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# Coupling Model of Energy Flow and Material Flow in SKS Lead Smelting

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**Abstract:** This paper studied the coupling model of material flow and energy flow in the production process of lead smelting enterprises, and established the mathematical model for material flow and energy flow to resolve optimization problems. From the point of energy flow, the paper analyzed three kinds of energy flow changes which have an effect on the enterprise products. Through calculation and analysis, it has been found that there is 38.42% energy-saving potential in this enterprise. Separately from the material flow and energy flow angle, the paper put forward five aspects suggestions to reduce the energy consumption of the enterprise products.

**Keywords:** Energy consumption, energy flow, material flow, SKS lead smelting.

## 1. INTRODUCTION

The paper analyzed the energy system of lead smelting enterprises, using the process of SKS (Shui Kou Shan) lead smelting. The SKS lead smelting process is a lead smelting technology in which oxygen blows from the bottom into the blast furnace. The key feature is that the Oxidation-reduction reactions take place in different melting furnaces. SKS lead smelting process, which has been widely applied in China, has many technical characteristics, such as low investment, low production costs, strong adaptability for raw materials, high level of automation and environmental friendliness. Now the technology has reached international advanced level and some countries also adopt this method to smelt metals like copper, lead and so on [1-3]. Research on the coupling model of SKS Lead Smelting Process helps recognizing the association between material flow and energy flow in each process and provides guidance for reducing the energy consumption of lead smelting enterprises [4-5].

A lot of researches on the theory and optimization of energy system have been conducted in the metallurgy industry [6-13]. At present, the e-p analysis method has been put forward by Academician Lu Zhongwu, which is widely applied in iron and steel enterprises [14-15]. Comparing the research achievement of system energy conservation in iron and steel enterprises, in this research, both the material flow and energy flow in the lead smelting corporation are simultaneously analyzed and SKS lead smelting process is broken down into material flow and energy flow which are related. With respect to the material flow, we framed a material flow diagram of production process from granulation of raw materials to crude lead production and built a lead flow model containing lead materials; with respect to energy flow, we framed an energy flow diagram containing energy production, transformation, use and disuse emission and built an energy model of lead smelting process; for the relationship between material flow and energy flow, we built the coupling model.

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## 2. ANALYSIS OF THE MATERIAL FLOW IN SKS LEAD SMELTING PROCESS

In the SKS lead smelting procedure, there is a main material flow called lead flow that moves from the first process to the final process all the way. It is possible that in each process, there are all five material flows or some of them as shown in Fig. (**1**).

(1) Input material flow: the lead products in process i-1 are used in process i as raw materials, with lead flow as $P_{i-1}$, t/t lead.

(2) External material flow: the lead raw materials are added to process i from the environment, with lead flow as $\alpha_i$, t/t lead.

(3) Discharged material flow: the lead materials are discharged from process i to the environment, with lead flow as $\gamma_i$, t/t lead.( $\gamma_i = \gamma_{i'} + \gamma_{i''}$, $\gamma_{i'}$ -the lead weight of qualified products which are sold in process i, $\gamma_{i''}$-the lead weight of unqualified products which are outputted into the environment, such as catering waste, production losses and so on, t/t lead)

(4) Cycling material flow: the unqualified products in process i or the following processes are returned to process i or the previous processes to be recycled, with lead flow as $\beta_i$ t/t lead.( $\beta_{i,i}$-the lead weight of materials returned to the original process; $\beta_{i,k}$-the lead weight of materials in process i returned to the previous process k, k=1,2, …,i-1; $\beta_{j,i}$-the lead weight of unqualified materials in process j returned to process i as raw materials, j=i+1,i+2,…,n; $\beta_i = \beta_{i,i} + \beta_{j,i}$)

(5) Output material flow: the qualified products are transferred from process i to process i+1, with lead flow as $P_i$, t/t lead.

It is found that that there are three different kinds of material flows besides the main material flow $P_i$ : the first material flow called $\alpha$ material flow contains the lead material flow inputted into each process from the environment; the second material flow called $\beta$ material flow contains the lead material flow returned to the original process and the lead material flow is returned to each process from the following processes; the third material flow called $\gamma$ material flow contains the lead material flow which does not return to the original process after being discharged to the environment. There is a close relationship among the main material flow, $\alpha$ material flow, $\beta$ material flow and $\gamma$ material flow in terms of quantity. In order to build an actual material flow model of each process, not only do we need to analyze all $\alpha$, $\beta$, $\gamma$ material flows, but also we need to find out the relationship between them and the main material flow. For each process, the principle that the weight is the balance of revenue and expenditure must be obeyed.

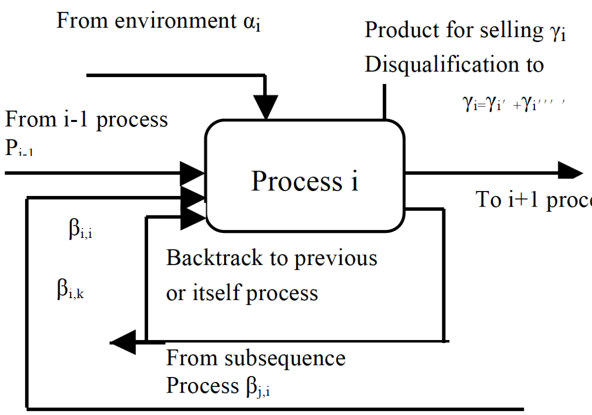


**Fig. (1)**. Material flow in production process.

According to the lead balance, we have:

$$P_{i-1}+\alpha_i+\beta_{i,i}+\beta_{j,i}=P_i+\gamma_i+\beta_{i,i}+\beta_{i,k} \quad (1)$$

## 3. ANALYSIS OF THE ENERGY FLOW IN SKS LEAD SMELTING PROCESS

Based on the product per unit, the energy flow of lead production process is shown in Fig. (**2**). According to the resource, destination and role, energy flow can be classified into five kinds of energy flows.

(1) Input energy flow: the energy called $E_{i-1}$ in process i-1 is introduced into process i, containing chemical energy, thermal energy, kinetic energy and so on;

(2) Output energy flow: the energy called $E_i$ is transferred from the i process to environment, such as thermal energy and chemical energy;

(3) External energy flow: the energy called $e_{\alpha i}$ is added to process i from environment, such as fuel, electricity, steam and so on;

(4) Loss energy flow: the energy called $e_{\gamma i}$ is lost in process i and the course of transmission;

(5) Recycling energy flow: the energy is recycled to be used in the process or the other processes, such as fuel, thermal energy and so on ($e_{\beta i}$-the energy recycled for the process itself, $e_{\zeta i}$-the energy recycled for other processes);

From Fig. (**2**), we have an energy equation:

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

As for the utilization of waste heat and energy in SKS lead smelting process, not only should we consider energy dissipation in time and space, but also we should match the utilization of different energy levels. When we face the problem of the further utilization of energy $E_i$, we should judge whether the energy can be used in the following processes. If it cannot be used, heat and energy would be wasted which can be recycled on the matching utilization of energy level principle. If it can be used, we should do our best to minimize the time and space between processes and prevent the energy from depreciation when consumed.

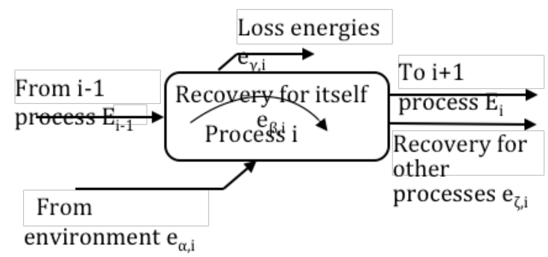


**Fig. (2).** Energy flow in production process.

## 4. ANALYSIS OF COUPLING OF SKS LEAD SMELTING PROCESS

In SKS lead smelting process, material flow merges with energy flow and finishes the production with the effect of energy flow. The coupling effect is realized by the quality of the products (the ratio of each material flow is $P_i$) and energy consumption of each process ($e_i$); as a result of their changes, the ratio of each material flow and energy consumption of each process change, and both have an impact on the energy consumption.

The minimum energy consumption per ton lead is the object function of the coupling model of the SKS lead smelting process. Its decision variables are flow rates of material flow and energy flow and constraint equation is the relation between material flow and energy flow.

The object function is

$$\text{Min } E_p=\sum_{i=1}^{n} e_i p_i \quad (3)$$

The constraint equation is

$$e_i=\left(e_{\alpha,i}+e_{\beta,i}\right)-\left(e_{\xi,i}+e_{\beta,i}\right);$$

$$p_i=\frac{C_n}{C_i}+\sum_{j=i+1}^{n}\frac{\gamma_j}{C_i}+\sum_{j=i+1}^{n}\sum_{m=1}^{i}\frac{\beta_{j,m}}{C_i}-\sum_{j=i+1}^{n}\frac{\alpha_j}{C_i};$$

$p_i = f\left(p_1, p_2, ...p_{i-1}, p_{i+1}, ...p_n\right);$

$e_{x,i} = f\left(p_i\right);$

$p_i > 0;$

$e_{x,i} \geq 0(e_{x,i}$ is $e_{\alpha,i}, e_{\beta,i}, e_{\xi,i})$.

Further analysis shows that when the energy consumption of each process, namely $e_i$, is constant, the influence of material flow changes on energy consumption per ton lead can be expressed by formula (4):

$$\Delta E_{p,p} = \sum_{i=1}^{n}\left[\frac{e_i}{C_i}\left(-\sum_{j=i+1}^{n}\Delta\alpha_j + \sum_{j=i+1}^{n}\Delta\gamma_j + \sum_{j=i+1}^{n}\sum_{m=1}^{i}\Delta\beta_{j,m} + \Delta\beta_{i,i}\right)\right] \quad (4)$$

$\Delta E_{p,p}$ -the amount of energy consumption change per ton lead caused by material flow change, kJ/t;

$e_i$ -energy consumption of each process, kJ/t;

$C_i$ -the lead-containing rate of the production in each process, %;

$\Delta\alpha_j$, $\Delta\beta_{j,m}$, $\Delta\gamma_j$ -the amount of each material flow change, t/t;

In formula (4), the energy consumption per ton lead decreases when external material flow increases, cycling material flow decreases and discharge material flow also decreases. The influence of three flows is always greater in the later process than in the former ones.

When the lead coefficient $P_i$ of each process is constant and technology condition of each energy conversion process is determined, the influence of energy flow on the energy consumption can be expressed by formula (5):

$$\Delta E_{p,e} = \sum_{i=1}^{n}\left[\ \left[-\Delta E'_{i-1} + \sum_{j=1}^{m_i} q_{j,i}\Delta b_j - \Delta e_{\xi,i}\right]p_i\right] \quad (5)$$

$\Delta E'_{i-1}$-the amount of energy change moved to process i from previous process, kgce/t;

$m_i$ -the number of kind of energy needed to be inputted to produce one ton process products in process i;

$q_{j,i}$ -the input amount of j energy needed to produce one ton products in process i,j t/t ($m^3$/t, kWh/t);

$\Delta b_j$-the amount of j energy change, kJ/t (kJ/$m^3$, kJ/kWh);

$p_i$ -lead coefficient of process i, t/t.

Based on formula (5) and from the perspective of energy flow, we can find that the main method to decrease the energy consumption per ton lead is: to make the energy to be processed sooner in the products used in the following process; to decrease the energy value of different energy medium; to reuse different kinds of waste heat and energy promptly and reasonably.

## 5. CALCULATION AND ANALYSIS OF ENERGY CONSUMPTION WHEN ENERGY FLOW CHANGES

In some SKS lead smelting processes, the energy called $\Delta E'_{i-1}$ which is carried by lead slag cannot be transferred in time because liquid lead slag produced at the bottom blowing furnace must be sent to blast furnace for smelting after it is cooled. Besides, the steam produced in the bottom blowing furnace and fuming furnace is discharged into the environment, so the energy for self-use ($\Delta e_{\xi,i}$) $\Delta$ e is zero. Based on the data of the year 2012 of this enterprise, we calculated that the average energy consumption per ton lead ($E_{p,e}$) is $894.95\times10^4$kJ/t using formula (5). From the energy consumption data of 2012, its average energy consumption per ton lead is $894.95\times10^4$kJ/t with the relative error $\varepsilon$ being 0.009%. Allowing for the unstable factors in the production process, such as raw materials, environment, temperature and so on, we can conclude that the relative error $\varepsilon$ is within the allowable range. So the model built in the paper is reasonable.

In the right part of formula (5), the three items reflect the influence on the energy consumption per ton lead of the energy flow change in energy transmission, energy flow change in energy transformation and recycled energy flow change respectively. The paper analyzed the energy conservation potential of the enterprise under the effect of energy flow in detail. We converted the energy carried by products and waste heat and energy recycled in each process to equivalent heat, assuming that all of it is used. Next, the influence of the three energy flow changes on the energy conservation per ton lead is analyzed in detail on the condition that $\Delta E'_{i-1}$and $\Delta e_{\xi,i}$ are not zero in the production process.

### 5.1. Influence of Waste Heat Recycling for Self Use in Bottom Blowing Furnace on the Energy Consumption Per Ton Lead

Fuel gas in bottom blowing furnace is directly sent into the furnace again after getting out of the furnace in order to recycle its waste heat in the production process. Statistic report shows that about 36863.12 ton of steam was produced by bottom blowing-waste heat furnace in 2012. Based on the related parameters of steam, 36863.12 ton steam can be converted to 3370391.06 kg of standard coal with the same heat, namely, one ton of crude lead is produced along with steam with the energy of 92.93kg standard coal. If the energy of $\Delta e_{\xi,2}$ is all introduced into the bottom blowing furnace process as recycled energy, the energy consumption per ton lead can be decreased to 788.41 $\times10^4$kJ/t with other factors being constant, that is, the energy consumption would be decreased by $106.53\times10^4$kJ/t.

### 5.2. Influence of Waste Heat Recycling for Use in Fuming Furnace on the Energy Consumption Per Ton Lead

In SKS lead smelting process, the function of fuming furnace is mainly to deal with the slag in blast furnace where there is a lot of heat. The waste heat and energy is recycled by waste heat furnace as well. There is 48647.4 ton steam and all of which was converted to 4447831.78kg standard coal with the same heat in the year 2012. If we input all the steam into the blast furnace, in other words, if 78.80kg

**Table 1. Influence of the maximum of recycled energy on the energy consumption per ton lead [kJ/t].**

| Factor | Energy Loss in Bottom Blowing Process | Energy Loss in Blast Furnace Process | Comprehensive Energy Loss |
|---|---|---|---|
| Bottom blowing furnace→Bottom blowing furnace | $-272.36\times10^4$ | | $-106.53\times10^4$ |
| fuming furnace→ Bottom blowing furnace | $-359.40\times10^4$ | | $-140.59\times10^4$ |
| Bottom blowing furnace→ Blastfurnace | | $-175.00\times10^4$ | $-106.53\times10^4$ |
| fuming furnace→Blastfurnace | | $-230.95\times10^4$ | $-140.59\times10^4$ |
| high lead slag→ Blastfurnace | | $-97.01\times10^4$ | $-97.01\times10^4$ |

standard coal is put into the blast furnace while one ton crude lead is produced, the energy consumption per ton lead would decrease to $168.20\times10^4$kJ/t with other factors being constant. That is to say, the energy consumption per ton lead decreases by$140.59\times10^4$kJ/t.

### 5.3. Influence of Sensible Heat Recovery of High Lead Slag on the Energy Consumption Per Ton Lead

There was 133946.40 ton high lead slag from the bottom blowing furnace and the average tapping temperature was 1030℃ at the end of 2012. Based on the characteristics of high lead slag, we can calculate that the heat involved is 8.98×1010 kJ, equally 3068950kg standard coal. If this amount of energy, as the energy of the bottom blowing furnace, is all introduced to blast furnace process, that is to say, there will be high lead slag carrying the energy of 54.37kg standard coal, the energy consumption per ton lead decreasing to $797.94\times10^4$kJ/t with other factors being constant. That is, the energy consumption per ton lead would decrease by$797.94\times10^4$kJ/t.

### 5.4. Analysis of Energy Consumption Under the Influence of Energy Flow and Energy Conservation Potential

From the above analysis, it can be observed that the steam released by the waste heat boilers in bottom blowing furnace process and fuming furnace process, and the sensible heat losses have a great influence on the energy consumption per ton lead in SKS lead smelting process. Table **1** shows the influence on comprehensive energy consumption of crude lead assuming that the energy is all recycled in the production process.

Bottom blowing furnace and fuming furnace reuse the same kind of waste heat and energy. The influence on energy consumption varies in different production processes; however, the influence on energy consumption in the whole production process is the same.

Table **1** shows that the total influence of the three energy flow changes on energy consumption per ton lead is 344.13 kJ/t. Besides, decreased usage of coke powder and smoke powered coal has a great influence on energy consumption per ton lead. In order to decrease energy consumption per ton lead, we should input the energy carried by high lead slag into blast furnace as much as possible and recycle the waste heat and energy in the bottom blowing furnace, blast furnace and fuming furnace in reasonable time.

## CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

## ACKNOWLEDGEMENTS

This work is supported by the Key Project of Science and Technology Plan of Hunan Province, China; Project(Y2008-01-010) Supported by Nonferrous Metal Science Foundation of HNG-CSU, China

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Received: May 26, 2015 Revised: July 14, 2015 Accepted: August 10, 2015