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Framework for advanced exergoeconomic performance analysis and optimization of an oil shale retorting process

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ABSTRACT

A framework based on advanced exergoeconomic analysis is proposed for evaluation and optimization of oil shale retorting processes. The proposed approach aims to facilitate identification of the improvement potential of energy conversion systems in oil shale retorting. A Fushun-type OSR (oil shale retorting) process is analyzed to illustrate the application of the proposed framework. The results indicate that the total exergy destruction rate of the OSR process under consideration is 442.62 MW, of which 54.60% is avoidable. The total exergy cost and total avoidable cost of the OSR process are 323.08×10^6 CNY/y and 115.51×10^6 CNY/y, i.e., the improvement potential of the OSR process is 35.75%. The retort is found to be the component of the OSR process having the greatest potential for decrease of exergy destruction cost. Following optimization, the cost per exergy unit of product of the six components of the OSR process decreases by 6.93%–11.28%. The total cost per exergy unit of product is reduced by 5.62%. The total avoidable cost is reduced by 17.03% and the exergy efficiency increased by 2.41%.

1. Introduction

Increasing energy demand is one of the most important problems facing the world. In addition to the search for new energy sources, energy demand is driving society to search for more efficient energy conversion systems. Consequently, determination of the location, magnitude, type and source of inefficiencies becomes an important aspect of efforts to improve energy efficiency and the cost effectiveness of energy conversion [1].

Conventional exergy analysis, a powerful tool for performing such tasks, has been widely applied in evaluation of the thermodynamic performance of energy conversion processes [2,3]. For example, Gao et al. [4,5] adopted conventional exergy analysis to evaluate a coal based polygeneration process, and Li et al. [6] applied conventional exergy analysis to compare three typical oil shale retorting processes. Conventional exergy analysis, however, only allows identification of the location and magnitude of the inefficiencies; it neither offers data on the efficiency of interactions between the components, nor provides detailed information about the potential for improvement of the components [7].

To address the deficiencies of conventional exergy analysis, Tsatsaronis and co-workers proposed an approach termed advanced exergy analysis [8–10]. In recent years, advanced exergy analysis has proved to be a useful tool for identification of component interaction and potential for system improvement. Advanced exergy analysis divides exergy destruction into two main types: endogenous/exogenous and avoidable/unavoidable exergy destruction [11]. The method has been applied to analyze natural gas liquefaction [12,13], a liquefied natural gas-based cogeneration system [14], a supercritical coal-fired power plant [15,16], a combined cycle power plant [17,18], an absorption refrigeration machine [9,14,19], and a food drying process [20].

Although conventional and advanced exergy analyses both provide valuable information, the results gained only indicate possible improvements from the thermodynamic point of view. Both types of analysis place strong emphasis on the importance of reducing exergy destruction and gaining optimum thermodynamic performance [21]. However, such approaches may lead to a failure to consider exergy destruction as a process driving force and, as a consequence, cause an increase in total capital investment and production cost [22]. As a result, an economically infeasible

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although thermodynamically effective system could be created. In order to solve these problems, both thermodynamic and economic performance analyses are required in the process optimization.

Conventional exergoeconomic analysis combines the concepts of exergy and economic analysis to address the deficiencies arising from the use of conventional exergy analysis alone [23]. Lozano and Valero [24] proposed the concept of cost per unit exergy as a metric identifying the relationship between the thermodynamic and the economic aspects of the analysis. Conventional exergoeconomic analysis has been used to analyze the thermo-economic performance of power generation processes [25–27], trigeneration systems for heating, cooling and power production [28–30], and polygeneration processes [31,32].

The technical limitations constraining reduction in exergy destruction are not considered in conventional exergoeconomic analysis. Therefore, as noted by Gungor et al. [7], advanced exergoeconomic analysis splitting exergy destruction and investment costs in each component into avoidable/unavoidable and endogenous/exogenous parts is needed. An example of such work is the paper by Kecebas et al. [33,34], in which the potential for energy saving of geothermal district heating-systems is analyzed, and conventional and advanced exergoeconomic analysis results compared. It was found that advanced exergoeconomic analysis is more useful than conventional exergoeconomic analysis for identification of options for energy and cost savings. In addition, advanced exergoeconomic analysis has been applied to evaluate a trigeneration system using a diesel–gas turbine [35], an electricity-generating facility that operates with natural gas [36], and a multi-effect evaporation–absorption heat pump desalination system [22]. However, no studies have been published on the application of advanced exergoeconomic analysis for evaluation and optimization oil shale retorting processes.

The main contributions of this paper are: (i) to propose a new advanced exergoeconomic analysis framework, based on advanced exergoeconomic analysis, for system evaluation and optimization; and (ii) to apply this framework to analyze and optimize the oil shale retorting process.

The paper is composed of five parts: First, an advanced exergoeconomic-based framework is developed. The framework consists of conventional and advanced exergy analysis, conventional and advanced exergoeconomic analysis, and optimization models. Second, a traditional Fushun-type oil shale retorting process is used to illustrate the application of the proposed framework. Conventional exergy and exergoeconomic analyses are then used to calculate the exergy efficiencies, exergy destruction, and product cost of the individual components of the system as well as the system as a whole. Next, advanced exergy and exergoeconomic analyses are conducted to identify the critical components influencing the thermo-economic performance of the whole system, and to assess options for improvement of the economic aspects of the system's operation. Finally, optimal operational conditions are determined by analysis of their impact on the system's thermo-economic performance and reduction in total avoidable costs. The exergy efficiency, total cost per exergy unit of product, and total avoidable cost of the system operating under optimal conditions are compared to those of the base system.

2. Analysis framework

The framework is based on advanced exergoeconomic analysis of the performance of the system and system optimization, as shown in Fig. 1. The framework consists of three parts:

1) **Modeling and simulation**. The process simulator Aspen Plus was used to simulate the whole system. This simulator is widely used in modeling and simulation of chemical and energy conversion systems [6,37]. The simulation results obtained should be validated against industrial data [38], after which the models used and the results of the simulation can be applied in system analysis and optimization.
2) **System analysis**. In system analysis, it is essential to calculate inefficiencies and identify their source, location and magnitude, as well as determine avoidable operational costs and improvement potential [39]. This work should be done prior to optimization of the thermo-economic performance of a process [1]. Exergy destruction, its cost and investment costs of the components of the system can be determined using conventional exergy and exergoeconomic analyses [40]. However, to gain knowledge of the sources of the irreversibility, cost impact, improvement potential and interdependencies between the system components, advanced exergy and exergoeconomic analysis are required [11]. Therefore, the proposed framework combines both conventional and advanced exergy based methods.

The advanced exergy based methods use the results obtained from the conventional exergy analyses. Therefore the conventional exergy and exergoeconomic analyses are conducted first [41]. Using the results of the conventional exergy and exergoeconomic analyses, the advanced methods are applied to split the exergy destruction and investment costs into endogenous/exogenous and avoidable/unavoidable parts [33]. The total avoidable cost of the components and the whole system are determined after conducting advanced exergy and exergoeconomic analyses. The avoidable cost data indicate the improvement potential of individual components, as well as that of the whole system, and thus facilitate subsequent optimization.

3) **System optimization**. At this stage, the mass, energy and cash balances, system thermodynamics and the kinetic model of the chemical reactions are determined considering current industrial best practices. The analysis results are used to create the theoretical basis for design of improved industrial processes. TAC (total avoidable cost) is the sum of the avoidable cost of capital investment (Z_k^{AV}) and the avoidable cost of exergy destruction ($C_{D,k}^{AV}$). The exergy and investment costs are functions of operational parameters, such as mass flow rate (m), composition (x), material properties (T, P, V). The objective function, expressed as total avoidable cost (TAC), relates thermo-economic performance of the system and its operating parameters.

However, TAC (total avoidable cost) alone cannot indicate the sources of the non-optimal thermo-economic performance of a system, i.e. it cannot identify if non-optimal thermo-economic performance is caused by irreversibility or by high investment costs. Thus, the advanced exergoeconomic factor (f_k^*) and the advanced relative cost difference (r_k^*) are introduced to reveal the major source of the costs associated with the system components.

The optimization steps in the proposed framework include:

Step 1: Ordering of the components on the basis of their total avoidable cost.
Step 2: Improvement in the performance of the component having the largest total avoidable cost.
Step 3: Improvement in the performance of the components having the largest advanced relative cost difference (r_k^*).
Step 4: Use of the advanced exergoeconomic factor (f_k^*) to identify the causes of the high costs:

a) If f_k^* is high, then reduction in the equipment costs, which may have increased due to improvements in equipment efficiency, needs to be considered.