Energy 87 (2015) 605–614

Contents lists available at ScienceDirect

Energy

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

Thermoeconomic analysis of oil shale retorting processes with gas or solid heat carrier☆

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ARTICLE INFO

Article history:
Received 6 January 2015
Received in revised form
4 May 2015
Accepted 6 May 2015
Available online 3 June 2015

Keywords:
Oil shale
Fushun retort
Gas full circulation retort
Dagong retort
Thermoeconomic analysis

ABSTRACT

Oil shale is regarded as one of the most promising alternative energy resources. In China, oil shale retorting technologies mainly consist of (i) conventional Fushun retorting technology, (ii) gas full circulation retorting technology, and (iii) Dagong retorting technology. There have been till now few quantitative analyses of the three technologies. This paper focuses on thermoeconomic analysis of three processes of these technologies. Results show that the exergy destruction of the Dagong retorting process is 38.6%, much lower than that of the Fushun retorting process, 65.7%. The total capital investment of the gas full circulation retorting process is the highest, 1.7 billion CNY, followed by the Dagong retorting process, 1.4 billion CNY and the Fushun retorting process, 1.2 billion CNY. The ROI (Return on investment) of the Dagong retorting process is the highest, 18%, while that of the Fushun retorting process is the lowest, 8.6%.

1. Introduction

Nowadays, oil can rarely satisfy the increasing demand of energy in the world [11]. Exploitation of alternative energy resources is attracting increasing attention. Oil shale, an unconventional energy resource, is regarded as one of the most promising alternatives [36]. According to statistics, the extractable amount of shale oil in the world is 654.7×10^9 t, four times of the world's crude oil reserve [6]. The amount of that in China is 47.6×10^9 t, double of China's crude oil reserve [40].

Exploitation and exploration of oil shale are mostly found in Estonia and China. Most of oil shale in Estonia is used for power generation, while in China for oil production [41]. The world oil production from oil shale is 1.63 Mt/y [21], 0.95 Mt/y oil from China and 0.5 Mt/y oil from Estonia [20]. There are mainly two types of retorting technologies: in-situ and ex-situ [35]. In China, only ex-situ retorting technologies are applied. They are Fushun retorting technology, gas full circulation retorting technology, and Dagong retorting technology [25].

Fushun retorting technology has been broadly applied in different plants. By 2014, the overall production of shale oil in China is 0.7 Mt/y [21]. It has a better adaptability to lean shale with the lowest oil content of 6%. In addition, it has the advantages of a simple structure as well as easier equipment maintenance. However, its oil yield is 65% as reported by Qian et al. [24]. This is because a part of the shale oil is burnt using excess oxygen from the gasification stage of the retort.

Gas full circulation retorting technology is developed based on Fushun retorting technology. Liaoning Chengda Co., Ltd applied it in a retorting plant in Huadian, Jilin province. The processing capacity of this plant is 3 Mt/y oil shale. The oil production is 0.25 Mt/y [27,29]. Another plant with the processing scale of 11 Mt/y oil shale is in Jimsar, Xinjiang province and is still under construction by Liaoning Chengda Co., Ltd. The expected oil production is 0.48 Mt/y in the first stage of the project [7]. Because no oxygen is in the oil-gas mixture, an electrostatic oil separator can be used in the condensate recovery system to capture oil. Thus, the oil yield is increased to 90% [2]. However, outsourcing fuel gas is needed as fuel gas to supply heat for the retorting reaction.

Dagong retorting technology is still in pilot-scale production. Its oil yield is reported as 90–96 % [21]. Daqing Oilfield Co., Ltd applied this technology and built an industrialized pilot-scale plant with the processing capacity of 0.6 Mt/y oil shale. Its oil production is 0.03 Mt/y [25]. This technology uses the ash from the semi-coke combustion to supply heat for the retorting reaction.

The goal of this paper is to quantitatively analyze the energy utilization and economic performance of the three retorting

☆ For publication in Energy.

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http://dx.doi.org/10.1016/j.energy.2015.05.045
0360-5442/

technologies. The advantages and disadvantages of these technologies are explored, and some suggestions are given for development of oil shale industry in China.

2. Oil shale retorting process

In a FS-OSR (Fushun oil shale retorting) process, oil shale is firstly grinded in a grinding unit, and then separated into two types of particles in a screening unit: detrital particles smaller than 10 mm in diameter, and particles between 10 and 75 mm in diameter. The detrital particles are burnt to generate electricity by a steam turbine. Other particles are fed into the retort. The retort includes a retorting stage and a gasification stage. In the retorting stage, the oil shale particles are converted into semi-coke and oil-gas mixture at 0.1 MPa and 525 °C [37]. The semi-coke is sent to the gasification stage and burnt by saturated air at 0.1 MPa and 850 °C. Gasified gas is led to the retorting stage to supply heat for the retorting reaction. The oil-gas mixture flowing out from the top of the retort is firstly separated by a water scrubbing tower. Some shale oil is obtained here. The rest mixture is further separated by a flash separator. The separated retorting gas is divided into three parts: recycle gas, burning gas, and remaining gas. The recycle gas is heated by combustion of the burning gas. The remaining gas is used to generate electricity. The schematic diagram of the FS-OSR process is shown in Fig. 1 [37].

A GFC-OSR (gas full circulation oil shale retorting) process is similar to the FS-OSR process, as shown in Fig. 2 [42]. The semi-coke discharged at the bottom of the retort is used to generate electricity. Shale oil and retorting gas are separated from the oil-gas mixture by the cryogenic separator, the electrostatic oil separator, and the water scrubbing tower. Most of the retorting gas is recycled back to the retort after heated by burning a part of the retorting gas and outsourcing fuel gas. The rest of the retorting gas is directly recycled back to the bottom of the retort, to exchange heat with the semi-coke.

Dalian University of Technology developed a solid heat carrier retorting technology in 1984 which is named as DG-OSR (Dagong oil shale retorting) technology [25]. In a DG-OSR process, oil shale particles smaller than 10 mm in diameter are fed into a heat exchanger, and preheated to 120–150 °C by hot flue gas generated by combustion of semi-coke. The hot oil shale is mixed with recycled hot ash and sent into the retort. The oil shale is then converted into semi-coke and oil-gas mixture [18]. The semi-coke is burnt by preheated air in a burning unit. The ash from the semi-coke combustion is divided into two parts: most of the ash is recycled back to the retort to supply heat for the retorting reaction; the rest ash is discharged after exchanging heat with air. Shale oil and retorting gas are separated by an oil scrubbing tower and a flash separator. The retorting gas is used to generate electricity. The schematic diagram of the DG-OSR process is shown in Fig. 3.

3. Process modelling and simulation

The FS-OSR, the GFC-OSR, and the DG-OSR processes all contain OSR (oil shale retorting units) and PGU (power generation units). The OSR unit includes an oil shale retorting and an oil-gas mixture separating units. The PGU unit has a steam turbine or a gas turbine. According to industrial practices, the processing capacity of a Fushun retort is about 100 t/d oil shale. Twenty retorts are combined in parallel as a group. A Fushun type retorting plant runs five groups, so that the plant's processing capacity is about 418 t/h oil shale. For simulation of the FS-OSR and the GFC-OSR processes, the feedstock of the oil shale with 7% oil content in Fushun, Liaoning, China is used. For simulation of the DG-OSR process, the feedstock of the oil shale with 14% oil content in Longkou, Shandong, China is used. The proximate and element analyses of the two types of oil shale are shown in Table 1 and their Fischer assay analysis is shown in Table 2 [12,24].

These three processes are simulated in Aspen Plus simulation software. RK-SOAVE (Redlich-Kwong-Soave) is selected as the property method for the retorting reaction. Oil shale is defined as a mixture of water, minerals, organic matters (kerogen and carbon residues), and others. These components can be modeled as MIXED, SOLID, and NC. The oil shale retorting mechanism of the three processes is the same. The retort is modeled as a continuously stirred tank reactor by RCSTR model. We assume that there are only

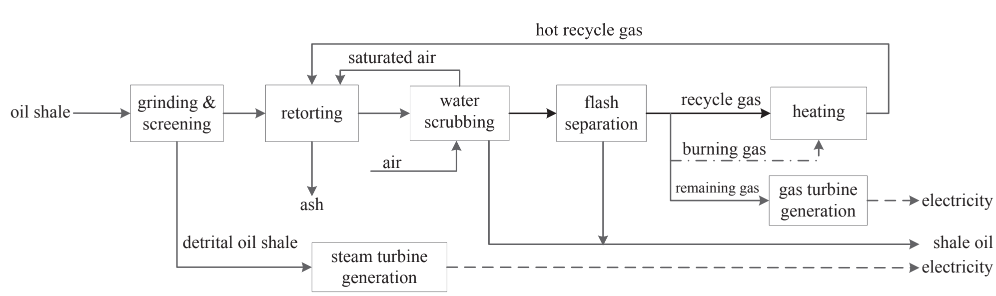

Fig. 1. Schematic diagram of the FS-OSR process.

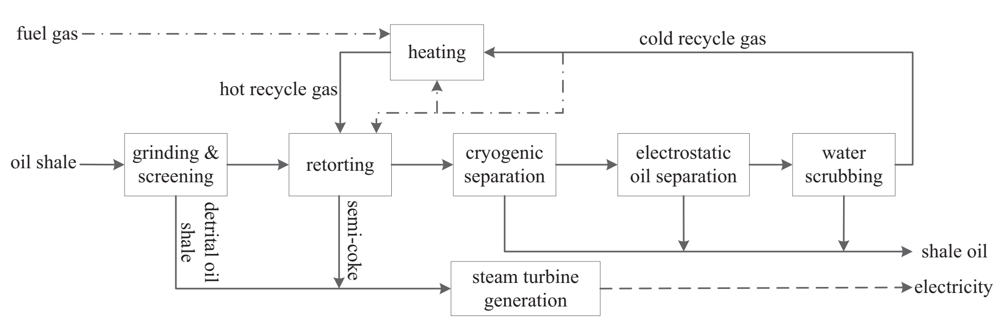

Fig. 2. Schematic diagram of the GFC-OSR process.