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Evaluation and integration of energy utilization in a process system through material flow analysis coupled with exergy flow analysis

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ABSTRACT

It is of significant importance to evaluate energy consumption and to optimize configuration of energy utilization in process systems. A comprehensive approach based on material flow analysis (MFA) and exergy flow analysis (EFA) is proposed to evaluate energy consumption and integrate energy utilization of a process system, in which energy-consuming devices and exothermic devices exist simultaneously. By using the proposed approach, the energy consumption of streams in the process system is evaluated by energy consumption distribution, and the energy efficiency of the system is improved by both the improvement of local sub-systems and the integration of energy utilization of the entire system. A natural gas purification plant with a processing capacity of 200×10^4 m^3/d is taken as the case study to demonstrate the detailed implementation of the proposed approach. Results show that the streams with high energy consumption intensity are indicators of energy-intensive sub-systems, and energy conservation of these sub-systems can dramatically reduce the energy consumption of the system. In this case study, after the process improvement, the energy consumption of the desulfurization sub-system reduces by 9.62%, and the energy consumption of the exhaust gas treatment sub-system reduces by 21.02%. Furthermore, after the integration of heat exchange network of the entire system, the energy consumption of the system reduces by 2.16×10^5 kW. By these from the part to the whole strategies, the total energy-saving can reach 1.07×10^6 kW in the system. The proposed approach can be used for effectively identifying the bottlenecks of the energy consumption and improving the energy utilization of process systems.

1. Introduction

It is of significant importance to evaluate energy consumption and to optimize configuration of energy utilization in process systems. In general, material flow analysis (MFA) and exergy flow analysis (EFA) are two main methods for analyzing and evaluating performance of energy carried by process streams, products or waste in process systems.

MFA is used to identify and quantify the consumption of natural resources based on the mass balance principle (Fröhling et al., 2013; Hoque et al., 2012), which could be used to evaluate energy consumption performances on national (Canellas et al., 2004; Carlsson et al., 2008), cross-country (Weisz et al., 2006), regional (Kovanda et al., 2009; McEvoy et al., 2004), city (Tanikawa and Hashimoto, 2009) and industrial or sectoral levels (Sendra et al., 2007; Tanimoto et al., 2010). It can also be expanded for life cycle analysis (LCA) for a certain product. Nakamura et al. (2009) used waste input–output material flow analysis (WIO-MFA) model to perform effective life cycle management of polyvinyl chloride. Peiró et al. (2013) presented a MFA of the complex inter-relationships

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Nomenclature

Parameters

$E_{0,i}$	cumulative energy consumption of device i, kW
E_{0,i_n}^{out}	cumulative energy consumption of output stream i_n, kW
E_{0,j_n}^{out}	cumulative energy consumption of output stream j_n, kW
$E_{ele,i}$	electric energy consumption of device i, kW
$E_{ele,i_p}^{in}{}'$	electric energy consumption of input stream i_p, kW
E_{ele,i_n}^{out}	electric energy consumption of output stream i_n, kW
$E_{fuel,i}$	fuel energy consumption of device i, kW
$E_{fuel,i_p}^{in}{}'$	fuel energy consumption of input stream i_p, kW
E_{fuel,i_n}^{out}	fuel energy consumption of output stream i_n, kW
E_{i_1}	the total energy consumption of a output stream i_1, kW
E_X^{ph}	the physical exergy of compounds
E_X^{ch}	the chemical exergy of compounds
$E_{X_{i_n}}^{out}$	exergy flow rate of output stream i_n
$E_{X_{j_n}}^{out}$	exergy flow rate of output stream j_n
E_{r_1}	the allocated total energy consumption of stream r_1, kW
EI_{r_1}	energy consumption intensity of stream r_1, kJ/kg
i	the energy-consuming device
i_n	output stream i_n of energy-consuming device i
i'_p	input stream i'_p of energy-consuming device i
j	the exothermic device
j_1	output stream j_1 of exothermic device j
M	number of exothermic devices in the system
N	number of energy-consuming devices in the system
n	number of output streams
n_1	product streams
n_2	waste streams
p	number of input streams
Q	heat input of devices, kW
Q_{i_1}	the input heat allocated to output stream i_1, kW
Q'_{i_p}	heat of input streams i_p, kW
Q_{i_n}	the input heat allocated to output stream i_n, kW
Q_{j_1}	the input heat Q and released heat $Q_{q,k}$ allocated to output stream j_1, kW
$Q_{q,j}$	the released heat of device j, kW
r_1	a stream
$W_{i_p}^{in}{}'$	mass flow rate of input stream i_p, kg/s
$W_{i_n}^{out}$	mass flow rate of output stream i_n, kg/s
$W_{j_n}^{out}$	mass flow rate of output stream j_n, kg/s
W_{r_1}	mass flow rate of stream r_1, kg/s

Superscripts

ch	chemistry
in	input stream
out	output stream
ph	physics
′	input stream

Subscripts

0	cumulative energy
ele	electric energy
fuel	fuel energy
X	exergy

between groups of scarce metals. Venkatesh et al. (2009) carried out a life cycle analysis of wastewater pipeline networks based on MFA.

Exergy implies an entropy-free energy form that can be perceived as a measure of usefulness (Hoque et al., 2012). On the basis of the concept of exergy, EFA has also been widely used in the aspects of process systems analysis and resources conservation (Dewulf et al., 2007). Sciubba (2004) presented an expanded exergy balance technique and calculated commodity cost through resource basis equivalent value, which could be used to deal with more complete and significant evaluation of complex systems. Tzanakakis and Angelakis (2011) took exergy as an objectively unified indicator for evaluation and optimization of land processing system and demonstrated the effectiveness of EFA. Considering the thermodynamics sustainability, Sciubba and Zullo (2011) used EFA to investigate dynamic characteristics of population.

The combination of MFA and EFA was also used in certain areas (Cherubini et al., 2008). Hoque et al. (2012) developed a model to evaluate the energy intensity of construction sector by using LCA combined with MFA and exergy accounting methodologies. Haberl (2006) demonstrated the utility of counting joules based on MFA and EFA. Haberl et al. (2006) presented assessments of energy inputs of the European Union and the United States based on MFA and EFA. Boateng et al. (2012) studied mass balance, energy, and exergy analysis of bio-oil production by fast pyrolysis. Wang et al. (2004) calculated the energy consumption of streams in petroleum refineries based on material flow, exergy flow and market value by proposing an energy-use allocation method in both process and device levels. However, in their work, the product stream and the waste stream are not distinguished individually, and hence the energy consumption distribution cannot be precisely determined. In order to reasonably allocate the energy consumption of waste streams, Kang et al. (2013) presented a MFA–EFA method at the device level in a process system, in which the energy inputs into the system, such as fuel energy and electric energy, are distinguished. Nevertheless, this method is not applicable for process systems that the intensively exothermic sub-systems or devices exist, a natural gas purification plant, for example.

The natural gas purification system is composed of desulfurization, dehydration, sulfur transformation and exhaust gas treatment sub-systems, which consumes plenty of natural resources and energy and generates large quantities of waste in different phases (Burlutskiy, 2014; Hoque et al., 2012; Valero and Valero, 2013). For the purpose of reducing the energy consumption of the system, the energy saving analysis and the integration of energy utilization should be conducted in three levels, i.e. devices, sub-systems and the entire system. Li et al. (2014) reported a process-driven model to analyze a natural gas purification system in the entire system level. The energy consumption of the entire system is reduced, and the energy efficiency of the system is also improved by local modification of the purification system. Liao et al. (2013) proposed some measures for optimization of energy utilization of the sulfur transformation sub-system. Zhao et al. (2013) and Li et al. (2009) reduced the energy consumption of the system by optimizing flash gas treatment process and wastewater treatment process, respectively. In addition, Liu and Ye (2010) proposed a method to improve energy-saving of the system in the device level. These above-mentioned works mainly focused on evaluating and improving energy utilization of the natural gas purification plants in the device level, sub-system level or the system level individually. However, an elaborate analysis of energy carried by process streams, products or waste streams in process systems is much favorable to providing guidance for the optimal energy configuration and optimized operations (Barba et al., 2015; Chen and Chen, 2015; Hall and Howe, 2012; Zhang et al., 2015).

The major objective of this work is to propose a systematic approach based on MFA coupled with EFA to evaluate energy