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Energy-use analysis and evaluation of distillation systems through avoidable exergy destruction and investment costs

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ABSTRACT

Based on the concepts of avoidable/unavoidable exergy destructions and investment costs, this article presents an exergy analysis and an exergoeconomic evaluation to identify the potential energy savings in distillation processes. Methods for calculating the avoidable/unavoidable exergy destructions and investment costs for distillation columns, and hot-utility/cold-utility heat exchangers are proposed. For a distillation column, the unavoidable exergy destruction is estimated through the minimum reflux ratio, and the unavoidable investment cost is determined according to the minimum theoretical stage number obtained under the condition of total reflux. For the utility heat exchangers, the unavoidable exergy destruction is estimated through the minimum possible temperature difference, and the unavoidable investment cost corresponds to the maximum allowed temperature difference that is related to practical applications. A light-ends separation plant is used to demonstrate the performance of the proposed approach. The results indicate that the exergy-savings potential enables comparisons of energy-savings potentials among different system components, and the value of the cost-savings potential points out the cost that could be avoided in today's technological and economic environment. The modified exergoeconomic factor provides the improvement direction in a more accurate way compared with the conventional one.

1. Introduction

Exergy analysis and exergoeconomic evaluation have been extensively studied during the past several decades to improve the energy efficiency or to reduce the energy consumption in process industries, especially for combined heat and power plants [1–3]. For energy-use analysis and optimization of energy-intensive distillation systems, Rivero [4] presented a detailed exergy analysis for a distillation system to determine the distribution of exergy destruction (he called them "exergy losses") inside the column and the optimal distribution of heat to be transferred inside the column, in which adiabatic and diabatic rectification/stripping columns were considered. Chen et al. [5] proposed an exergoeconomic approach that simultaneously takes into account capacity expansions and energy-savings, and an aromatic fractionation unit was used to demonstrate application of the approach. It was concluded that the capacity of the aromatic fractionation unit increased by 28.0% and the energy consumption decreased by 81.4%. Rivero et al. [6] presented an analysis and evaluation to a crude oil combined distillation unit. The results obtained revealed that the most important factor affecting the transformation, operation and production costs is the raw material cost, and the critical points for optimizing the plant were identified. Based on the three-link energy structural model, Chen et al. [7] presented a detailed energy and exergy analyses for a delayed coking plant, and relevant energy-use improving measures were proposed. The energy consumption of the modified plant decreased 37.2% in comparison with the existed one. Chang et al. [8] suggested that the exergy losses caused by configuration constraints could be defined as intrinsic exergy destruction ("losses"), and extra exergy destruction corresponded to transport-rate limitations. In a de-ethanizer unit, the improvement measures on configuration and transport rate resulted in an 11.4% reduction of the overall column intrinsic exergy destruction and an 81.7% reduction of total individual stage extrinsic exergy destruction, respectively. As recognized, exergy analysis is effective in determining the locations, types, magnitudes, and causes of the thermodynamic inefficiencies of process. An exergoeconomic evaluation provides the system designer with

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information not available through conventional energy analysis and economic evaluation.

In addition to energy efficiency and cost effectiveness, the environmental aspects of energy systems were simultaneously considered with exergy analysis and exergoeconomic evaluation. Ahmadi et al. [9] reported a modeling of a tri-generation system, in which the environmental impact assessment and related parametric investigation are carried out. Meanwhile, multi-objective optimization in terms of exergy, economic and environmental factors was performed to determine the best design parameters of different kinds of power plants [10,11]. Tsatsaronis et al. [12] presented an exergoeconomic analysis for a zero-emission process in terms of generating electric energy and hydrogen, which was based on two chemical reactions. Although the overall process was characterized by very high energy and exergy efficiencies, the overall process was capital intensive. With the combination of exergy analysis and life cycle assessment, originally proposed by Meyer et al. in [13], Boyano et al. [14] provided a better understanding of the environmental impact formation in a steam methane reforming process for hydrogen production. The most relevant components of the process were identified and information on possibilities for reducing the overall environmental impact was provided. Today analyses and evaluations based on the exergetic, exergoeconomic and exergoenvironmental approaches ("exergy-based methods") represent the most elaborate and effective methodologies for improving the thermodynamic efficiency, and reducing the energy consumption, the product costs and the greenhouse gas emissions in process industries.

Motivated to improve the so-called conventional exergy–based methods, Tsatsaronis et al. [15,16] proposed that the exergy destruction and investment cost may be split into unavoidable and avoidable parts, which has proven to be helpful in analyzing and evaluating energy conversion systems. The unavoidable part is the exergy destruction and investment within one system component that could not be eliminated even if the best available technology in the near future would be applied, whereas the avoidable exergy destruction (or investment cost) is the difference between the total and unavoidable exergy destruction (or investment cost). According to the general definition of the avoidable exergy destruction and avoidable cost, the exergy destruction rate $\dot{E}_{D,k}$ and the investment cost rate $\dot{Z}_k$ are given as follows [15,16].

$$\dot{E}_{D,k} = \dot{E}_{D,k}^{UN} + \dot{E}_{D,k}^{AV} \tag{1}$$

$$\dot{Z}_k = \dot{Z}_k^{UN} + \dot{Z}_k^{AV} \tag{2}$$

The unavoidable and avoidable exergy destruction rates $\dot{E}_{D,k}^{UN}$ and $\dot{E}_{D,k}^{AV}$, the cost rates associated with the unavoidable and avoidable exergy destruction $\dot{C}_{D,k}^{UN}$ and $\dot{C}_{D,k}^{AV}$, and the unavoidable and avoidable parts of the investment cost $\dot{Z}_{D,k}^{UN}$ and $\dot{Z}_{D,k}^{AV}$ could be obtained from the following equations [15,16]:

$$\dot{E}_{D,k}^{UN} = \dot{E}_{P,k}\left(\frac{\dot{E}_D}{\dot{E}_P}\right)_k^{UN} \tag{3}$$

$$\dot{E}_{D,k}^{AV} = \dot{E}_{D,k} - \dot{E}_{D,k}^{UN} \tag{4}$$

$$\dot{C}_{D,k}^{UN} = c_{F,k}\dot{E}_{D,k}^{UN} \tag{5}$$

$$\dot{C}_{D,k}^{AV} = c_{F,k}\dot{E}_{D,k}^{AV} \tag{6}$$

$$\dot{Z}_k^{UN} = \dot{E}_{P,k}\left(\frac{\dot{Z}}{\dot{E}_P}\right)_k^{UN} \tag{7}$$

$$\dot{Z}_k^{AV} = \dot{Z}_k - \dot{Z}_k^{UN} \tag{8}$$

where $c_{F,k}$ is the average cost per exergy unit of fuel (it is equal to the unit cost of exergy destruction $c_{D,k}$), and the component exergy destruction cost rate $\dot{C}_{D,k}$ is the sum of $\dot{C}_{D,k}^{UN}$ and $\dot{C}_{D,k}^{AV}$, as $\dot{C}_{D,k} = \dot{C}_{D,k}^{UN} + \dot{C}_{D,k}^{AV}$. The exergy efficiency ε_k and the exergoeconomic factor f_k for component k are given as follows [17,18].

$$\varepsilon_k = \frac{\dot{E}_{P,k}}{\dot{E}_{F,k}} = 1 - \frac{\dot{E}_{D,k}}{\dot{E}_{F,k}} \tag{9}$$

$$f_k = \frac{\dot{Z}_k}{\dot{Z}_k + \dot{C}_{D,k}} \tag{10}$$

The modified exergy efficiency ε_k^* and exergoeconomic factor f_k^* are based on avoidable exergy destruction and on avoidable cost of a system component and are given by [15,16].

$$\varepsilon_k^* = \frac{\dot{E}_{P,k}}{\dot{E}_{F,k} - E_{D,k}^{UN}} = 1 - \frac{E_{D,k}^{AV}}{\dot{E}_{F,k} - E_{D,k}^{UN}} \tag{11}$$

$$f_k^* = \frac{\dot{Z}_k^{AV}}{\dot{Z}_k^{AV} + \dot{C}_{D,k}^{AV}} \tag{12}$$

Compared with conventional exergy analysis and exergoeconomic evaluation methods, the modified one considers the constraints of current economic and technological factors on energy-conversion processes. The modified exergy efficiency ε_k^* and exergoeconomic factor f_k^* are very effective in suggesting the feasible retrofit direction and the potential to improve energy efficiency and/or reduce energy consumption.

An advanced exergy analysis method which involves the endogenous and exogenous concepts was recently proposed for further splitting of the proposed avoidable and unavoidable exergy destruction and investment cost into four parts [19–21]. Such splitting seems helpful in improving the accuracy of the exergy analysis and exergoeconomic evaluation. It was emphasized that the efforts to improve the energy efficiency should be focused on the avoidable endogenous and the avoidable exogenous parts. The method was already proved to be reliable and useful in related studies [22–24]. However, the applications of the modified or the advanced exergy analysis and exergoeconomic evaluation methods focused only on thermal systems, absorption refrigeration and other energy conversion systems. Up to date there is no application to complex energy-intensive chemical processes, such as petroleum and petrochemical processes.

Distillation is one of the most important unit operations with a high energy consumption for the separation of liquid mixtures in process industries. The modification and optimization of distillation columns for the energy efficiency is a relatively complex task. In addition, effectively identifying the true potential for energy-savings in a distillation process is crucial to the reduction of its energy-use. These problems have been studied extensively in the past, and the most elaborate methodologies proposed are the temperature-enthalpy profiles and the driving force method. The column grand composite curve (CGCC) [25] and the invariant rectifying-stripping curve (IRS) [26] are mainly based on temperature-enthalpy profiles, while the exergy loss profile [27]