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Material Flow, Energy Flow and Energy Flow Network in Iron and Steel Enterprise

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1. Introduction

Based on the theory of Metallurgical Process Engineering (Yin, 2011) and methodology of Systems Energy Conversion (Lu & Cai, 2010), the physical essence of the steel production process is re-observed, and the steel production system is decomposed into two parts: materials transportation process and energy transportation process.

The research on material flow, energy flow and the relationship between them will benefit the construction of a resource saving and environmentally friendly enterprise. Recently, more and more researchers are paying their attentions to the study of material flow and energy flow of iron and steel enterprise. The modern iron & steel joint enterprise is a complicated iron-coal chemical system, and the steel production process is, in essence, the dynamic operation of the materials flow under the drive and effect from energy flow following the definite rules (Yin, 2000, 2007, 2008). Lu proposed the *e-p* analysis method (Lu et al., 2000) and the standard material flow diagram for blast furnace - converter process (Dai & Lu, 2004) which is used to analyze the Fe resource efficiency. Based on the standard process energy consumption, the influence of material flow of iron and steel enterprise on its energy consumption was studied (Chen et al., 2002). The relationship between materials flow and energy flow was established (Cai et al., 2006) and they were expressed by the item of energy consumption per ton of steel (Cai et al., 2008).

In the following sections material flow and energy flow model of an iron and steel enterprise will be developed. In each model the flow of a unit, a process and an enterprise will be represented in order. Network is the running type of energy flows. Then, the operating behaviour and effectiveness of energy flow network and the interacting mechanism among several energy flows are analyzed in order to find out the new direction of energy conservation in an iron and steel industry enterprise. And finally, the conclusions on the research will be given.

2. Material flow

The material flow is formed when the material runs along its life cycle trace in an enterprise. An iron and steel enterprise is composed of several processes, and each process is also composed of several units. For instance, blast furnace - basic oxygen furnace route consists

of processes related to the production of iron and steel, such as coke making, sintering, pelletizing, iron making, steel making, and steel rolling. For iron making process, it consists of several blast furnaces with different volume. These blast furnaces are the units in iron making process. So, the units' material flow structure, flow rate, flow direction is varied. They together determine the structure, flow rate, flow direction and flow indices of the whole material flow of an enterprise. To analyze the material flow of an enterprise, the material flow model of a unit should be established.

2.1 Material flow model of a unit

For iron and steel enterprise, five material flows shown in Fig. 1 may emerge in j -th unit of i -th process, described as unit (i, j) . The flow rates of five material flows are average values of a statistical period (one year, one month, one day, etc.). Actually, flow rates of all material flows through a unit changes when time is changed. So, flow rate of material flow is the assembly average of the material flow rate per unit time.

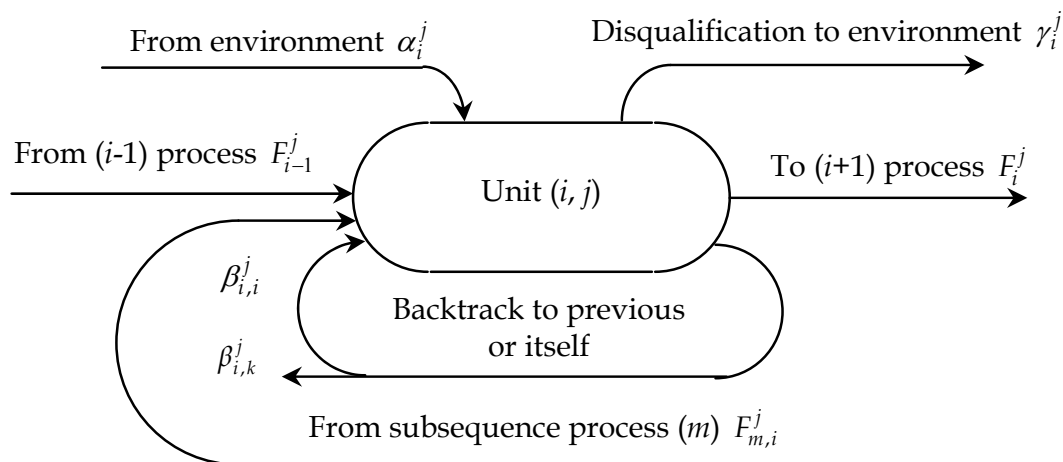


Fig. 1. Material flow model of a unit

- i. Material flows from the anterior producing unit (F_{i-1}^j). They are products of $(i-1)$ -th process served as materials of unit (i, j) . e.g., hot metal of blast furnace flowed into a converter.

$$F_{i-1}^j = \int_{\tau_0}^{\tau_1} P_{i-1-F}^j(\tau) d\tau / \int_{\tau_0}^{\tau_1} P_n(\tau) d\tau \quad (1)$$

- ii. Material flows from environment (α_i^j). They are materials of unit (i, j) from the outside of this unit. e.g., steel scrap flowed into a converter.

$$\alpha_i^j = \int_{\tau_0}^{\tau_1} P_{i-\alpha}^j(\tau) d\tau / \int_{\tau_0}^{\tau_1} P_n(\tau) d\tau \quad (2)$$

- iii. Material flows to the environment (γ_i^j). They consist of emitted wastes ($\gamma_i^{j'}(j)$) and saleable products ($\gamma_i^{j''}(j)$), i.e., $\gamma_i^j = \gamma_i^{j'} + \gamma_i^{j''}$. e.g., the iron dust emitted from a sintering machine.

$$\gamma_i^j = \int_{\tau_0}^{\tau_1} P_{i-\gamma}^j(\tau) d\tau / \int_{\tau_0}^{\tau_1} P_n(\tau) d\tau \quad (3)$$

- iv. Material flows recycled through unit (i, j) ($\beta_{i,i}^j$, $\beta_{i,k}^j$ and $\beta_{m,i}^j$). The waste products of unit (i, j) and its downstream processes recycled into unit (i, j) or other upstream processes as materials. e.g., iron dust from converter served as materials of sintering, crop ends of steel rolling served as materials of steel making.

$$\begin{cases} \beta_{i,i}^j = \int_{\tau_0}^{\tau_1} P_{i,i-\beta}^j(\tau) d\tau / \int_{\tau_0}^{\tau_1} P_n(\tau) d\tau \\ \beta_{i,k}^j = \int_{\tau_0}^{\tau_1} P_{i,k-\beta}^j(\tau) d\tau / \int_{\tau_0}^{\tau_1} P_n(\tau) d\tau \\ \beta_{m,i}^j = \int_{\tau_0}^{\tau_1} P_{m,i-\beta}^j(\tau) d\tau / \int_{\tau_0}^{\tau_1} P_n(\tau) d\tau \end{cases} \quad (4)$$

- v. Material flows to the followed producing unit (F_i^j). They are qualified products of unit (i, j) . e.g., hot metal from iron making process.

$$F_i^j = \int_{\tau_0}^{\tau_1} P_{i-F}^j(\tau) d\tau / \int_{\tau_0}^{\tau_1} P_n(\tau) d\tau \quad (5)$$

where, $P_{i-1-F}^j(\tau)$, $P_{i-\alpha}^j(\tau)$, $P_{i-\gamma}^j(\tau)$, $P_{i,k-\beta}^j(\tau)$ and $P_{i-F}^j(\tau)$ are flow rates of each material flow; $P_n(\tau)$ is the output flow rate of the last process; τ_0 and τ_1 are the initial time and end time of the statistical period, respectively.

Based on 1 ton of steel, the input-output relationship model for unit (i, j) is developed as

$$F_{i-1}^j + \alpha_i^j + \beta_{m,i}^j + \beta_{i,i}^j = F_i^j + \gamma_i^j + \beta_{i,k}^j + \beta_{i,i}^j \quad (6)$$

Therefore, the parameters and evaluating index of material flow of unit (i, j) are listed as

- i. Waste rate (w_i^j). It is defined as the wastes produced by per unit of qualified product of unit (i, j) and is expressed as

$$w_i^j = (\gamma_i^j + \beta_{i,k}^j + \beta_{i,i}^j) / F_i^j \quad (7)$$

- ii. Recycle rate of waste (r_{w-i}^j). It is defined as the rate of recycled wastes to total wastes produced and is expressed as

$$r_{w-i}^j = (\beta_{i,k}^j + \beta_{i,i}^j) / (\gamma_i^j + \beta_{i,k}^j + \beta_{i,i}^j) \quad (8)$$

From the view of reducing resource consumption, it is the demanded material flow per unit of product that is the most concerned for one producing unit. Thus, metal yield ratio of unit (i, j) is taken for evaluating the material flow of a producing unit.

- iii. Metal yield ratio (R_i^j). It is defined as the output of products per unit of material and is expressed as

$$R_i^j = F_i^j / (F_i^j + \gamma_i^j + \beta_{i,k}^j + \beta_{i,i}^j) = F_i^j / (F_{i-1}^j + \alpha_i^j + \beta_{m,i}^j + \beta_{i,i}^j) = 1 / (1 + w_i^j) \quad (9)$$

It can be found from Eq. (9) that the metal yield ratio is related with the waste rate. To increase the metal yield ratio, waste rate of this unit should be reduced.

2.2 Material flow model of a process

Material flows through a producing process are shown in Fig. 2. Process i is consisted of k_i units. Then, the material flow of process i is the sum of material flows of the k_i units.

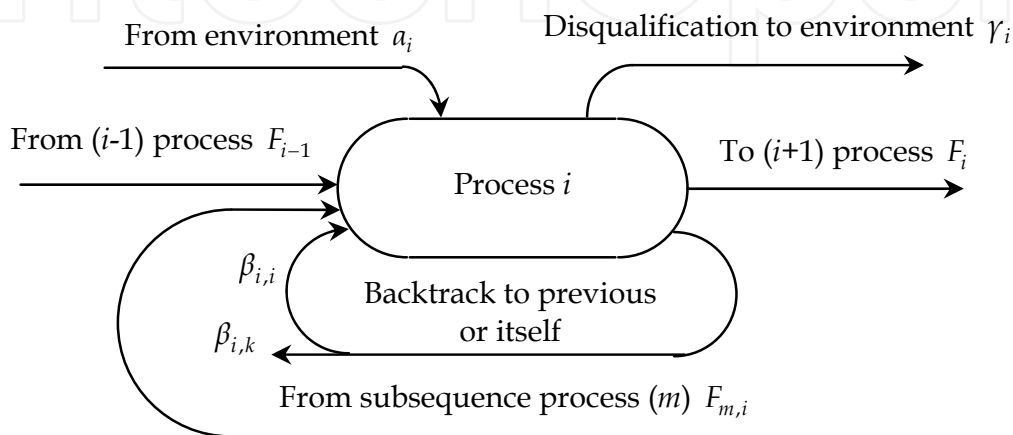


Fig. 2. Material flow model of a process

The material flows include: (i) Material flows from the anterior process (F_{i-1}); (ii) Material flows from environment (α_i); (iii) Material flows to the environment (γ_i); (iv) Material flows recycled through process i ($\beta_{i,i}$, $\beta_{i,k}$ and $\beta_{m,i}$); and (v) Material flows to the followed process (F_i). They are written as

$$\left\{ \begin{array}{l} F_{i-1} = \sum_{j=1}^{k_i} F_{i-1}^j \\ \alpha_i = \sum_{j=1}^{k_i} \alpha_i^j \\ \gamma_i = \sum_{j=1}^{k_i} \gamma_i^j \\ \beta_{i,i} = \sum_{j=1}^{k_i} \beta_{i,i}^j, \beta_{i,k} = \sum_{j=1}^{k_i} \beta_{i,k}^j, \beta_{m,i} = \sum_{j=1}^{k_i} \beta_{m,i}^j \\ F_i = \sum_{j=1}^{k_i} F_i^j \end{array} \right. \quad (10)$$

So the input-output relationship model for process i is developed as

$$F_{i-1} + \alpha_i + \beta_{m,i} + \beta_{i,i} = F_i + \gamma_i + \beta_{i,k} + \beta_{i,i} \quad (11)$$

Likely, the parameters of material flow of process i are waste rate (w_i) and waste recycle rate (r_{w-i}); and metal yield ratio of process i (R_i) is taken for evaluating the material flow. They are expressed respectively as

$$w_i = (\gamma_i + \beta_{i,k} + \beta_{i,i}) / F_i \tag{12}$$

$$r_{w-i} = (\beta_{i,k} + \beta_{i,i}) / (\gamma_i + \beta_{i,k} + \beta_{i,i}) \tag{13}$$

$$\text{and } R_i = F_i / (F_i + \gamma_i + \beta_{i,k} + \beta_{i,i}) = F_i / (F_{i-1} + \alpha_i + \beta_{m,i} + \beta_{i,i}) = 1 / (1 + w_i) \tag{14}$$

From the view of reducing resource consumption, it is the demanded material flow per unit of product that is the most concerned for one process. To obtain a smaller demand of natural resource, it is better if waste is less for iron and steel enterprise. As for the waste produced, it is best to be recycled to reduce the consumption of natural resource. i.e., the objective of material flow recycling is to obtain a smaller w_i and a larger r_{w-i} mentioned in Eqs. (12) and (13).

2.3 Material flow model of an enterprise

Based on the material flow model of a process, it is considered that the iron and steel enterprise is composed of n processes. And the material model of an enterprise is shown in Fig. 3.

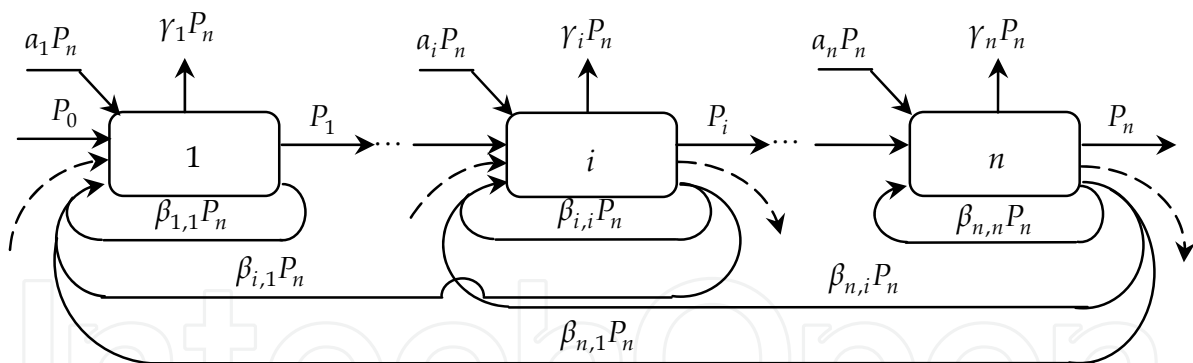


Fig. 3. Material flow model of an enterprise

P_i in Fig. 3 is the output of process i in statistical period and is expressed as

$$P_i = \left(1 + \sum_{l=i+1}^n \gamma_l + \sum_{l=i+1}^n \sum_{m=1}^i \beta_{l,m} - \sum_{l=i+1}^n \alpha_l \right) P_n \tag{15}$$

The material flow input-output balance of enterprise is

$$P_0 + \left(\sum_{i=1}^n \alpha_i \right) P_n = P_n + \left(\sum_{i=1}^n \gamma_i \right) P_n \tag{16}$$

Material flow per unit product can be gotten if both sides of Eq. (16) are divided by P_n . Then main parameters of material flow are:

- i. External material flow per ton of steel.

$$\alpha = \sum_{i=1}^n \alpha_i \quad (17)$$

- ii. Recycled material flow per ton of steel.

$$\beta = \sum_{i=1}^n \sum_{l=i}^n \beta_{l,i} \quad (18)$$

- iii. Emitted material flow per ton of steel.

$$\gamma = \sum_{i=1}^n \gamma_i \quad (19)$$

- iv. Waste rate of an enterprise.

$$w = \sum_{i=1}^n (p_i \cdot w_i) \text{ or } w = \gamma + \beta \quad (20)$$

- v. Waste recycle rate of an enterprise.

$$r = \beta / (\gamma + \beta) \quad (21)$$

Resource efficiency is the output of final product per unit natural resource used. It is the evaluating index for material flow of an iron and steel enterprise with the expression as

$$R = 1 / (1 + \gamma - \alpha) \quad (22)$$

Considering the waste rate and waste recycle rate of an enterprise, Eq. (22) can be rewritten as

$$R = 1 / [1 + w(1 - r) - \alpha] \quad (23)$$

It can be seen from Eq. (23) that resource efficiency (R) will be raised by reducing waste rate of an enterprise (w), increasing waste recycle rate of an enterprise (r), and/or increasing external material flow per ton of steel (α). To increase the resource efficiency of an iron and steel enterprise, for one thing the waste output of every process should be reduced, for another the formed waste should be utmost recycled and reused.

3. Energy flow

The energy flow is formed when the energy runs along the route of conversion, usage, recovery and emission. Similar as material flow, energy flow model of a unit will be established, based on which energy flow model of a process or an enterprise are developed.

3.1 Energy flow model of a unit

For iron and steel enterprise, six energy flows shown in Fig. 4 may emerge in j -th unit of k -th energy conversion process, described as unit (k, j) . The flow rates of six material flows are average values of a statistical period (one year, one month, one day, etc.). Actually, flow rates of all energy flows through a unit changes when time is changed. So, flow rate of energy flow is the assembly average of the energy flow rate per unit time.

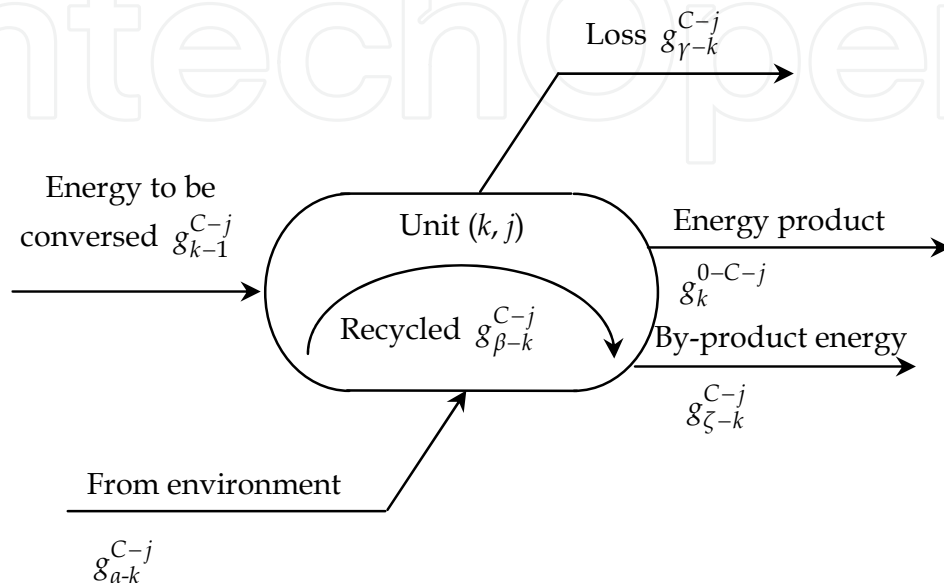


Fig. 4. Energy flow model of a unit

i. Energy flow of energy to be converted.

$$g_{k-1}^{C-j} = \int_{\tau_0}^{\tau_1} g_{k-1}^{C-j}(\tau) d\tau / \int_{\tau_0}^{\tau_1} F_k^{0-C-j}(\tau) d\tau \quad (24)$$

ii. Energy flow of energy product.

$$g_k^{0-C-j} = \int_{\tau_0}^{\tau_1} g_k^{0-C-j}(\tau) d\tau / \int_{\tau_0}^{\tau_1} F_k^{0-C-j}(\tau) d\tau \quad (25)$$

iii. Energy flow from environment.

$$g_{a-k}^{C-j} = \int_{\tau_0}^{\tau_1} g_{a-k}^{C-j}(\tau) d\tau / \int_{\tau_0}^{\tau_1} F_k^{0-C-j}(\tau) d\tau \quad (26)$$

iv. Energy flow loss.

$$g_{\gamma-k}^{C-j} = \int_{\tau_0}^{\tau_1} g_{\gamma-k}^{C-j}(\tau) d\tau / \int_{\tau_0}^{\tau_1} F_k^{0-C-j}(\tau) d\tau \quad (27)$$

v. Energy flow recycled.

$$g_{\beta-k}^{C-j} = \int_{\tau_0}^{\tau_1} g_{\beta-k}^{C-j}(\tau) d\tau / \int_{\tau_0}^{\tau_1} F_k^{0-C-j}(\tau) d\tau \quad (28)$$

vi. Energy flow of by-product energy.

$$g_{\zeta-k}^{C-j} = \int_{\tau_0}^{\tau_1} g_{\zeta-k}^{C-j}(\tau) d\tau / \int_{\tau_0}^{\tau_1} F_k^{0-C-j}(\tau) d\tau \quad (29)$$

where, $g_{k-1}^{C-j}(\tau)$, $g_k^{0-C-j}(\tau)$, $g_{\alpha-k}^{C-j}(\tau)$, $g_{\gamma-k}^{C-j}(\tau)$, $g_{\beta-k}^{C-j}(\tau)$ and $g_{\zeta-k}^{C-j}(\tau)$ are flow rates of each energy flow; $F_k^{0-C-j}(\tau)$ is the output flow rate of energy product; τ_0 and τ_1 are the initial time and end time of the statistical period, respectively.

Based on 1 ton of steel, the energy flow input-output relationship for unit (k, j) is

$$g_{k-1}^{C-j} + g_{\alpha-k}^{C-j} + g_{\beta-k}^{C-j} = g_k^{0-C-j} + g_{\beta-k}^{C-j} + g_{\zeta-k}^{C-j} + g_{\gamma-k}^{C-j} \quad (30)$$

Considering energy product is energy carrier, energy value of energy product is selected as the evaluating index of energy flow of unit (k, j) . Its expression is

$$b_k^j = (g_{k-1}^{C-j} + g_{\alpha-k}^{C-j} + g_{\beta-k}^{C-j}) - (g_{\beta-k}^{C-j} + g_{\zeta-k}^{C-j}) \quad (31)$$

where $(g_{k-1}^{C-j} + g_{\alpha-k}^{C-j} + g_{\beta-k}^{C-j})$ is the sum of energy flows consumed in this unit, $(g_{\beta-k}^{C-j} + g_{\zeta-k}^{C-j})$ is the sum of energy flows recycled in this unit.

It can be found from Eq. (31) that the energy value of energy product is determined by energy flows consumed and recycled.

3.2 Energy flow model of a process

Energy flows through a producing process are shown in Fig. 5. Process k is consisted of m_k units. Then, the energy flow of process k is the sum of energy flows of the m_k units.

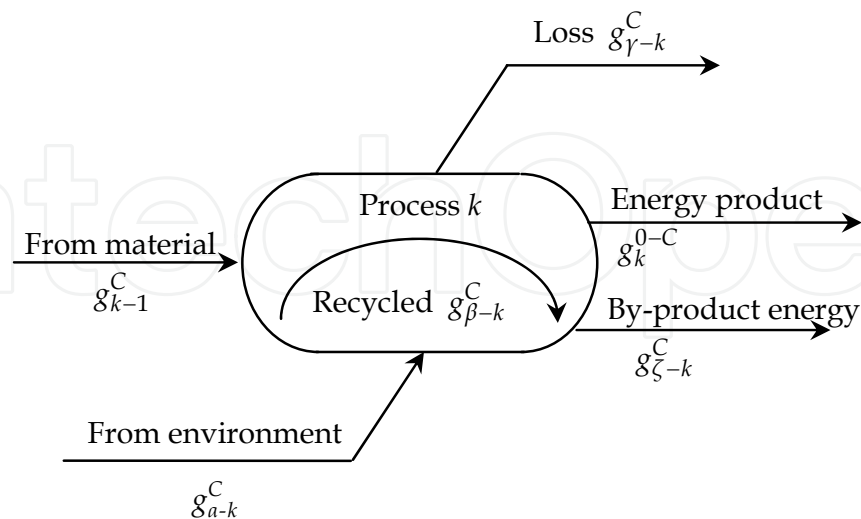


Fig. 5. Energy flow model of a process

The energy flows include: (i) Energy flows from material entering process (g_{k-1}^C); (ii) Energy flows of energy product after conversion (g_k^{0-C}); (iii) Energy flows consumed coming from

outside process ($g_{\alpha-k}^C$); (iv) Energy flows loss ($g_{\gamma-k}^C$); (v) ; Energy flows recycled ($g_{\beta-k}^C$); and (vi) Energy flows of by-product energy ($g_{\zeta-k}^C$). They are written as

$$\left\{ \begin{array}{l} g_{k-1}^C = \sum_{j=1}^{m_k} (\omega_{k,j} \cdot g_{k-1}^{C-j}) \\ g_k^{0-C} = \sum_{j=1}^{m_k} (\omega_{k,j} \cdot g_k^{0-C-j}) \\ g_{\alpha-k}^C = \sum_{j=1}^{m_k} (\omega_{k,j} \cdot g_{\alpha-k}^{C-j}) \\ g_{\gamma-k}^C = \sum_{j=1}^{m_k} (\omega_{k,j} \cdot g_{\gamma-k}^{C-j}) \\ g_{\beta-k}^C = \sum_{j=1}^{m_k} (\omega_{k,j} \cdot g_{\beta-k}^{C-j}) \\ g_{\zeta-k}^C = \sum_{j=1}^{m_k} (\omega_{k,j} \cdot g_{\zeta-k}^{C-j}) \end{array} \right. \quad (32)$$

where $\omega_{k,j}$ is the product weights of each energy conversion unit with the expression as

$$\omega_{k,j} = F_k^{0-C-j} / F_k^{0-C} \quad (33)$$

where F_k^{0-C-j} is the output of energy products of unit (k, j) and F_k^{0-C} is the output of energy products of process k .

The energy flow input-output relationship model for process k is developed as

$$g_{k-1}^C + g_{\alpha-k}^C + g_{\beta-k}^C = g_k^{0-C} + g_{\beta-k}^C + g_{\zeta-k}^C + g_{\gamma-k}^C \quad (34)$$

Energy value of energy product of a process is also the evaluating index of energy flow of energy conversion process, which is expressed as

$$b_k = (g_{k-1}^C + g_{\alpha-k}^C + g_{\beta-k}^C) - (g_{\beta-k}^C + g_{\zeta-k}^C) \quad (35)$$

where $(g_{k-1}^C + g_{\alpha-k}^C + g_{\beta-k}^C)$ is the sum of energy flows consumed in process k , $(g_{\beta-k}^C + g_{\zeta-k}^C)$ is the sum of energy flows recycled in process k .

The generation of waste energy per unit energy product is

$$g_{w-k}^C = g_{\beta-k}^C + g_{\zeta-k}^C + g_{\gamma-k}^C \quad (36)$$

Define the recycle rate of waste energy of a process as

$$r_{e-k}^C = (g_{\beta-k}^C + g_{\zeta-k}^C) / g_{w-k}^C \quad (37)$$

Then the energy value of energy product can be rewritten as

$$b_k = (g_{k-1}^C + g_{a-k}^C + g_{\beta-k}^C) - r_{e-k}^C \cdot g_{w-k}^C = g_{k-1}^C + (1 - r_{e-k}^C) \cdot g_{w-k}^C \quad (38)$$

3.3 Energy flow model of an enterprise

It has several energy conversion ways for any type of energy. Each conversion needs several transportation and energy conversion devices. The energy flow model of an enterprise is shown in Fig. 6. Energy media k has l types of conversion. Anyway, the final output energy is g'_k after several conversions from the original energy g_k .

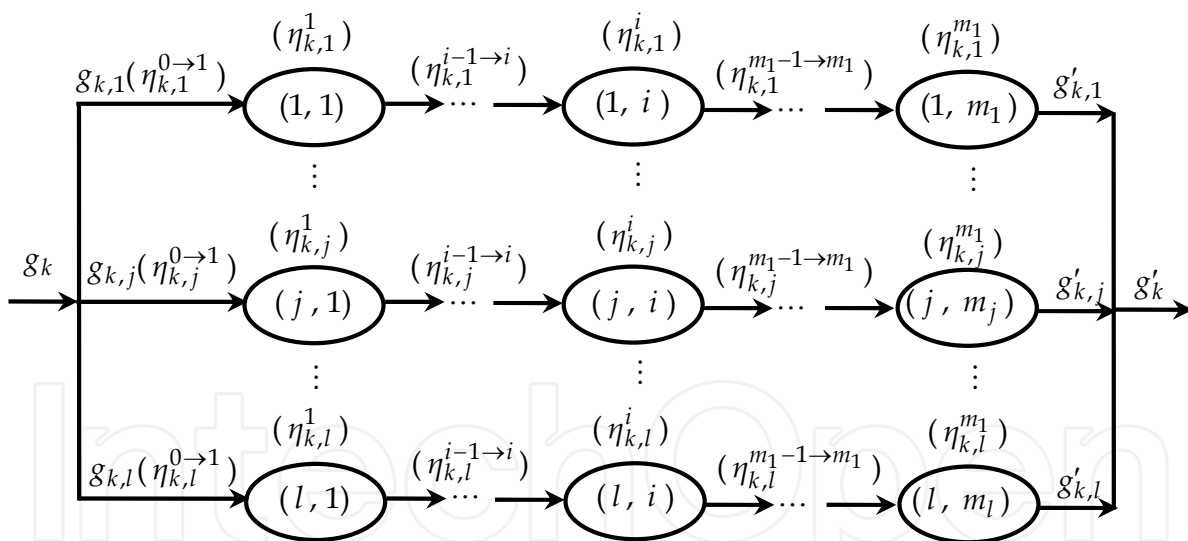


Fig. 6. Energy flow model of an enterprise

As for j -th energy conversion way of k -th energy media, supplied energy $g_{k,j}$ becomes $g'_{k,j}$ through m_j conversion devices and m_j times of transportation. The energy conversion efficiency of j -th energy conversion way is

$$\eta_{k,j} = g'_{k,j} / g_{k,j} = \prod_{i=0}^{m_j-1} (\eta_{k,j}^{i \rightarrow i+1} \cdot \eta_{k,j}^{i+1}) \quad (39)$$

where $\eta_{k,j}$ is the energy conversion efficiency of j -th energy conversion way, $\eta_{k,j}^{i \rightarrow i+1}$ is the transportation efficiency from unit i to unit $(i+1)$ in j -th energy conversion way, and $\eta_{k,j}^{i+1}$ is the energy efficiency of unit $(i+1)$ in j -th energy conversion way.

The energy conversion efficiency of media k is

$$\eta_k = \sum_{j=1}^n \left[\omega_{k,j} \cdot \prod_{i=0}^{m_j-1} (\eta_{k,j}^{i \rightarrow i+1} \cdot \eta_{k,j}^{i+1}) \right] \quad (40)$$

where $\omega_{k,j}$ is the ratio of energy input of j -th energy conversion way to total energy input, expressed as

$$\omega_{k,j} = g_{k,j} / g_k \quad (41)$$

It is indicated from Eq. (40) that some measures must be taken to improve the conversion efficiency and reduce the energy value of an energy product for an iron and steel enterprise. They are: increasing the weight factors of the energy conversion modes whose efficiency is higher; reducing the amount of the conversion units, optimizing the transportation mode of energy, and shortening the distance of transportation.

4. Energy flow network

Energy flow is dynamically operates in energy flow network following some rules. The energy flow network of iron and steel enterprise is composed of energy origin nodes (such as blast furnace, coke oven, converter), connectors (such as gas pipe), intermediate buffers (such as gas holder), and energy terminal nodes (such as sintering machine, blast furnace, heating furnace, boiler). The energy flow network of modern iron and steel enterprise is shown in Fig. 7.

According to the input-output feature of energy flow network, the energy flow network of iron and steel industry is divided into six regions. It includes energy transfer region (C), energy usage region (U), waste heat recycling region (R), surplus energy buffer region (B), energy storing region (S) and city energy system (CES).

In Fig. 7, the direction of arrow represents the flow direction of energy flow, parameters above flow lines represent the flow rates or allocation proportion of energy flows, and parameters below flow lines represent the temperatures or energy values of energy flows. C_F and C_G represent fuel conversion and power generation, respectively. U_H , U_M and U_L represent high-grade, medium-grade and low-grade energy consumers, respectively. R_H , R_P

and R_C represent heat recovery, power recovery and combined heat and power recovery, respectively. B_C and B_D represent centralized and distributed energy buffers, respectively. t is the temperatures of energy flows, according to which the energy values of energy flows can be gotten. λ in Fig. 7 is the allocation proportion of energy flow with

$$\lambda'_0 + \lambda''_0 = \lambda_{CF} + \lambda_{CG} = \lambda_{CG_1} + \dots + \lambda_{CG_n} = 1 \tag{42}$$

where λ'_0 and λ''_0 represent the ratios of energy flow converted (G'_0) and unconverted (G''_0) to external energy flow (G_0), respectively; λ_{CF} and λ_{CG} represent the ratios of energy flow of fuel conversion part (G_{CF}) and power generation part (G_{CG}) to converted energy flow (G'_0), respectively; and so on.

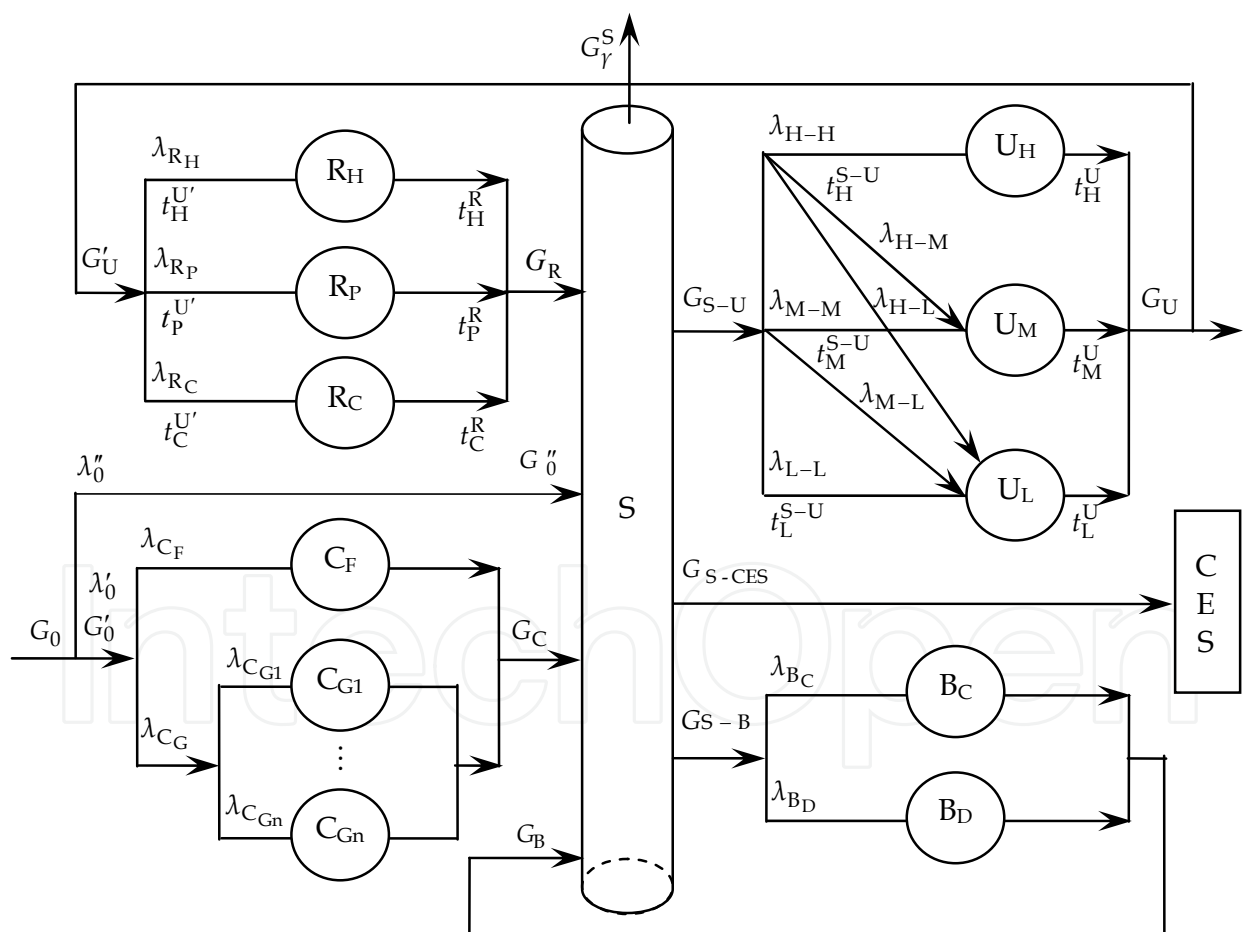


Fig. 7. Energy flow network model of an enterprise

Define η as the energy transportation efficiency of each process or user. η_{H-H}^U , η_{H-M}^U , and η_{H-L}^U represent the conversion efficiencies of high-grade energy to high-grade energy, high-grade energy to medium-grade energy and high-grade energy to low-grade energy, respectively. η_{C-U}^T represents the transportation efficiency from Region C to Region U. Then energy efficiencies of C, U, R and B are

$$\left\{ \begin{array}{l} \eta_C = \sum_{i=L}^H \sum_{j=L}^i (\lambda_{i-j}^C \cdot \eta_{i-j}^C) \\ \eta_U = \sum_{i=L}^H \sum_{j=L}^i (\lambda_{i-j}^U \cdot \eta_{i-j}^U) \\ \eta_R = \sum_{i=L}^H \sum_{j=L}^i (\lambda_{i-j}^R \cdot \eta_{i-j}^R) \\ \eta_B = \sum_{i=L}^H \sum_{j=L}^i (\lambda_{i-j}^B \cdot \eta_{i-j}^B) \end{array} \right. \quad (43)$$

Systems energy efficiency is the evaluating index for energy flow network of iron and steel enterprise. It is defined as the output of steel product per unit of net energy input and is expressed as

$$\eta_S = \frac{\int_{\tau_0}^{\tau} \frac{1}{g_0(\tau) - g_{B-CES}(\tau)} d\tau}{\tau - \tau_0} \quad (44)$$

where g is the energy input per ton of steel.

Eq. (44) can be rewritten as

$$\eta_S = \frac{\int_{\tau_0}^{\tau} \frac{1}{g_{\gamma}^C(\tau) + g_{\gamma}^S(\tau) + g_{\gamma}^{U/R}(\tau) + g_{\gamma}^B(\tau)} d\tau}{\tau - \tau_0} \quad (45)$$

where $g_{\gamma}^C(\tau)$, $g_{\gamma}^S(\tau)$, $g_{\gamma}^{U/R}(\tau)$, and $g_{\gamma}^B(\tau)$ are the energy losses of Region C, S, U and R, and B, respectively.

i. Energy loss of Region C

$g_{\gamma}^C(\tau)$ is the energy loss of Region C and energy transportation process. It is expressed as

$$g_{\gamma}^C(\tau) = g_0'(\tau)(1 - \eta_C \eta_{C-S}^T) \quad (46)$$

ii. Energy loss of Region S

$g_{\gamma}^S(\tau)$ is the energy loss of Region S. It is related with the volume of energy storages and maximum energy consumptions of buffer users and CES. Its expression is

$$g_{\gamma}^S(\tau) = g_{X-S}(\tau) - g_S^{\max}(\tau) - g_{S-B}^{\max}(\tau) - g_{S-CES}^{\max}(\tau) \quad (47)$$

where $g_{X-S}(\tau)$ is the energy loss of energy storages, $g_S^{\max}(\tau)$ is the surplus volume of energy storages, $g_{S-B}^{\max}(\tau)$ is the maximum energy consumption of buffer users, and $g_{S-CES}^{\max}(\tau)$ is the maximum energy consumption of CES.

iii. Energy loss of Regions U and R

$g_{\gamma}^{U/R}(\tau)$ is the energy loss of Regions U and R. It is the sum of effective energy demanded for the production of iron and steel and energy losses of energy usage and recovery processes. Its expression is

$$g_{\gamma}^{U/R}(\tau) = g_C(\tau) \frac{(1 + \zeta - \zeta \eta_{U-R}^T \eta_R \eta_{R-S}^T \eta_{S-U}^T \eta_U)}{\eta_{S-U}^T \eta_U} \quad (48)$$

iv. Energy loss of Region B

$g_{\gamma}^B(\tau)$ is the energy loss of Region B and energy transportation process. It is expressed as

$$g_{\gamma}^B(\tau) = g_{S-B}(\tau) (1 - \eta_{S-B}^T \eta_B \eta_{B-S}^T) \quad (49)$$

It can be achieved that from Eqs. (44) to (49) that systems energy efficiency of an iron and steel enterprise is related with energy conversion efficiency, energy usage efficiency, waste heat recovery efficiency and energy transportation efficiency.

With the continuous improvement of the technology and method of energy conservation, the energy conservation potential of the energy flow network of future steel enterprise lies in imbalance: the quantitative imbalance between the energy supply and energy demand of device, the qualitative imbalance of energy gradation between energy flow inlet and outlet, and the dynamic imbalance between the generation and consumption of secondary energy. So, the dynamic method of imbalance must be used to recognize the running regularity of energy flows, such as gas, oxygen and steam. And the imbalance between energy generation and utilization should be scientifically plan, design and schedule to seek for a new approach from non-equilibrium state to orderly structure. i.e., more attentions should be paid to energy conversion efficiency, energy usage efficiency, waste heat recovery efficiency and energy transportation efficiency.

5. Conclusion

Based on the five material flows including those from the anterior producing unit or process and those recycled through a unit or process, the material flow model for a production unit, a process and an enterprise are constructed in this chapter. The influence that the material flow of a process has on the metal yield ratio is described, and so is the influence of the parameters on the resource efficiency of an enterprise. For iron and steel enterprise, the produced waste material should be recycled to the process itself or others to reduce the consumption of natural resource.

In this chapter, energy flow through an energy conversion unit or a process, such as the converted energy and the energy of the product, is decomposed into six parts, and the energy flow model for a conversion unit, a process, and an enterprise are established. The influence that the flux of each energy flow, the largening extent of equipments and the recovery of residual heat (or energy) have on the energy value of the product is analyzed.

It is proposed in this chapter that the energy flow network is divided into six regions according to their functions: energy conversion region, energy usage region, waste heat recycling region, surplus energy buffer region, energy storing region and city energy system. The energy flow network model is established for evaluating the comprehensive energy level with the index of system energy efficiency.

Directions of next research include: (i) The forecasting of energy generation and energy consumption; (ii) The optimized allocation of surplus energy; and (iii) The optimized connection between energy flow network of an iron and steel enterprise and city energy system.

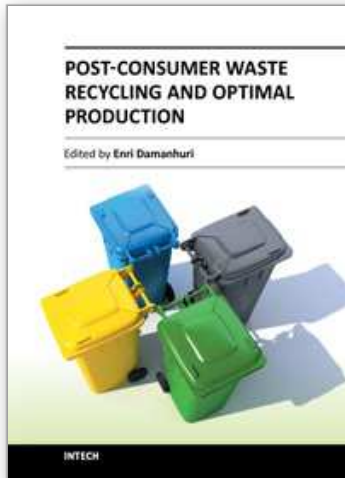
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Post-Consumer Waste Recycling and Optimal Production

Edited by Prof. Enri Damanhuri

ISBN 978-953-51-0632-6

Hard cover, 294 pages

Publisher InTech

Published online 23, May, 2012

Published in print edition May, 2012

This book deals with several aspects of waste material recycling. It is divided into three sections. The first section explains the roles of stakeholders, both informal and formal sectors, in post-consumer waste activities. It also discusses waste collection programs for recycling. The second section discusses the analysis tools for recycling system. The third section focuses on the recycling process and optimal production. I hope that this book will convey both the need and means for recycling and resource conservation activities to a wide readership, at both academician and professional level, and contribute to the creation of a sound material-cycle society.

How to reference

In order to correctly reference this scholarly work, feel free to copy and paste the following:

Wen-qiang Sun and Jiu-ju Cai (2012). Material Flow, Energy Flow and Energy Flow Network in Iron and Steel Enterprise, Post-Consumer Waste Recycling and Optimal Production, Prof. Enri Damanhuri (Ed.), ISBN: 978-953-51-0632-6, InTech, Available from: <http://www.intechopen.com/books/post-consumer-waste-recycling-and-optimal-production/material-flow-energy-flow-and-energy-flow-network-in-iron-and-steel-enterprise>

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