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Research on the Energy flow of Aluminum Industry in China

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ABSTRACT

Based on the energy flow theory and the sample data of the consumption of energy of aluminum industry in China from 2010-2014, This article introduces the framework of energy flow analysis of aluminum production in China, including the boundary of the energy flow analysis, the energy consumption calculation and analysis, calculates and investigates the process energy flow and the energy flow index in detail. Through the in-depth data collection and collation work, we build a static picture of the actual energy flow of aluminum production in our country, calculate the specific energy consumption index, and analyze the influence of various energy flow on the comprehensive energy consumption of unit product.

Keywords: Aluminum industry, Energy flow, Comprehensive energy consumption

INTRODUCTION

Since the first world oil crisis broke out in 1970s, a series of problems such as energy consumption, energy shortage, energy security and the analysis of the whole resource and environment status have been concerned. Along with the development of material flow analysis (abbriviated MFA, or substance flow analysis, abbriviated SFA), the energy flow analysis (abbriviated EFA) has been focused by decision-makers. The problem is how to convert, distribute, use and recycle the energy efficiently, to achieve the goal of minimizing energy consumption and improving the economic, environmental and social benefits of the enterprise.

The energy flow analysis of aluminum production is relatively late in China and other countries， but it has achieved fruitful research results。For example，one of the most representative research is tan, Reginald B.H., using the method of life cycle assessment, evaluated the energy efficiency and waste emission at different stages of aluminum production, put forward a variety of schemes to improve the environmental load of the unit aluminum production, and compared and analyzed the various programs. By using the standard logistics chart method, Liu Li-ru quantitatively analyzed the influence of the change of energy consumption and conversion ratio on the comprehensive energy consumption of alumina in Bayer process. American Aluminum Association(AA) released Life Cycle Inventory Report for the North America Aluminum Industry in 1998, International Aluminum Institute(IAI) released Life Cycle Assessment of Aluminum: Inventory Data for the Worldwide Primary Aluminum Industry in 2003, International Aluminum Institute(IAI)released update report in 2007, and European Aluminum Association (EAA) released Environmental Profile Report for the European Aluminum Industry: Life Cycle Inventory Data for Aluminum Production and Transformation Processes in Europe in 2008. All of these reports have analyzed the energy flow in aluminum production.

SCOPE AND HYPOTHESIS

Energy flow in aluminum production is the process that the energy (coal, electricity, natural gas, etc.) in the production process is according to the path of the use, distribution, conversion and recovery along with material flow. The energy flow of aluminum production enterprise mainly includes the following four aspects:⑴Purchased electricity, coal and natural gas; ⑵ Energy born by aluminum ingot (by-products, semi-finished products and finished products); ⑶ Waste energy and heat produced in the process of production; ⑷ Energy conversion in the process of energy flow (Converting from one form to another, such as coal to electricity).

From the perspective of the whole life cycle, the production of aluminum products mainly consists of the following four stages: ⑴ the production of aluminum ingot——as raw material of aluminum products; ⑵ the downstream processing for aluminum products; ⑶ the use of aluminum products; ⑷ the recovery process of aluminum products.

The related data of the stage ⑵ to ⑷ are too complex to statistics, and it is difficult to use energy flow analysis method because of the wide range of products. In addition, most of the energy consumption in China's aluminum production process is mainly concentrated in the first stage. So the scope should be the stage ⑴ in this article, reflecting the energy consumption for the production of the aluminum ingots, including bauxite mining, alumina production, aluminum reduction and aluminum ingot casting production process, as shown in Figure 1. The energy flow between each step is shown by the arrow in Figure 1, which represents the input / output energy flow of the system through the dashed line.

The research hypothesis of this article includes:

⑴100% products in each production process are sent to the next production process;

⑵ The energy consumed by each production process come from a part of by-product in other processes, and not all from outside the system;

⑶ Energy consumption is not involved in the preparation of raw materials;

⑷ Transport energy consumption is not within the scope of consideration.

FRAMEWORK AND PRINCIPLES

The energy flow in aluminum production is mainly the Carbon flow. It starts from the mining of bauxite, through washing, grinding and other machining processes to powder; through roasting aluminum powder and other multi-channel complex process to produce alumina; aluminum metal was obtained by strong current electrolytic reduction; aluminum metal, after weighing, batching, charging, refining, casting and remelting process cast into ingots. In the production process of aluminum industry, the carbon flow in the process of transformation, distribution, utilization and recycling will be transported to various production processes, to ensure the normal operation of the production of aluminum products. Combined with the characteristics and functions of the energy flow in the aluminum industry, the energy flow model of the aluminum industrial production enterprise is the four subsystems of utilization, conversion, distribution and recovery, and the relationship between the four subsystems is shown in Figure 2.

Interpretation of Parameter symbolic is shown in Table 1.

In the model framework of the extended three stage energy flow, each subsystem (use, conversion, distribution, recycling) interrelated, influence and control by each other. At the same time, every system satisfies the law of conservation of matter and the law of conservation of energy. Its feature points as shown in table 2.

The formula (1) can be made on the basis of the law of conservation of energy, the analysis framework of the energy flow of aluminum production (Fig. 2) and the balance relation of each system (table 2):

$E_0 = E_n + E_{r6}$ (1)

According to the different sources, functions and flows of energy flow in aluminum production process, we divide the energy flow in the process of aluminum production (as shown in Figure 3) into 6 different energy flows：

Input energy flow, energy flow from the upper channel E_{i-1};

Output energy flow, the energy flow in this process E_i;

Add energy flow, energy flow of working procedure $\chi_{\alpha,I}$;

Recycling of energy flow $\chi_{\beta,I}$;

Loss of energy flow in the process $\chi_{\gamma,I}$;

Recycling of energy flow in other areas $\chi_{\xi,I}$.

From Figure 3 shows that the process of energy flow balance can be expressed as:

$E_{i-1}+\chi_{\alpha,i}+\chi_{\beta,i} = E_i+\chi_{\beta,i}+\chi_{\gamma,i}+\chi_{\xi,i}$ (2)

For the production process of aluminum products, the process energy consumption is equal to the difference between the total energy in the process i ($\chi_{\alpha,i}+\chi_{\beta,i}$) and the total recycling energy ($\chi_{\xi,i}+\chi_{\beta,i}$). The Specific calculation formula is:

$e_i = e_i' - e_i'' = (\chi_{\alpha,i} + \chi_{\beta,i}) - (\chi_{\xi,i} + \chi_{\beta,i})$ (3)

From the view of energy balance, process energy consumption is equal to the sum of the energy loss in the process i $\chi_{\gamma,I}$ and the difference between the energy in the process i and the energy in the process i-1 ($E_i - E_{i-1}$):

$e_i = e_i' - e_i'' = \chi_{\gamma,i} + (E_i - E_{i-1})$ (4)

In formula (3) and (4),

e_i is the process energy consumption in the process i;

e_i' is the energy input to the process i;

e_i'' is the energy of the process i that can be recovered.

DATA AND ANALYSIS

China's aluminum production is not suitable for direct production with a simple Bayer process. In this article, we analyze the energy flow of aluminum industry in China with a wide range of application and based on the Bayer sintering process. The combination method can be divided into three kinds of process-parallel, series and parallel. This article focuses on the analysis of parallel method. The whole process of production of aluminum industry in parallel method.

Raw materials mainly include coal, electricity, water, lime, bauxite and sodium carbonate.

The main products include alumina, liquid aluminum, etc.

The sample data of 2010-2014 are mainly from “the China Nonferrous Metals Industry Year Book”,”China Aluminum Industry Yearbook " and "China Statistical Yearbook",shown in Table

The main by-product include sodium sulfate, sodium sulfate, sodium aluminate solution, carbon materials.As shown in table 3.

The statistical basis should be Tons of aluminum in this article. The energy consumption indicators include the main economic and technical indicators from

China Nonferrous Metals Industry Yearbook, the relevant energy consumption data from Energy statistics yearbook and the data reavealed by the official website of the National Bureau of statistics and the aluminum branch of the Nonferrous Metals Industry Association. Some of the non statistical process data, which comes from the relevant research literature and the research of the main technical indicators of the typical aluminum industry enterprises.

According to the characteristics of aluminum production in China, combined with the relevant energy consumption indicators, the static picture of the energy flow in aluminum production in China can be roughly described. Based on the extended three link model, aluminum production system is divided into four subsystems, such as use, conversion, distribution and recovery, as described below:

（1）The function of the conversion system is mainly to convert energy form, including water supply, power generation, steam and anode reaction. By the converting system, energy forms into chemical energy, electricity, heat and steam, used by downstream user.

（2）The distribution system mainly includes energy storage, scheduling and transmission. The energy involved includes steam, electricity, heat, and flow energy. In view of the complex structure of the distribution system, the distribution of energy in the system can flow to a specific process, but also can flow to any non specific process particular process. So this paper only considers the input and output distributed in the whole system, so as to simplify the analysis.

（3）Through the use system, aluminum production process from raw materials to products. This system is the major energy users in the whole production process, including bauxite mining, alumina production, aluminum reduction and primary aluminum ingot. The energy involved in the form of heat, flow energy, steam and so on.

（4）The main function of the recovery system is the energy recovery, utilization and discharge. This system is the key to energy saving and emission reduction of aluminum industry in China. The specific energy flow of the above four systems is shown in Figure 4.

In the energy flow diagram of the aluminum production enterprise, various energy sources which are invested by the enterprise through the conversion system, the distribution system, the use system and the recovery system become waste to be discharged. As shown in Figure 4, according to the order of the upper and lower, the 3 line boxes are frame conversion, energy distribution and utilization. The data on each arrow indicates the size of the energy flow in each line box(unit is kgce), based on 1 t aluminum. As shown in the figure, the production of 1 t aluminum, the input of energy is 2370 kgce, the loss of energy is 922 kgce, the actual consumption of the production process is 1448 kgce.

The calculation of energy consumption index of aluminum production enterprise includes the comprehensive energy consumption, energy efficiency and energy environmental efficiency. Before calculating the energy consumption indicators, we should summarize and describe the actual energy flow framework of aluminum production firstly.

According to figure 3-2, we can estimate the input and output of each energy flow system in aluminum production enterprise. As shown in Figure 5.

The relevant parameters and data collection in the energy flow analysis framework (Fig 2) of the aluminum production enterprise is shown in table 4.

In Figure 3-3, the subsystems (conversion, distribution, utilization, recycling) are interconnected, influenced and constrained, and each system satisfies the law of conservation of matter and the law of energy balance. The energy balance of each subsystem is as follows: In the conversion system, the input energy flow includes (1-λ)E0,，E1’，Er3’ three strands of energy flow,

energy input= $(1-\lambda)E_0+E_1^{'}+E_{r3}^{'}=2149.353+251.343+5.3=2405.996$; output energy flow including E1，Er3 two strands of energy flow, energy output= $E_1+E_{r3}=2111.683+294.313=2405.99$.

Energy balance equation for the conversion system: $(1-\lambda)E_0+E_1^{'}+E_{r3}^{'}=E_1+E_{r3}$.

In the distribution system, the input energy flow includes E1，λE0，E2’，Er5’ four strands of energy flow, Energy input = $E_1+\lambda E_0+E_2^{'}+E_{r5}^{'}=2111.683+220.647+286.99+69=2688.32$;

Output energy flow including E1’，E2，Er5,

Energy output= $E_1^{'}+E_2+E_{r5}=251.343+2299.877+137.1=2688.32$.

Energy balance equation for the conversion system: $E_1+\lambda E_0+E_2^{'}+E_{r5}^{'}=E_1^{'}+E_2+E_{r5}$.

In the use system, energy input =$E_2+E_{r4}^{'}=2299.877+29=2328.877$;

Energy output= $E_2^{'}+E_{r4}+E_n=286.99+593.887+1448=2328.877$.

Energy balance equation for the conversion system: $E_2+E_{r4}^{'}=E_2^{'}+E_{r4}+E_n$.

In the recovery system,

Energy input = $E_{r3}+E_{r4}+E_{r5}=294.313+593.887+137.1=1025.3$;

Energy output= $E_{r3}^{'}+E_{r4}^{'}+E_{r5}^{'}+E_{r6}=5.3+29+69+922=1025.3$.

Energy balance equation for the conversion system:

$$E_{r3}+E_{r4}+E_{r5}=E_{r3}^{'}+E_{r4}^{'}+E_{r5}^{'}+E_{r6}.$$

Similarly, from the overall perspective of, according to the law of conservation of energy, aluminum production actual energy flow analysis framework (Figure 3-3) and the balance of systems, the total energy input is equal to the total energy output, that is, to satisfy the equation

$$\mathrm{E_0}=\mathrm{E_n}+\mathrm{E_{r6}}=1448+922=2370\mathrm{E_0}=\mathrm{E_n}+\mathrm{E_{r6}}=1448+922=2370.$$

Based on the actual energy flow diagram (Fig.4), the energy flow diagram (Fig. 6) of aluminum production can be drawn. In Figure 6, the benchmark energy flow diagram of aluminum production is a production flow energy flow diagram of "fully enclosed one way" type. Meet the following two assumptions:

(1) In all production processes, the flow of energy flows from upstream to downstream processes.

(2) Input and output of energy flow outside the system is not involved in the primary energy transfer.

In Figure 6, P1-P4 Respectively express the Aluminium ratio coefficient of bauxite mining, alumina production, electrolytic aluminum production and primary aluminum ingot in the primary aluminum production process. That is the percentage of the quantity of qualified products produced by the process i (The liquid product is calculated by m, and the solid product is calculated by t.) and the final qualified aluminum production , the unit is the amount of product /t-Al. E_1- E_4

represents the energy consumption of each process (process i) during the statistical period. According to e-p analysis, the comprehensive energy consumption of ton aluminum is equal to the total amount of energy consumed by the aluminum industrial enterprises during the statistical period.

Based on the energy flow chart of aluminum production, the comprehensive energy consumption of ton aluminum can be calculated:

$$E_p = \sum_{i=1}^{n} e_i p_i = E_1 \times P_1 + E_2 \times P_2 + E_3 \times P_3 + E_4 \times P_4 = 259.51 \times 0.15 + 590.6 \times 0.56028 + 1960.55 \times 1 + 384.1 \times 1.63 = 2956.46$$

The comprehensive energy consumption of ton aluminum is 2956.46Kgce/t, equivalent to about 21057.4kwh/t. This is consistent with the data in the statistical yearbook of nonferrous metals 2014.

In this paper, the enterprise energy flow related data as shown in table 3-2, these data indicate the general situation of the enterprise energy flow, and will further analyze the main energy consumption index (table 3-3) of aluminum production enterprises. The role of energy consumption indicators analysis are mainly through the evaluation of enterprise overall energy consumption status, compared with the existing advanced standards to identify gaps, and tap the potential of energy saving.

According to the energy flow chart (Fig. 4), the energy efficiency η_e is calculated. Energy efficiency refers to the production of qualified aluminum products which can be produced in the process of aluminum production. The formula is:

$$\eta_e = \frac{1}{E_{r6}+E_n} = \frac{1}{1448+922} = \frac{1}{2370} = 0.0422\%$$

In the same way, we can calculate the energy environment efficiency q_e. Energy environmental efficiency refers to the amount of aluminum products that the energy flows through the use, conversion, distribution and recovery systems corresponding to unit loss energy in the aluminum production process. The formula is:

$$q_e = \frac{1}{E_{r6}} = \frac{1}{1448} = 0.0691\%$$

CONCLUSION AND SUGGESTION

(1)For some enterprises, The lower comprehensive energy consumption of aluminum production is 2956.46 Kgce/t. This is the international advanced level. But for most parts, the comprehensive energy consumption of aluminum production is more than 2956.46 Kgce/t. They should make efforts to reduce the energy consumption in each process, so that the total amount of energy input to be controlled. At the same time, we should strengthen the recycling process of waste heat energy, improve energy efficiency and energy environmental efficiency, reduce energy loss.

(2) In the alumina production, equipment energy consumption mainly concentrated in the silicon removing machine (proportion of energy consumption is 13.69%), clinker kiln (proportion of energy consumption is 49.94%), lime furnace (proportion of energy consumption is 5.73%), evaporator (proportion of energy consumption is 6.89%) and roasting kiln (proportion of energy consumption is 14. 77%). The total energy consumption of these five energy consuming equipment is about 91% of the total energy consumption of the whole process. Therefore, reducing the energy consumption of these 5 equipment is beneficial to improving the energy efficiency and energy environmental efficiency, reducing the total energy consumption of enterprises.

In addition, evaporation of spent

liquor process use falling film evaporator, then high thermal efficiency and heat transfer coefficient are high, significantly reduce the evaporation process of steam consumption. The process of alumina production is multi-processes, and the process is long. Using new type of high efficiency equipment, can improve the level of production automation, so as to effectively reduce the production of energy consumption. The use of gas suspension roasting aluminum hydroxide, compared with the rotary kiln, can greatly reduce the fuel consumption. Alumina circulating roaster operation rate can reach 94%, saving oil 24000t, saving power 1 million 100 thousand kWh and Creating economic value 36 million yuan every year.

(3) In the aspect of electrolytic aluminum production, the energy consumption of electrolytic aluminum smelting phase is the most concerned. Enterprises can apply the fine management, research and analyse the energy saving potential of each production link at this stage. Then reducing the energy consumption in the smelting process, it is beneficial to reduce the overall energy consumption of the electrolytic aluminum production process. For example, the renewal of the sensitive components that affect the electrolysis can reduce the total input energy of the electrolytic aluminum by 5%~10%. In addition, enterprises through the introduction of 110kV straight down rectifier units, built second rectifier. 110kV straight down rectifier unit can improve the rectification efficiency of 2%, improve the current efficiency of about 1%, to achieve the purpose of energy saving and improve the economic efficiency of enterprises.

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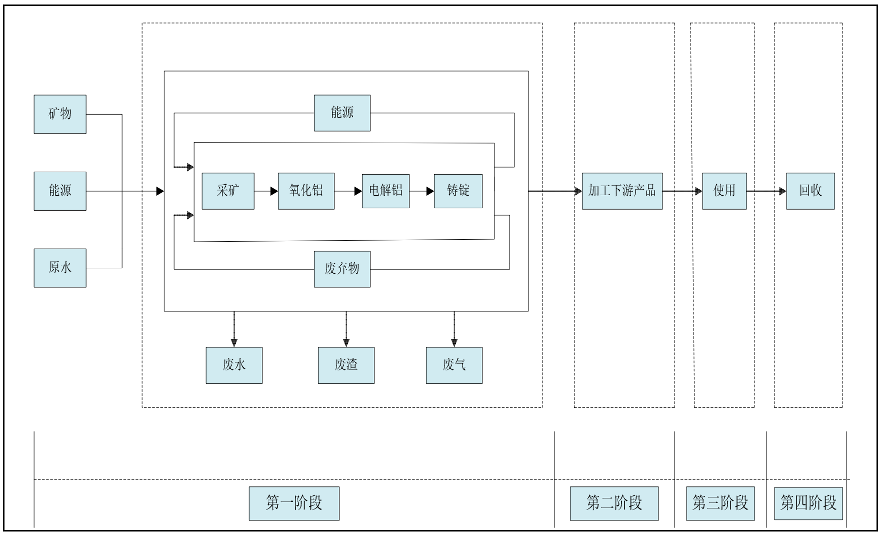

Fig. 1 System boundary

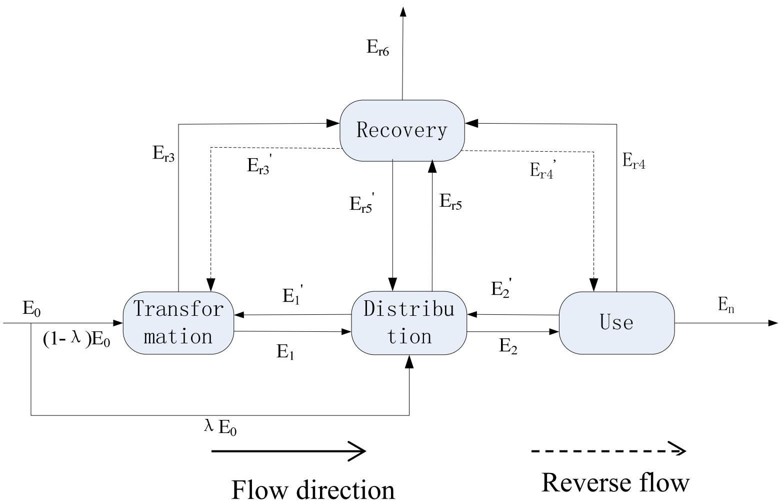

Fig. 2 Framework of energy flow analysis

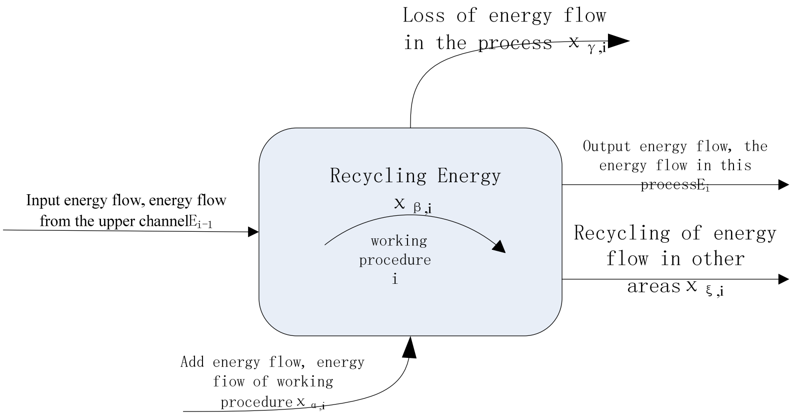

Fig. 3 Energy flow diagram of aluminum production process

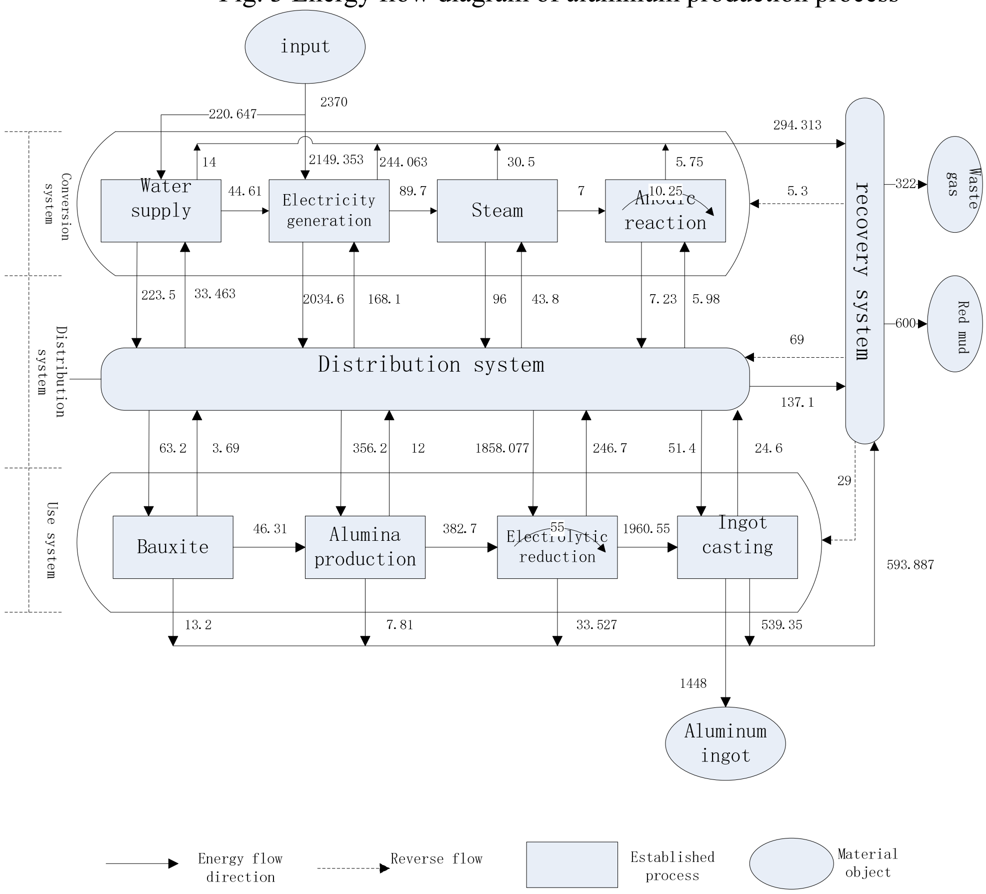

Fig. 4 China aluminum production energy flow chart

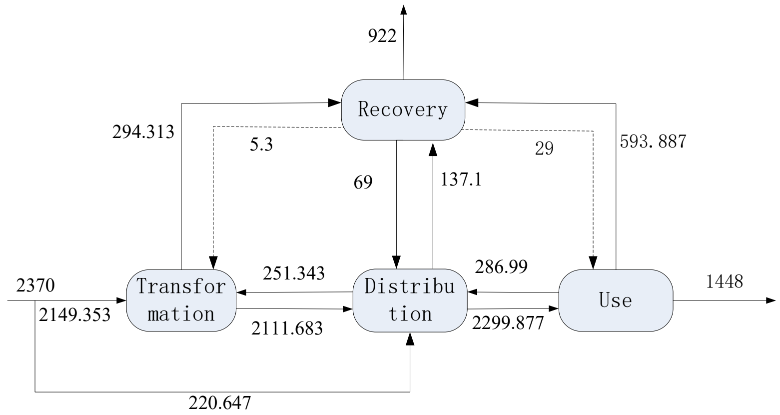

Fig. 5 practical energy flow framework

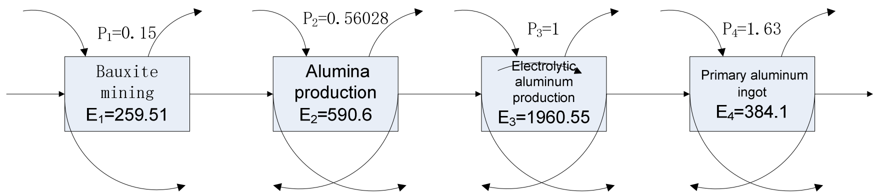

Fig.6 Aluminum production benchmark energy flow chart

Table 1 interpretation of Parameter symbolic

Parameter symbolic	meaning	Parameter symbolic	meaning
E_0	Total energy of an input	E_{r3}	The energy that transfer from conversion system to recovery system
λ	Direct utilization of energy	E_{r3}'	The energy of recovery system used by conversion system
$(1-\lambda)E_0$	Energy of an input conversion system	E_{r4}	The total energy that transfer from utilizing system to recovery system
λE_0	Energy of direct input distribution system	E_{r4}'	The energy of recovery system used by utilizing system
E_1	The energy transferred from conversion system to distribution system	E_{r5}	The total energy that transfer from distribution system to recovery system
E_1'	The energy transferred from distribution system to conversion system	E_{r5}'	The energy that transfer from recovery system to distribution system
E_2	The energy transferred from distribution system to utilizing system	E_{r6}	Total energy consumption lost in production
E_2'	The energy transferred from utilizing system to distribution system	E_n	Energy of the final product

Table 2 Feature points of model framework

Stage	Conversion of energy	Distribution of energy	Use of energy	Recovery of energy
Function	Conversion of energy form	Energy storage, scheduling and transmission	Change of raw material to product	Energy utilization, recovery and discharge
Form of energy	Chemical energy, electricity, heat and steam	Heat, steam, electricity and flow energy	Heat, flow energy and steam	Heat and flow energy
Relationship of system equilibrium	$(1-\lambda)E_0+E_{r3}'+E_1'=E_1+E_{r3}$	$\lambda E_0+E_1+E_{r5}'+E_2'=E_2+E_{r5}+E_1'$	$E_2+E_{r4}'=E_{r4}+E_n+E_2'$	$E_{r3}+E_{r4}+E_{r5}=E_{r5}'+E_{r4}'+E_{r6}+E_{r3}'$

Table 3 Energy consumption data

project name	Specific indicator	value
Finished product （10^4t）	Alumina	2906.5
	virgin aluminum（Electrolytic aluminum）	1624.4
Energy consumption	The consumption of ore（kg/t）	2120
	Lime（kg/t）	260
	Raw coal（kg/t）	374.38
	Alkali（kg/t）	83.74
	Flocculant（kg/t）	0.465
	Power consumption（kWh/t）	282.9
	Steam（kg/t）	1060
	Water（kg/t）	1565
Other items	The alumina consumption of virgin aluminum（kg/t）	1929
	The carbon anode consumption of virgin aluminum （kg/t）	498.63
	The salt fluoride consumption of virgin aluminum （kg/t）	21.9
	Total recovery of alumina（%）	75.4

Table 4 Collection of related parameters and data

Energy consumption index	Numerical value
E_0	2370
λ	9.31%
λE_0	220.647
$(1-\lambda)E_0$	2149.353

E_1	2111.683
$E_1^{'}$	251.343
E_2	2299.877
$E_2^{'}$	286.99
E_{r3}	294.313
$E_{r3}^{'}$	5.3
E_{r4}	593.887
$E_{r4}^{'}$	29
E_{r5}	137.1
$E_{r5}^{'}$	69
E_{r6}	922
E_n	1448