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# Substance flow analysis of neodymium based on the generalized entropy in China

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A B S T R A C T

Rare earth plays an important role in fields of aerospace, electronic products, catalyst, agriculture and others. China is the largest producer and consumer of rare earth materials in the world. Neodymium is widely used in rare earth industry. Substance flow analysis (SFA) is an established method to analyze the structure and characterization of substance flows. This paper provided SFA and generalized entropy analysis for neodymium in China in 2002 and 2011. System boundary included exploitation, concentration, smelting, manufacture, use and disposal. Neodymium flow amounts and generalized entropy value were calculated, respectively. Mining utilization efficiency, smelting ratio, export rate were comparatively analyzed in 2002 and 2011. The results demonstrated that the utilization efficiency of neodymium in the rare earth concentrates production stage increased more than 69%, while the utilization efficiency of neodymium in the manufacture stage increased more than 28% in 2011 compared to 2002. The generalized entropy results indicated that congregated degree of neodymium was larger in 2011 compared to 2002 after concentrate production stage and manufacture stage, the congregated degree increased 45.5% and 12.5%, respectively. Based on the results, some advices were proposed, which provided available reference information for resource conservation and environmental friendly development of the Chinese rare earth industry.

## 1. Introduction

Rare earth is important strategic resource, which is widely used in fields of national defense, aerospace, wind power generation, agriculture and others(Wang, 2012). Many countries focus on the research and application of rare earth advanced material (Huang and Li, 2015).China is the largest rare earth producer, consumer and exporter in the world. Approximately 90% global rare earth concentrate is produced from China. Rare earth reserves in China accounted for 23% of total global reserves (White papers of the Chinese rare earth condition and policy, 2012). Considering scarcity of resource and environment pollution in rare earth industry, as early as the year of 2004, the policy makers raised barriers to entry for rare earth mining and smelting enterprise. Ministry of environmental protection of China published Emission standard of pollutants for rare earths industry in 2011. In the aspect of export of neodymium metal, the export tax was increased until 2012, when the export tax was cancelled. Rare earth ores are mainly distributed in Inner Mongolia, Sichuan province and southern areas in China, and these ores were achieved industrial application (Huang et al., 2011). Light rare earth neodymium is mainly produced from Inner Mongolia and Sichuan province in China. As shown in Figs. 1 and 2, numerous rare earth were consumed in advanced materials fields, approximately 41% rare earth consumed in permanent magnet material fields in 2013 in China, whereas, more than 98% were NdFeB magnets (China Society Rare Earth yearbook, 2011). Consequently, neodymium was the most widely used rare earth element.

Substance flow analysis (SFA) is useful method to analyze the characterization of substance flows in defined time and space. It includes two models, which are static and dynamic models. Static SFA model emphasizes the substance flow of the system over limited periods, dynamic SFA has been applied to several materials and substances to estimate their flow and stock in designated time and space (Paul and Helmet, 2004; Matsuno et al., 2012). Dynamic substance flow analysis of neodymium and dysprosium associated with neodymium magnets in Japan have been conducted (Sekine et al., 2017). Static SFA of copper, cadmium, silver, iron, chromium etc were researched (Yellishetty and Mudd, 2014; Cha et al., 2013; Graedel et al., 2004; Johnson et al., 2005; Johnson et al., 2006; Wang et al., 2007; Marie et al., 2013; Ramzy and Williams, 2012). This paper aimed to research static substance flow of neodymium.

Entropy is a thermodynamic concept, which is an index to describe

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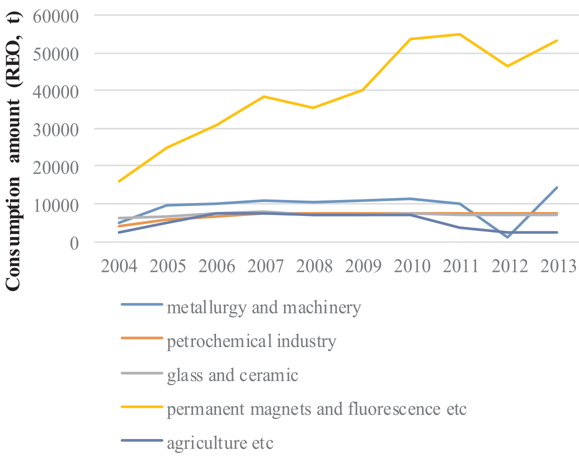


**Fig. 1.** Rare earth consumption in China.

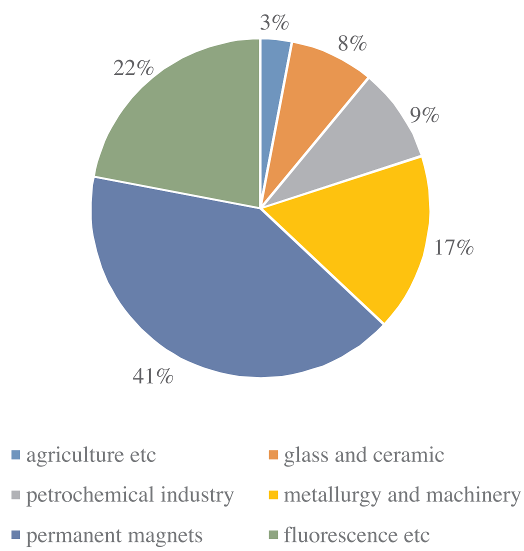


**Fig. 2.** Rare earth consumption fields in 2013 in China.

disorder of the system. In 1940s, the concept entropy was brought into information field by Shannon (Zhang et al., 2005), which defined as information entropy or generalized entropy. It is a tool to measure the uncertainty associated with a random variable originally in the field of information theory (Ghosh et al., 2017). Shannon proposed mathematics formula to measure information using generalized entropy. The former study related entropy included hazardous inorganic substance, European copper cycle, copper cycle in China, lead cycle (Rechberger 2001; Rechberger and Graedel, 2002; Yue et al., 2009; Bai et al., 2015). In this paper, generalized entropy was introduced to substance flow analysis of neodymium, which was used to reveal accumulation or scatter level of neodymium in the life cycle stage.

## 2. Methodology

### 2.1. Static SFA model

Static SFA model included the stages of production, manufacture, use and disposal (Guo et al., 2010; Susanne et al., 2004). Based on the static SFA procedure, the study included the essential following steps.

(1) Research system boundary definition

This study analyzed the neodymium cycle in China in the year 2002 and 2011.

(2) Life cycle flow analysis

In this paper, the substance flow of neodymium was divided into five stages–concentrate production, concentrate smelting, manufacture, use and disposal depending on the characteristic of the rare earth industry.

In the SFA study, data of inflows, outflows and stocks followed the mass conservation law. The data of this study were mainly obtained by statistic yearbook, literature, and theoretical calculation.

In the rare earth concentrates production stage, the rare earth ore consumption amounts (calculated as neodymium oxide) were calculated by rare earth concentrates output (China Society Rare Earth yearbook, 2011) and rare earth utilization efficiency. In the rare earth smelting stage, neodymium amounts contained in rare earth products were calculated based on the neodymium content in products. Import and export amounts of neodymium were obtained from official website (http://www.cre.net/list.php?catid=37). Use and wastage amounts of neodymium were calculated. Calculation method mentioned above was proposed as following formula.

$$O_{Nd} = \sum_{i=1}^{k} \frac{c_i}{u_i} \bullet \mathrm{w_i} \quad (1)$$

$$C_{Nd} = \sum_{\mathrm{i=1}}^{\mathrm{k}} c_i a_i \quad (2)$$

$$T_{Nd} = O_{Nd} - C_{Nd} \quad (3)$$

Where $O_{Nd}$ refers to amounts of neodymium contained in the ores, $C_{Nd}$ refers to amounts of neodymium contained in the concentrates, $T_{Nd}$ refers to amounts of neodymium contained in the tailings, $c_i$ refers to output of concentrates i, $u_i$ refers to total rare earth substance application efficiency in smelting of concentrates i, $w_i$ refers to the ratio of neodymium in the ore i, $a_i$ refers to the ratio of neodymium contained in the concentrates i.

### 2.2. Generalized entropy model

Generalized entropy was defined by Shannon using monotonic function of occurrence probability (Li, 2011). Supposing that the probability of objects was different, average generalized entropy was calculated. The calculation formula was shown as Eq. (4) (Rechberger 2001; Rechberger and Brunner, 2002).

$$H = -\lambda \sum_{i=1}^{n} p_i \ln p_i \quad (4)$$

Where $H$ was average generalized entropy, $p_i$ was probability of object i, λ was a constant.

In this paper, generalized entropy was combined with substance flow analysis, which revealed accumulation or scatter level of substance. Entropy was used to describe substance distribution characterization in substance flow analysis. Based on the above calculation formula, generalized entropy in substance flow was defined as Eq. (5) in this study.

$$H_{\mathrm{i}} = -\sum_{i=1}^{k} m_i c_i \ln(c_i) \quad (5)$$

$$X_{\mathrm{i}} = M_i c_i \quad (6)$$

$$\mathrm{m}_i = \frac{M_i}{\sum_{i=1}^{k} X_i} \quad (7)$$

In this paper, the object substance was neodymium, therefore, $H_i$ was generalized entropy of flow i, $X_i$ were neodymium amounts of flow i, $M_i$ were total material amounts of flow i, $c_i$ was neodymium concentration of flow i.

In this study, supposing that when neodymium concentration in research system equal to neodymium concentration in lithosphere ($e_{EC}$), the maximum entropy was obtained, which was shown as Eq. (8).