
		Energy (MW)	Ratio (%)	Energy (MW)	Ratio (%)	
Input	Oil shale	770.72	71.73	770.72	72.39	0.00
	Air	3.34	0.31	3.38	0.32	1.29
	Water in air	23.63	2.20	23.30	2.19	1.42
	Recycle gas	228.89	21.30	220.81	20.74	3.66
	Water	2.43	0.23	2.52	0.24	3.72
	Total	1029.01	95.77	1020.74	95.87	0.81
Output	Retorting gas	288.32	26.83	289.83	27.22	0.52
	Steam	146.25	13.61	148.77	13.97	1.69
	Shale oil	248.02	23.08	234.75	22.05	5.65
	Ash	89.21	8.30	93.73	8.80	4.82
	Recycle gas	228.89	21.30	220.81	20.74	3.66
	Waste water	10.91	1.02	11.73	1.10	6.99
	Other/loss	17.41	1.62	21.12	1.98	17.57
	Total	1029.01	95.77	1020.74	95.87	0.81

a: *RE* (%) =(simulation data - industrial data)/ industrial data *100%

In summary, the simulation results show that the obtained values of the composition of the retorting gas as well as the mass and the energy balances are reasonably consistent with industrial data.

4.2 Conventional analysis of exergy

Based on the low heating value of oil shale (Δh_L^θ) and the high heating value of shale oil (Δh_H^θ), the standard exergies of oil shale and shale oil are formulated as follows [15]:

$$e_{os}^\theta = \Delta h_L^\theta + 2438 \times \omega \quad (45)$$

$$e_{so}^\theta = 0.975 \times \Delta h_H^\theta \quad (46)$$

where e_{os}^θ is the standard exergy of oil shale, kJ/kg; Δh_L^θ is the low heating value of oil shale, kJ/kg; 2438 kJ/kg is the amount of heat needed for water vaporization; ω is

1 the mass fraction of water in oil shale, %; e_{so}^θ is standard exergy of shale oil, kJ/kg;
 2 and Δh_H^θ is the high heating value of shale oil, kJ/kg.

3 Based on the exergy balance, a detailed conventional exergy analysis was
 4 performed, the results of which are shown in Table 7. The total exergy input of the
 5 FsOSR process is 1012.83 MW. The exergy of the products is 346.06 MW. Thus, the
 6 exergy efficiency of the whole process is 34.17%. It is clear from Table 7 that 26.02%
 7 of the total input exergy of the fuel is destroyed in the retort as a result of the oil shale
 8 retorting and semi-coke gasification reactions conducted at high temperature. The
 9 heating furnace has relatively large exergy destruction due to gas combustion and heat
 10 transfer at high temperature difference. The collecting tube, the washing tower, the
 11 indirect cooling tower, and the electric oil separator cause much smaller exergy
 12 destruction. In these components, temperature drop, leading to a fall in the quality of
 13 the energy, is the major cause of the exergy destruction.

15 Table 7 Results of conventional exergy analysis of the FsOSR process

	$E_{F,k}$ (MW)	$E_{P,k}$ (MW)	$E_{D,k}$ (MW)	ε_k (%)	y_k (%)	y_k^* (%)
retort	1012.83	749.28	263.55	73.98	26.02	59.54
collecting tube	749.28	708.22	41.07	94.52	4.05	9.28
washing tower	591.86	561.21	30.66	94.82	3.03	6.93
indirect cooling tower	488.70	467.57	21.13	95.68	2.09	4.77
electric oil separator	458.04	441.10	16.94	96.30	1.67	3.83
heating furnace	286.72	217.45	69.27	75.84	6.84	15.65
overall system	1012.83	346.06	442.62	34.17	43.70	100.00

16 4.3 Advanced analysis of exergy

17 The advanced exergy analysis model of the FsOSR process is formulated as
 18 shown in Fig. 6. $E_{F,tot}$, $E_{P,tot}$ and $E_{D,tot}$ of the FsOSR process are as follows:

$$19 \quad E_{F,tot} = E_{F,R} = E_{F,oil\ shale} + E_{F,air} + E_{F,water} + E_{F,recycle\ gas} \quad (47)$$

$$20 \quad E_{P,tot} = E_{P,OC} + E_{P,OW} + E_{P,OI} + E_{P,OE} + E_{P,RE} + E_{P,H} \quad (48)$$

$$E_{D,tot} = E_{D,R} + E_{D,C} + E_{D,W} + E_{D,I} + E_{D,E} + E_{D,H} \quad (49)$$

where $E_{D,R}$, $E_{D,C}$, $E_{D,W}$, $E_{D,I}$, $E_{D,E}$, and $E_{D,H}$ are the exergy destruction of the retort, collecting tube, washing tower, indirect cooling tower, electric oil separator, and heating furnace, respectively; $E_{P,OC}$, $E_{P,OW}$, $E_{P,OI}$, and $E_{P,OE}$ are the shale oil product exergies of the collecting tube, washing tower, indirect cooling tower, and electric oil separator, respectively; $E_{P,RE}$ is the remaining gas exergy; and $E_{P,H}$ is the product exergy of the heating furnace.

Fig.6. Advanced exergy analysis model of the FsOSR process

During system operation, the exergetic value of the product, $E_{P,tot}$, is constant. The results of the advanced exergy analysis of the FsOSR process are shown in Table 8.

Table 8 Results of the advanced exergy analysis of the FsOSR process

$E_{D,k}$ (MW)	$E_{D,k}^{EN}$	$E_{D,k}^{EX}$	$E_{D,k}^{UN}$	$E_{D,k}^{AV}$	$E_{D,k}^{UN,EN}$	$E_{D,k}^{AV,EN}$	$E_{D,k}^{UN,EX}$	$E_{D,k}^{AV,EX}$
retort	198.21	65.34	114.67	148.88	99.45	98.76	15.22	50.12
collecting tube	32.67	8.4	25.99	15.08	23.48	9.19	2.51	5.89
washing tower	24.43	6.23	15.22	15.43	13.83	10.6	1.39	4.84
indirect cooling tower	17.24	3.89	12.8	8.33	11.81	5.43	0.99	2.9
electric oil separator	14.29	2.65	8.08	8.86	7.59	6.7	0.49	2.16
heating furnace	69.27	-	24.16	45.11	24.16	45.11	-	-
overall system	356.11	86.51	200.93	241.69	180.32	175.79	20.6	65.91

Endogenous/Exogenous exergy destruction: Table 8 shows that a large part of the exergy destruction in all components of the system is endogenous. The proportion

of endogenous exergy destruction differs significantly for the various components. For example, the endogenous exergy destruction of the retort and the heating furnace is 75.21% and 100% respectively. The results also show that all exogenous exergy destruction, except in the heating furnace, is positive, which means that the performance of any component can be improved by performance enhancement of the other components of the system.

Unavoidable/Avoidable exergy destruction: Constraints defining practically feasible operation conditions, i.e. unavoidable conditions, were determined based on the knowledge and experience of the authors. This was done by assessing the realistically feasible potential for improvements that could be achieved for each component in the foreseeable future [24, 25]. Energy consumption and exergy destruction in equipment such as the compressor decreases as its efficiency improves. Naturally, this will contribute to performance improvement of the whole system, but simultaneously it will generate higher capital costs. Thus, the efficiency of the components can be improved only to a certain level because of technical constraints and economic constraints [18]. In this paper, the unavoidable conditions of the k^{th} component are assumed as follows [7, 15]: $\varepsilon_R = 85\%$, $\varepsilon_C = 96\%$, $\varepsilon_W = 97\%$, $\varepsilon_I = 97\%$, $\varepsilon_E = 98\%$, and $\varepsilon_H = 90\%$. Table 8 shows that unavoidable exergy destruction for each component and the whole system is not equal to zero. This means that the real potential for improvement of the system's components is not determined by its total exergy destruction but by its avoidable parts. The avoidable exergy destruction of the retort and the heating furnace are 56.50% and 65.12%, showing the largest improvement potential. Consequently, these parts of the system should be the focus of efforts to improve the FsOSR process. The avoidable exergy destruction of the remaining components is higher than 36%, also giving room for improvement.

Combined analysis: The retort has the largest avoidable endogenous exergy destruction, followed by the heating furnace, and the washing tower. The retort also

1 has the largest avoidable exogenous exergy destruction ($E_{D,k}^{AV,EX}$), followed by the
 2 collecting tube and the washing tower. The $E_{D,k}^{AV,EX}$ of the retort, collecting tube,
 3 washing tower, indirect cooling tower, and electric separator is higher than zero. This
 4 indicates that in order to reduce one of the above five components' exergy destruction
 5 should focus on improving the other components' performances. However, $E_{D,k}^{AV,EX}$ of
 6 the heating furnace is zero because that the $E_{D,k}^{EX}$ of the heating furnace is zero.
 7 Consequently, the performance of the other components in the system has no
 8 influence on the heating furnace. To diminish the exergy destruction of the heating
 9 furnace, efforts should be exclusively concentrated on reducing the avoidable
 10 endogenous exergy destruction in the heating furnace itself.

11 **4.4 Comparison of conventional and advanced exergy analysis**

12 The concepts of exergy destruction ($E_{D,k}$) and exergy destruction ratio (γ) are
 13 used for conducting conventional exergy analysis. The advanced exergy analysis is
 14 based on division of exergy destruction into two main groups: endogenous/exogenous
 15 exergy destruction and avoidable/unavoidable exergy destruction. The advanced
 16 exergy analysis has the following advantages in comparison to the conventional ones:

17 (1) The advanced exergy analysis can identify the share of the exergy destruction
 18 that can be avoided. The conventional exergy analysis indicates only that the total
 19 exergy destruction of the FsOSR process is 442.62 MW. The results obtained from
 20 splitting the $E_{D,k}$ into its unavoidable ($E_{D,k}^{UN}$) and avoidable ($E_{D,k}^{AV}$) parts show that
 21 45.40% of the exergy destruction is unavoidable and cannot be reduced as shown in
 22 Fig. 7.

23 (2) The advanced exergy analysis can determine the interactions between the
 24 components of the system. The results obtained from splitting the $E_{D,k}$ into its
 25 endogenous ($E_{D,k}^{EN}$) and exogenous ($E_{D,k}^{EX}$) parts show that 19.54% of the exergy

destruction is caused by the interactions between the components of the FsOSR process as shown in Fig. 7.

(3) The advanced exergy analysis can identify the improvement potential of each component. The improvement potential of each component can be determined on the basis of avoidable-endogenous ($E_{D,k}^{AV,EN}$) and avoidable-exogenous ($E_{D,k}^{AV,EX}$) exergy destruction. The highest priority should be given to the retort, followed by the heating furnace and the washing tower as shown in Table 8, section 4.3. The indirect cooling tower and the electric oil separator have the lowest priority for improvement.

Fig.7. Division of total exergy destruction of the FsOSR process

4.5 Improvement strategy

Based on the results discussed above, the retort has the largest avoidable exergy destruction. Special attention should be paid to improvement of the operation of the retort when aiming to improve the overall performance of the FsOSR process. As shown in Table 8, the endogenous exergy destruction and exogenous exergy destruction of the retort are large and roughly equal. Therefore, improvement in the performance of the retort could be achieved by:

Reducing exogenous exergy destruction: Exogenous exergy destruction of the

retort is mainly caused by the other components in the system, such as the collecting tube (C), washing tower (W), indirect cooling tower (I), electric separator (E), and heating furnace (H). In this paper, we study the effect of unavoidable exergy efficiency of the remaining components on the $E_{D,k}^{AV}$ of the retort as shown in Fig.8. The avoidable exergy destruction of the retort rises as the unavoidable exergy efficiencies of the other components increase. The collecting tube has the largest influence on possible reduction of the exogenous exergy destruction of the retort, followed by the washing tower. The heating furnace has relatively small influence, mainly because of the large impact of the collecting tube and retort resulting from their very close proximity. However, as the unavoidable exergy efficiency of the components increase, then the equipment cost would also raise slightly.

Fig.8. Relationship of $E_{D,R}^{AV}$ and the unavoidable exergy efficiency of the other components

Reducing endogenous exergy destruction: For the sake of reducing the endogenous exergy destruction of the retort, one of effective ways is to optimize its key operational parameters. The temperatures of the retorting and the feeding air have a great impact on production of the shale oil and the retorting gas [46, 47]. As a result, they affect the endogenous exergy destruction of the retort.

(1) Effect of retorting temperature on reduction of endogenous exergy

destruction. In the temperature range between 420°C and 520°C, the total exergy destruction and the avoidable exergy destruction of the retort are greatly reduced, while the unavoidable exergy destruction increases as shown in Fig. 9. This is caused by the fact that the decomposition rate of oil shale increases quickly in this range of temperatures and increasingly more oil shale is completely converted into shale oil and retorting gas. This increases the irreversibility of the retorting reaction, resulting in a gradual increase of exergy destruction. When the temperature is higher than 520°C, there is no big change in the total exergy and the avoidable exergy destruction of the retort because only a small amount of the remaining organics can be decomposed at this temperature range. Consequently, there is no big improvement potential when the temperature rises higher than 520°C. In light of the above analysis, the suggested temperature for operation of the retort is 520°C.

Fig.9. Effect of the retorting temperature on the exergy destruction of the retort

(2) Effect of temperature of feeding air on reduction of endogenous exergy destruction. In Chinese oil shale industry, the temperature of the feeding air is called as the saturation of the feeding air. It is explained by the fact that the fraction of steam in the feeding air depends mainly on its temperature. The steam in the feeding air acts not only as the gasification agent, but it is also a carrier providing heat for the

1 retorting stage [14]. The effect of the temperature of feeding air on the endogenous
 2 exergy destruction is shown in Fig. 10. An increase in the temperature is accompanied
 3 by a decrease in the total exergy destruction and avoidable exergy destruction of the
 4 retort. At the same time, the unavoidable exergy destruction increases. The avoidable
 5 and unavoidable exergy destructions of the retort fall or rise significantly when the
 6 temperature is higher than 60°C. It is a result of the change in the partial pressure of
 7 the steam, which has a great impact on the other parameters of the retort. Thus, high
 8 temperature of the feeding air reduces the endogenous exergy destruction. The
 9 suggested temperature of the feeding air should be to 90°C.

Fig.10. Effect of the temperature of feeding air on the exergy destruction of the retort

14 For the purpose of this analysis, the existing Fushun oil shale utilization plant is
 15 a reference system. To demonstrate the advantages of the proposed improvement
 16 strategies, the obtained results were compared to the characteristics of base system,
 17 Fig. 11. When comparing the reference and the improved systems it is seen that the
 18 retorting temperature increases from 500°C to 520°C and that of feeding air from
 19 83°C to 90°C. As the results show, the total exergy destruction of the improved system
 20 decreases from 263.55 MW to 238.91 MW; the avoidable exergy destruction is
 21 decreased from 148.88 MW to 107.20 MW; while the unavoidable exergy is increased

from 114.67 MW to 131.71 MW. It is mainly caused by the fact that more oil shale is completely converted into shale oil and retorting gas as the value of the above mentioned parameters increase. Moreover, retorting and gasification reactions increase the irreversibilities of the system, leading in consequence to the growth of unavoidable exergy destruction. Because the production of shale oil and retorting gas is growing, the profitability of the FsOSR process increases. As a result, the economic performance of the process could be improved. A more detailed economic/exergoeconomic analysis will be conducted in a forthcoming paper.

Fig.11. Comparison of the exergy destruction of the reference and improved systems

5. Conclusions

In this paper, conventional and advanced exergy analyses were applied to evaluate the performance of a Fushun-type oil shale retorting process (FsOSR). The process was modeled and simulated to calculate and analyze its mass and energy balance. The simulation results were validated by comparison with industrial data. The following conclusions are drawn:

1. The model of the system proposed in this paper is accurate, as illustrated by comparison of the results of the process simulation and the industrial data. About

- 1 21.90 t/h of shale oil can be produced from 500 t/h oil shale.
- 2 2. The exergy efficiency of the FsOSR process based on conventional exergy
3 analysis is 34.17%. The retort has the largest exergy destruction ratio, 26.02%,
4 followed by the heating furnace. The electric oil separator has the smallest exergy
5 destruction ratio, 1.67%.
- 6 3. Based on advanced exergy analysis, 80.46% of the total exergy destruction is
7 endogenous. About 45.40% of the exergy destruction is unavoidable and cannot
8 be reduced due to technical limitations.
- 9 4. Improvement priorities include not only modification of the system's components
10 but also consideration of the interactions of the components. Efforts should be
11 focused on improving the performance of the retort as it has the greatest impact
12 on the total avoidable exergy destruction.

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17 **Nomenclature**

18	E	exergy, MW
19	e_{os}^{θ}	standard exergy of oil shale, kJ/kg
20	e_{so}^{θ}	standard exergy of shale oil, kJ/kg
21	FsOSR	Fushun-type oil shale retorting
22	h	enthalpy, kJ/mol
23	Δh_L^{θ}	standard low heating value of oil shale, kJ/kg
24	Δh_H^{θ}	standard high heating value of shale oil, kJ/kg

1	k	reaction rate constants, s^{-1}
2	R	gas constant, $8.314 \text{ kJ/kmol} \cdot \text{K}$
3	s	entropy, $\text{kJ mol}^{-1} \text{K}^{-1}$
4	T	temperature, K
5	A	pre-exponential factor
6	t	time, s
7	x	the concentration at a time t , kg/m^3
8	y	exergy destruction ratio, %

9 **Subscripts**

10	F	fuel
11	P	product
12	D	destruction
13	L	loss
14	C	collecting tube
15	W	washing tower
16	I	indirect cooling tower
17	E	electric oil separator
18	H	heating furnace
19	k	k^{th} component
20	tot	total
21	ph	physical
22	ch	physical
23	0	reference condition

24 **Superscripts**

25	AV	avoidable
26	EN	endogenous
27	EX	exogenous
28	UN	unavoidable

29 **Greek Letters**

30	ε	exergy efficiency, %
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1 ω mass fraction of water in oil shale, %

2

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