Composite metric for simultaneous technical and economic analysis and optimization of energy conversion processes

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ABSTRACT

Dramatically increasing demand for energy is at odds with the world's finite reserves of non-renewable energy resources, obliging society to improve the efficiency of energy conversion systems. In study of energy conversion systems, technical analysis focuses on maximizing the energy utilization efficiency, whereas economic analysis focuses on maximizing the economic benefit. Thus the results obtained from the two approaches are often contradictory. These inconsistencies not only complicate decision making, but also affect further design and optimization. The paper addresses this problem by introducing a new composite metric. Use of this new metric for evaluation and optimization of energy conversion processes can prevent the situation of energy-efficient but costly or cost-efficient but energy-inefficient. The new metric is studied on an oil shale retorting process. The new metric indicates that the oil shale retorting process integrated with retorting gas used for hydrogen production has the best overall techno-economic performance, 563.63 CNY/MJ, much higher than that of conventional oil shale retorting process, 430.96 CNY/MJ. The performance of the new metric is appraised by comparison with indicators that are predominantly either technical or economic. The results show that the new metric can effectively trade-off the technical and economic performance and provides a more balanced analysis than other metrics, especially when applied to the optimization of integrated processes.

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1. Introduction

Reserves of non-renewable energy resources like oil, coal and natural gas are limited. Over the past 30 years, the annual average growth rate of the world's energy consumption has been around 1.8% (BP, 2015). Energy-saving and the development of energy efficient solutions are receiving more and more attention.

Efforts aimed at reducing the use of non-renewable energy resources have focused on the development of alternative energy resources and the optimization of industrial processes (Yong et al., 2016). As a part of such undertakings, technical and economic analyses are conducted to identify and compare the advantages and disadvantages of different alternative energy conversion processes.

The technical analysis is usually carried out using energy and exergy analysis. Energy analysis identifies the quantitative relationship between different forms of energy based on the first law of thermodynamics. However, the first law of thermodynamics considers only the quantity of energy without taking into account its quality. Thus, it is dependent only on mass or energy flow parameters and does not consider parameters related to surrounding environment (Schulze et al., 2016). When applied to analysis and optimization of energy conversion processes, it sometimes fails to detect significant energy losses, which can lead to erroneous conclusions (Tsatsaronis, 1993). For instance, energy analysis does not detect waste in an adiabatic reactor or adiabatic throttling process and cannot identify energy degradation in an adiabatic heat exchanger (Tsatsaronis, 1993).

Exergy analysis is based on the second law of thermodynamics. The second law of thermodynamics reflects the irreversibility, spontaneity and direction of various energy conversion processes, and allows both energy quantity and energy quality to be assessed (Hepbasli, 2008). In the irreversible conversion processes, i.e. the non-ideal conditions, energy is always conserved because energy can be neither destroyed nor produced. It only changes from one

form to another. However, exergy is consumed or destroyed due to the irreversiblities. Exergy analysis is widely used to evaluate the thermodynamic performance of energy conversion systems as it can identify the location, magnitude, type and sources of inefficiencies (Wang et al., 2016). For example, Esen et al. (2007b) conducted a detailed energy and exergy analysis of a ground-coupled heat pump system working under varying operating conditions. The results indicate that increasing of source temperature can greatly increase the exergy efficiency of the system. Gao et al. (2004) applied it to a coal-based polygeneration process, and found that the synthesis on the basis of thermal energy cascade utilization is the main contribution to the performance benefit of the polygeneration system. Furthermore, they also used it to evaluate a new kind of natural gas-based polygeneration system for methanol and power production (Gao et al., 2008). The results indicated that the new system can save energy about 6 percentages versus single product systems. Juraščík et al. (2010) found the largest exergy losses of a biomass-to-synthetic natural gas system take place in the biomass gasifier, CH_4 synthesis part and CO_2 capture unit by conducting a detailed exergy analysis. Li et al. (2015) focused on exergy analysis of three typical oil shale retorting processes. Results indicate that the Fushun retorting technology has the largest exergy destruction.

Assessment of a process based on exclusively energy and exergy analysis can lead to identification as optimal of a solution that offers considerable energy savings but is very expensive due to the equipment required or the topology of the process (Ghaebi et al., 2012). Overemphasis on reduction in exergy destruction, with the aim of achieving optimum thermodynamic performance, might thus cause an increase in total investment and production costs (Petrakopoulou et al., 2014). For example, energy efficiency optimization of the heat exchanger network in an energy conversion process can decrease exergy destruction considerable, because the temperature difference is reduced, but may significantly increase the number of heat exchangers and leads to higher investment costs. As a result, an economically infeasible although thermodynamically effective system could be proposed. Clearly, both technical analysis of process and assessment of its economic performance must be performance simultaneously.

There are several commonly used economic indicators for assessment of industrial processes, e.g. net present value, internal rate of return, profitability, payback period and other economic indicators. These indicators, which consider the time value of money, have been widely used the economic evaluation of energy conversion processes, for example, in evaluation of coal based polygeneration (Lin et al., 2010), biofuel production (Im-orb et al., 2016), etc. Yi et al. (2012a, b) used net present value and internal rate of return to compare the economic performance of the conventional and the novel coal-based polygeneration processes. Esmaili et al. (2016) analyzed the economic performance of an integrated gasification combined cycle process with sorbent CO_2 capture by using internal rate of return and payback period. Esen et al. (2006) adopted payback period and annual cost to analyze the economic performance of a horizontal ground source heat pump system and compared with the conventional methods. Besides, they also well analyzed the economic advantages of the ground-coupled heat pump (GCHP) system over an air-coupled heat pump (ACHP) system (Esen et al., 2007a). Esen and Yuksel (2013) introduced the net present value method to demonstrate that renewable energy sources should be efficiently used to heat a greenhouse during the typical winter conditions in eastern Turkey. He and You (2014) compared the economic advantages of one conventional and three novel shale gas processing technologies by net present values. They found that the net present values of three novel processes are 1.7–2.4 times greater than that of the conventional one.

If analysis of such industrial processes focuses solely on economic aspects without considering thermodynamic performance, it can easily lead to a preference for cost-effective but energy-inefficient alternatives. For example, Gao et al. (2008) found that the economic performance of coal-to-methanol process could be improved by increasing the recycle ratio of unreacted gas leaving the methanol synthesis reactor. However, exergy efficiency decreases if the recycle ratio is higher than 2.5. Similarly, Yang et al. (2013) showed that an increase in the recycle ratio of CO_2 in a dry reforming reaction, can lead to greater economic profitability of a coal-to-olefins process. However, the energy consumption of the compressor of the coal-to-olefins process is greatly increased, and as a result, the exergy efficiency decreases greatly when the recycle ratio of CO_2 is higher than 0.85.

In systems engineering for selection of approaches to improve the efficiency of large industrial systems, the results of the technical analysis are often inconsistent with those of the economic analysis. For example, product upgradation is an important method of improving the economic profitability of energy conversion processes. The upgrading enables the production of high valued chemicals and in consequence contributes to improvement in the economic performance of the process. However, product upgradation decreases the exergy efficiency of the process due to the introduction of additional unit(s). Process integration is another important method for improvement of the economic profitability of energy conversion processes. The economic improves with increased process integration. Simultaneously, because exergy efficiency is less than 1 for each unit, the exergy efficiency deteriorates. Thus, these inconsistencies not only complicate decision making, but also affect further design and optimization.

Conventional technical and economic analyses of energy conversion processes, if conducted separately, are very likely to provide biased results. Multi-objective optimization method is a useful tool for analysis of technical and economic performances. It has been used to optimize the techno-economic performance of biomass-based integrated energy system (Ahmadi et al., 2014), low-grade organic Rankine cycles (Feng et al., 2015), and solar thermal energy system (Kim et al., 2016). However, complex system configuration, multiple feedstock and product options as well as huge number of decision variables and built-in unit specifications/parameters create serious challenges for multi-objective optimization. Especially, a vast number of variables and parameters complicate the assessment of investment decisions and requires lots of time to get the feasible or optimal solution (He and You, 2015).

To avoid the situation of energy-efficient but costly or cost-efficient but energy-inefficient during the optimization of energy conversion processes, a new metric is proposed to balance technical performance and economic performance requirements during the optimization of the energy conversion process. A conventional oil shale retorting process is selected to illustrate the applicability and advantages of the proposed metric. The main objectives of this study are: (a) to investigate the discrepancy between technical and economic analysis; (b) to propose a new metric for simultaneous technical and economic assessment of energy conversion processes; (c) to apply this new metric to analyze and optimize a Fushun-type oil shale retorting process; (d) to manifest the advantages of the new metric by comparing with conventional technical and economic indicators.

2. Methods

This section presents some of the most common indicators used for the technical and economic evaluation of energy conversion