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A composite efficiency metrics for evaluation of resource and energy utilization

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ABSTRACT

Polygeneration systems are commonly found in chemical and energy industry. These systems often involve chemical conversions and energy conversions. Studies of these systems are interdisciplinary, mainly involving fields of chemical engineering, energy engineering, environmental science, and economics. Each of these fields has developed an isolated index system different from the others. Analyses of polygeneration systems are therefore very likely to provide bias results with only the indexes from one field. This paper is motivated from this problem to develop a new composite efficiency metrics for polygeneration systems. This new metrics is based on the second law of thermodynamics, exergy theory. We introduce exergy cost for waste treatment as the energy penalty into conventional exergy efficiency. Using this new metrics could avoid the situation of spending too much energy for increasing production or paying production capacity for saving energy consumption. The composite metrics is studied on a simplified co-production process, syngas to methanol and electricity. The advantage of the new efficiency metrics is manifested by comparison with carbon element efficiency, energy efficiency, and exergy efficiency. Results show that the new metrics could give more rational analysis than the other indexes.

1. Introduction

Polygeneration systems are of increasing interest to different countries. It was found that these systems could improve both resource utilization and energy utilization, lower environmental pollution, and save investment [1,23]. Till now, a large number of polygeneration projects have been launched, for example, the "Vision 21" in US [29]and the Syngas Park in EU [34]. China has been playing an active role in development of polygeneration systems. The IGCC (integrated gasification combined cycle) plant of China Huaneng Group has been successfully launched in Tianjin, laying a solid foundation for commercial applications of coal-based polygeneration systems.

Because of the coexistence of chemical conversion and energy conversion, polygeneration systems have been studied in different fields. Chemical engineers are apt to pay attention on chemical conversions while ignore energy conversions. They usually use resource utilization efficiency indexes to evaluate polygeneration systems, such as yield and element efficiency. Simply increasing efficiencies of chemical conversions, however, could incur unreasonable energy consumption [10]. For example, excessive unreacted gas circulation rate could increase energy consumption in methanol synthesis. In contrast, the polygeneration systems designed by power engineers tend to increase efficiencies of energy conversions. They are apt to use thermodynamic efficiencies for process design and analysis. Ref. [18] proposed a polygeneration system of liquid fuel and electricity. They used energy efficiency for system design and analysis. Ref. [7] used exergy efficiency to analyze a coal-based co-production process of methanol and electricity. They found that the coal gasification and the combined cycle units are those with the highest irreversibility and the largest exergy destructions. Overemphasis on energy conversion might lose sight of chemical conversions, finally leading to decrease of production capacity and overall benefit.

In addition to chemical engineers and power engineers, researchers in environmental science and economics are also interested in polygeneration systems. Environmental experts pay attention on emission mitigation, such as CO_2, NO_X, and SO_X reduction. They analyzed the energy efficiency and the economic performance of the polygeneration systems with carbon capture techniques [20,26]. There are also a number of literature studying the systems from economic point of view. One representative work

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was carried by Floudas and his group. They built a comprehensive framework for polygeneration systems of liquid fuel, hydrocarbon chemicals, and electricity by hybrid feedstocks, involving coal, natural gas, and biomass. Their objective was to optimize the total investment [3]. Besides, Kreutz and his group [17,21] conducted a series of studies on coal or biomass to liquids and electricity from economic point of view. Jin and his group made thermodynamic and economic analysis of a coal-based polygeneration system [20]. However, similar to the studies of chemical and power engineers, economic and environmental experts usually focus on economic performance and environmental impact while lose sight of the others.

There are some studies that calculate the saving energy of polygeneration systems compared to the single production systems that produce identical products. The calculations are based on the first [11] or the second [28] thermodynamic laws. However, using saving energy for analyzing polygeneration systems does not consider resource utilization, which might lead to incorrect analysis. For example [22], stated that the water gas shift reaction in the co-production process of methanol and electricity is efficient in energy utilization. Its exergy destruction is only 0.6% of the overall destruction. In their opinion, this small destruction could be ignored. However, from resource utilization and environmental performance, this process is not welcomed because water gas shift reaction consumes CO to increase the amount of H_2, accompanying large amount of CO_2. Ref. [36] therefore suggested that studies of polygeneration systems should consider energy utilization and resource utilization at the same time. They used element efficiency and exergy efficiency as two objectives for optimization of a co-production system. There are also some studies that combine analyses of resource utilization, energy utilization, environmental impact, and economy performance [14,24]. These studies could not provide a comprehensive analysis but simply report these different performances separately.

According to the above discussion, analyses of polygeneration systems are very likely to provide bias results with either indexes for resource utilization or those for energy utilization.

It is necessary to develop a metrics that could give the balanced evaluation of energy utilization and resource utilization simultaneously. The authors proposed an integrated framework for coal-based energy and chemical processes [35]. A key task in this framework is to develop a comprehensive efficiency metric for considering both resource utilization and energy utilization. This paper is motivated from the above problem and develops a new composite efficiency metrics. This metrics is based on exergy efficiency. The waste exergy in the conventional exergy balance is replaced by the exergy cost for treating the same magnitude of waste. This treating exergy is defined as the exergy penalty embedded into the conventional exergy efficiency to develop the new metrics. With this energy penalty, the metrics could give more balanced evaluation of resource utilization and energy utilization than the conventional indexes. In Sections 2 and 3, several typical indexes for resource utilization and energy utilization are briefly described. The theory of the new efficiency metrics is described in Section 4. In the end of this paper, this new metrics is applied on a simplified co-production process, syngas to methanol and electricity. Its advantages are studied by compared with element efficiencies, energy efficiency, and exergy efficiency.

2. Resource utilization indexes

Chemistry reactions are cores of chemical processes, mainly comprising chemical conversions. Resource utilization indexes are commonly used for chemical conversions, including yield, conversion rate, and element efficiency. All these indexes are based on mass balance of processes. The mass balance of a process is formulated as follows.

$$\sum m_{\text{in}} = \sum m_{\text{prd}} + \sum m_{\text{byprd}} + \sum m_{\text{wst}} \tag{1}$$

Of these indexes, EE (element efficiency) is important and commonly used for chemical processes. It is defined as the ratio of the mass of element X in products and the mass of X in input [36]:

$$\text{EE}(X) = \sum m^X_{\text{prd}} / \sum m^X_{\text{in}} \tag{2}$$

Element efficiency tracks utilization of a certain element in chemical processes. It is conducive to improving yield and preventing from resource loss.

3. Energy utilization indexes

Energy utilization indexes are used to evaluate energy conversions. According to the first and the second laws of thermodynamics, energy efficiency and exergy efficiency are defined and broadly used.

3.1. Energy efficiency

According to the first law of thermodynamics, input energy is equivalent with output energy. In energy conversions, feedstock is converted into energy through reactions, such as combustion. As to energy balance, output energy is the sum energy of products, byproducts, and waste:

$$\sum E_{\text{in}} = \sum E_{\text{prd}} + \sum E_{\text{byprd}} + \sum E_{\text{wst}} \tag{3}$$

Energy efficiency is the enthalpies of output steams over the high heat value of feedstock [2,37]:

$$\eta = \sum E_{\text{prd}} / \sum E_{\text{in}} \tag{4}$$

3.2. Exergy efficiency

Refs. [13,33] deemed that energy efficiency could not give a whole interpretation of the essence of energy conversion. It is necessary to introduce exergy efficiency since exergy could quantify the increase of entropy through irreversible processes [6]:

$$\Delta S \geq \frac{\Delta Q}{T} \tag{5}$$

If formula (5) is equality, the system is reversible, otherwise it is irreversible. For an isolate system, the entropy increases as the system proceeds:

$$\Delta S_{\text{isolate}} \geq 0 \tag{6}$$

Exergy is derived from the second law of thermodynamics. Its definition states that a form of energy or a certain state of material equilibrates with surroundings through a reversible process. The maximal work done in the reversible process is the exergy of the energy or the material [31]. There are some literature suggesting that waste exergy could reflect the impact of a process on environment [25,32]. The formulation of exergy destruction is shown below :

$$\Delta \text{Ex} = T_0 \Delta S_{\text{isolate}} \tag{7}$$

The exergy of a system involves stream exergy, heat exergy, and work exergy. The calculation of stream exergy is more complicated