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Influence of the production fluctuation on the process energy intensity in iron and steel industry

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A B S T R A C T

This paper mainly studies how the production fluctuation affects the process energy intensity in iron and steel industry. First of all, the production state is divided into five conditions according to the production volatility. Meanwhile, the process energy intensity model is constructed. And model analysis showed that operating rate and qualification rate are two key parameters that represent the production volatility. A case study showed that the process energy intensity is inversely proportional to the normal production operating rate and qualification rate, but proportional to the operating rate in the other production states. Moreover, the production halt operating rate and normal production qualification rate significantly influence the process energy intensity in terms of production volatility. And then, some management suggestions were introduced on how to reduce the fluctuation of the process production. The application of the model is quantitative analysis methods, which can describe influence of production fluctuation on the process energy intensity. Based on this, corresponding measures are adopted for reducing energy consumption, including adjustment of production planning and strategy etc.

A R T I C L E I N F O

Keywords:
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1. Introduction

The iron and steel industry, which is the basic raw materials industry, influences the operation of national economy directly [1]. The crude steel production of the world increased from 750 Mmt (Million metric ton) in 1996 to 1545 Mmt in 2012. This is mainly because the crude steel production of China is continuously at the top in the world for a dozen years since 1996, which correspondingly enlarges the energy demand. Take Chinese steelmakers, the energy consumption increased from 168 Mtce (Million ton coal equivalent) in 2000 to 597 Mtce in 2012. The energy consumption of six energy-intensive sectors- excavating industry, chemicals, non-metallic industry, iron and steel, non-ferrous metals, petroleum – accounts for 71.4 % of total industry energy consumption as shown in Fig. 1. It depicts the ratio of energy consumption in each sector to total energy consumption in 2012, with the iron and steel industry having the largest share at 23.6 %. Heavy energy-consuming of the iron and steel industry will inevitably lead to increasing of energy costs and aggravation of the ecological environment.

1) Energy expense challenges

The energy cost of iron and steel making accounts for up to 20 % of the total production costs [2]. Coal and electricity are the primary energy source of the iron and steel industry. Meanwhile,

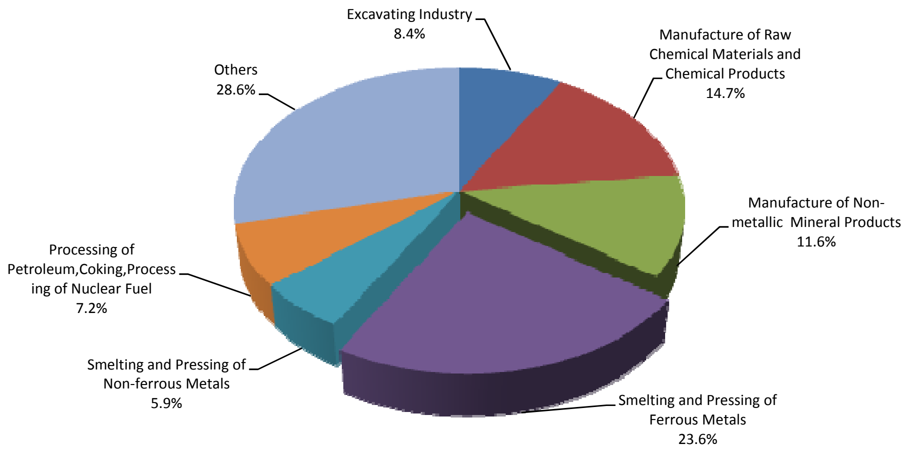

Fig. 1 Energy consumption ratio of each sector (Date source: CHINA STATISTICAL YEARBOOK 2012)

due to governmental macro-control, energy prices of coal and electricity have been increasing dramatically since 1980 in China; so high energy consumption and high energy price raises the energy expense of steel making [3]. So energy cost reduction is a very important factor in reducing the total cost.

2) Ecological challenges

In terms of ecological challenges, the first issue is carbon dioxide (CO_2) emissions. The energy efficiency has a direct impact on overall energy consumption and related CO_2 emissions [4].In 2009, the CO_2 emission from the Chinese iron and steel sector amounted to 1.17 billion metric tons, which is 16.29 % of the total Chinese CO_2 emissions and is nearly equal to 50 % of the world's steel industry's CO_2 emissions [5]. And the CO_2 emissions from energy (fuel) consumption accounts for 95 % of the total CO_2 emissions by the steel industry, which illustrates the important influence of energy (fuel) consumption on CO_2 emissions [6]. Meanwhile, GHG emissions problems of steel industry exist widely in other countries as well [7-9]. Secondly, the pollution problem of the steel industry, such as SO_2 and NOx, cannot be ignored either [10-12].

Facing the challenges from globalization, enhancing enterprise competitiveness and efficiency by applying new technology and new management means, improving energy efficiency, and reducing production costs is desperately needed.

2. Literature review

Currently, energy conservation research works performed in the steel industry have primarily concentrated on three aspects: equipment process improvement, process optimization, and energy conservation through management.

1) Equipment process improvement

Equipment process improvement refers mostly to replacing outdated, low-efficiency equipment by advanced, high-efficiency equipment. Early energy conservation efforts were primarily concentrated on the optimization and alteration of individual equipment.

Equipment scale enlargement is one of the important measures in energy conservation. For example, blast furnaces are process equipment that have the most concentrated material and energy flow in the iron and steel industry production process [13]. And through a comparison of a 5576 m^3 blast furnace from Shougang Jingtang Steel and a 4080 m^3 blast furnace from QianAn steel, Zhu et al. [14] discovered that constructing two 5576 m^3 blast furnaces can obtain similar yields as constructing three 4080 m^3 blast furnaces; however, the former has clear advantages in terms of investment reduction and energy conservation. Meanwhile, large-scale sintering machines and scale enlargement of a coke oven have low energy consumption and a high technical economic index.

Meanwhile, advanced production technology and equipment can improve energy efficiency. Pulverized coal injection technology (PCI) and continuous casting technology (CCT) are effective energy saving technology. The wide use of advanced combustion equipment [15] and power equipment [16] can promote energy efficient utilization. And the use of the spark plasma sintering (SPS) technology allowed for an energy saving in the order of 90-95% [17]. COREX process displays many energy and ecological advantages [18]. The surface of blast furnace tuyere was cooled by using cooling air instead of cooling water, which could reduce the energy taken away by the cooling water [19]. In addition, Tiago et al. [20] analyzed the feasibility of the biomass energy utilization to the EAF steelmaking process. Moreover, the recovery and utilization of residual energy and heat (RUREH) plays an important role for energy saving and CO2 emission reduction [21-22].

2) Process optimization

As technology continues to progress, room for energy savings through process equipment improvement becomes smaller, and thus, process optimization comes into play.

The issues of the steel industry studied in process optimization are the internal process function match and coordinated operation; the goal is to achieve continuous, compact production to reduce energy consumption during the production process. Examples of process optimization include technologies such as increasing the continuous casting ratio, long process flow (blast furnace - converter) to short process flow (electric arc furnace steel – continuous casting short process), continuous thin slab casting and rolling processes (CSPs), and rolled steel billet hot charging technology. Since the 1990's, China's steel industry per ton overall energy consumption declined significantly; among which, 48 % of the energy savings was due to the process restructuring and optimization [23].

Lu et al. [24] studied how the way ferrite flows in the iron and steel production process influences energy consumption and proposed important concepts, such as the base operating energy consumption graph. Thereafter, Chen et al. [25] and Yu et al. [26] used relevant concepts to calculate the influence of material flow structure change on energy consumption intensity in an actual production process and searched for an optimized production organization mode that minimized energy consumptions. Moreover, with the development of Circular Economy, industry ecosystem is gradually concerned. Dong et al. [5] agreed with a great potential for implementing circular economy in steel industry, and mode of future steel enterprises in circular economy society was discussed. Song et al. [27] and Chao et al. [28] thought that industry ecosystem is beneficial to itself, economy and environment.

3) Energy conservation through management

Energy waste issues in the operation process of the steel industry brought by "evaporating, emitting, dripping, or leaking" and disorderly management have become increasingly prominent. One of the most promising means of reducing energy consumption and related energy costs is implementing an energy management [29]. Wang et al. [30] noted that the potential of energy management system and industrial energy saving policies by transiting steel industry energy flow from "disorderly" to "orderly" is extremely large. Jean-Christian et al. [31] noted when sound energy management practices are included, the participants assessed the cost-effective energy conservation potential to be 9.7 %, which was 2.4 % higher than the potential for solely adopting cost-effective technologies. Tang et al. [32] thought that energy management of steel industry is basically in the safety and insurance mode of production-oriented, leading to inefficient energy management, high energy consumption and great loss of benefits. Therefore, it is necessary to establish a systematic energy efficiency management system oriented by quality and value of energy. Liu et al. [33] pointed out various environmental managements have been taken by the companies, including certain proactive efforts such as conducting cleaner production audit, pursuing ISO 14001 certification and the implementation of ESAs.

Because the steel industry production is influenced by factors, such as market demand, up-downstream process linkage, and equipment operation conditions, the production fluctuation changes greatly [23]; this change greatly influences the process energy intensity. When implementing lean energy management, the influence of production volatility on the process energy intensity should be fully considered. However, quantitative research on this aspect has rarely been reported. For this reason, this paper takes “process” as the starting point and explores and extracts the primary factors of influence of production fluctuation on the process energy intensity. Chen et al. [34] put forward there were six states in a production process, and process energy intensity formula was constructed. Combined with (E-P) method of cleaner production [35], production states were re-defined and re-divided taken into account this principle of division in this paper, process energy intensity formula was re-established. And the model is further verified using actual examples. And then, some suggestion and management measures were introduced.

3. Study object

With the view of process structure, iron and steel enterprise possesses the characteristics of the up-downstream processes are connected in series, and each unit is connected in parallel in the same work procedure. Therefore, When production fluctuations occurs in a unit, it will inevitably bring the production fluctuations of up-downstream processes or other units of the same procedure, thus affecting the energy intensity. In this paper, a unit in the production process is selected as study object (shown in Fig. 2). And then, the influence of production fluctuation on the process energy intensity is discussed. Meanwhile, measures of reducing production volatility, which can reduce impact on process energy intensity, are proposed under different production disposition.

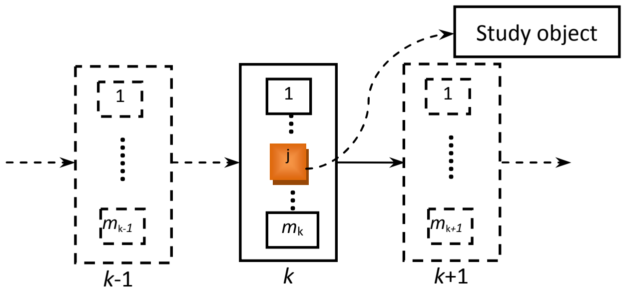

Fig. 2 The relationship between study object and it’s up-downstream

Fig. 2. is the production process flow diagram. In which, k – the k-th procedure; k-1, k+1 – the up-downstream processes, respectively; j – the j unit of the k-th procedure.

4. Methodology

4.1 Production state description

Based on (E-P) method of cleaner production, the steel industry total process energy consumption, process production, and the process energy intensity have the following relationship:

$$E = E_0 + K \cdot P \tag{1}$$

$$e = E_0/P + K \tag{2}$$

In which, E – total process energy consumption within the statistical cycle, tce (ton coal equivalent); E_0 – energy consumption not directly related to production within the statistical cycle, such as energy consumed by the company general service, tce; P – process production within the statistical cycle, t; K – the normal production state energy intensity, tce/t; e – the process energy intensity within the statistical cycle, tce/t.

Fig. 3. is the process energy production graph (E-P graph), where the total process energy consumption increases as production increases, whereas the process energy intensity decreases in an inversely proportional manner. When the production is zero (stop production), equipment used for the company general service still consumes energy; therefore, the total process energy

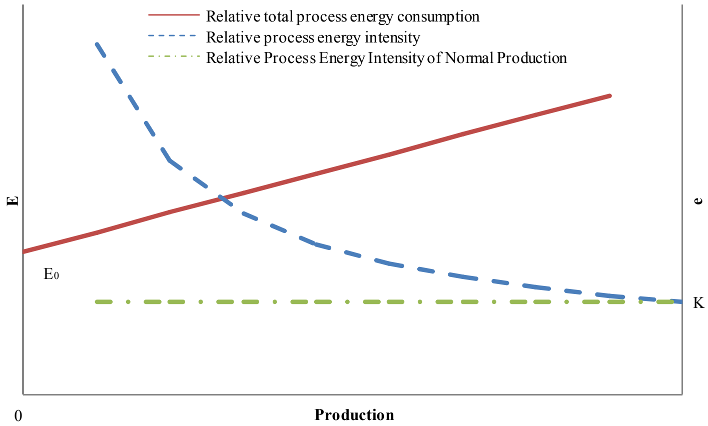

Fig. 3 Relationship between energy consumption and production of process

consumption is not zero, and thus, the process energy intensity is infinite in this situation. When the process production is relatively low (abnormal production), despite the total process energy consumption being low, due to the low production amount, the process energy intensity is extremely high. With the gradual increase in production, the total process energy consumption increases correspondingly; however, the process energy intensity decreases significantly; also, when production increases to the designed capacity (normal production), the process energy intensity approaches a stable state.

Therefore, this paper divides the process production state into three conditions of stop production, abnormal production, and normal production. Additionally, transitional states must exist between these three states, as shown in Fig. 4. The processes of transitional states (4), (5), and (6) belong to production decrease; the energy consumption is relatively low and thus, will not be considered. Moreover, the occurrence probability of the direction transition from normal production to abnormal production process (process (1) in Fig. 4.) is extremely low and therefore, will not be considered. Transitional states (2) and (3) are processes from low production volume to high production volume, in which the majority of the equipment in the process is at a start-up stage, and the energy consumption is relatively high. So it is adequate to only consider process transitional states (2) and (3). Here, state (2) is defined as a stop production transition, and state (3) is defined as an abnormal production transition.

Combined with Fig. 2, the relationship between the total energy consumption and the process energy intensity for each production state can be obtained, as shown in Fig. 5. While, the total process energy consumption in normal production is highest, but the process energy intensity is lowest; the total process energy consumption in stop production is lowest; however, because the production volume is zero, the process energy intensity is infinite.

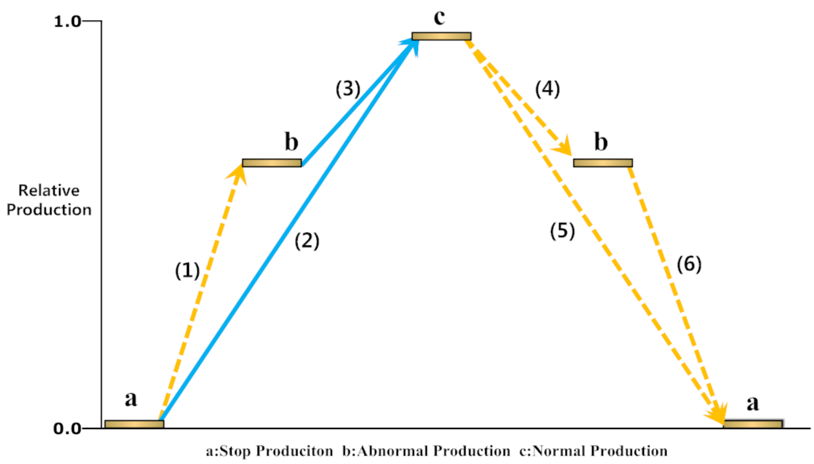

Fig. 4 Illustration of the production state

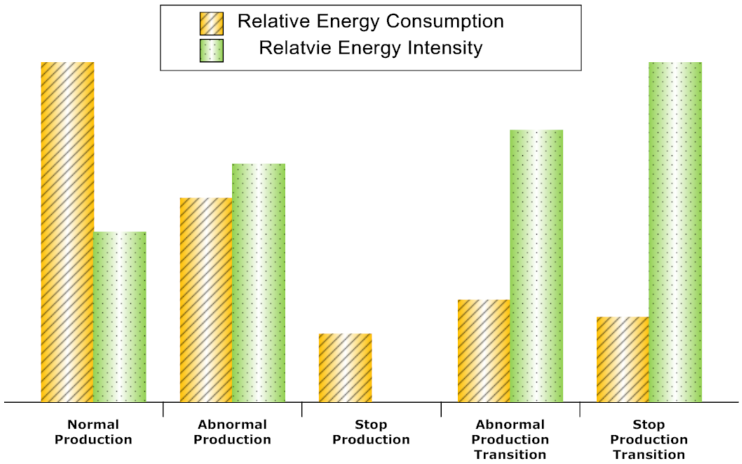

Fig. 5 Relationship of all production states between the relative energy consumption and relative energy intensity

4.2 Mathematical model

The concept of the statistical average of energy and material flow is introduced. Energy flow is the ratio of the total energy flow amount in the i^{th} state and time duration, Shown in Eq. 3.

$$E_i = \sum_{l=1}^{n_i} \int_0^{t_{i,l}} E_{i,l}(t)\, dt \,/ \sum_{l=0}^{n_i} t_{i,l} \tag{3}$$

In which, i – subscript, i =1, 2, 3, 4, 5, which represents normal production, abnormal production, stop production, abnormal production transition, and stop production transition, respectively; E_i – statistical average of energy flow in i-th production state, tce/h; n_i – number of times the i-th production state occurred; $E_{i,l}$ – instantaneous energy flow in the l-th occurrence of i-th state, tce/h; $t_{i,l}$ – time of l-th occurrence of i-th state, h.

By the same principle, the material flow statistical average can by expressed by Eq. 4:

$$M_i = \sum\nolimits_{l=0}^{n_i} \int_0^{t_{i,l}} M_{i,l} dt \,/ \sum\nolimits_{l=0}^{n_i} t_{i,l} \tag{4}$$

In which, M_i – statistical average of material flow in i-th production state, t/h; $M_{i,l}$ – instantaneous material flow in the l-th occurrence of i-th state, t/h;

1) Total process energy consumption

The total process energy consumption is the sum of the energy consumption in each of the five production states within the statistical cycle:

$$\begin{aligned} E &= E_1T_1 + E_2T_2 + E_3T_3 + E_4T_4 + E_5T_5 \\ &= T(E_1\eta_1 + E_2\eta_2 + E_3\eta_3 + E_4\eta_4 + E_5\eta_5) \end{aligned} \tag{5}$$

In which, T_i – duration of i-th state, h; T – statistical cycle, h; η_i – operating rate of i-th state, %, it is defined as T_i/T.

2) Process production

The process production in the statistical cycle is the sum of the qualified product in each of the normal production, abnormal production, stop production, abnormal production transition, and stop production transition (volume of stop production is 0) state:

$$\begin{aligned} P &= M_1T_1\eta_{p1} + M_2T_2\eta_{p2} + M_4T_4\eta_{p4} + M_5T_5\eta_{p5} \\ &= T\big(M_1\eta_1\eta_{p1} + M_2\eta_2\eta_{p2} + M_4\eta_4\eta_{p4} + M_5\eta_5\eta_{p5}\big) \end{aligned} \tag{6}$$

In which, η_{pi} – qualification rate of i-th state, %.

3) The process energy intensity

The process energy intensity is:

$$e = E/P = (E_1\eta_1 + E_2\eta_2 + E_3\eta_3 + E_4\eta_4 + E_5\eta_5)/(M_1\eta_1\eta_{p1} + M_2\eta_2\eta_{p2} + M_4\eta_4\eta_{p4} + M_5\eta_5\eta_{p5}) \quad (7)$$

Let $\alpha_i = E_i/E_1$, $\beta_i = M_i/M_1$; then, the process energy intensity model is

$$e = K(\eta_1 + \alpha_2\eta_2 + \alpha_3\eta_3 + \alpha_4\eta_4 + \alpha_5\eta_5)/(\eta_1\eta_{p1} + \beta_2\eta_2\eta_{p2} + \beta_4\eta_4\eta_{p4} + \beta_5\eta_5\eta_{p5}) \quad (8)$$

In which, α_i – ratio of energy flow statistical average value in *i*-th production state and normal production state, simply as the *i*-th production state energy flow ratio; β_i – ratio of the material flow statistical average value in *i*-th production state and normal production state, simply as the *i*-th production state material flow ratio. And Eq. 8 is the process energy intensity model based on (E-P) method of cleaner production.

5. Case studies

The steel rolling mill of an iron and steel enterprise is analyzed quantitatively by using the process energy intensity. And the data for this study are excerpted from daily production report and energy report of this rolling process. The process energy intensity in normal production of this rolling process is 72.4 kgce/t (kgce: kilogram coal equivalent) through data analysis.

5.1 Model modification and base operating condition determination

1) Model modification

Within the statistical cycle, the durations of the two transitional states are short; the production in these two states can be approximated as 0; thus, the process energy intensity model can be simplified:

$$e = K(\eta_1 + \alpha_2\eta_2 + \alpha_3\eta_3 + \alpha_4\eta_4 + \alpha_5\eta_5)/(\eta_1\eta_{p1} + \beta_2\eta_2\eta_{p2}) \quad (9)$$

And then, the following constraint exists:

$$\eta_1 + \eta_2 + \eta_3 + \eta_4 + \eta_5 = 1 \quad (10)$$

Eq. 10 indicates that when one operating rate changes, other operating rates will be adjusted to satisfy the constraint relation. And then, the following provision is made for the constraint equation; when normal production increases, abnormal production decreases accordingly, and the operating rate of the other states remain unchanged, and vice versa.

2) Base operating condition determination

A certain statistical cycle of the rolling process is used as a reference point to discuss the influence of each parameter on the process energy intensity; this reference point is defined as the base operating condition. The related parameters are listed in Table 1. The process energy intensity under the base operating condition is 78.1 kgce/t by calculating. And then, the influence of each parameter in the model on the process energy intensity is analyzed through the discussion of the Eq. 9. Namely when the influence of change in one factor is discussed, other parameters remain constant. Meanwhile, it can be seen from Eq. 9: the main factors that affect the process energy intensity are operating rate and qualification rate. Therefore, these two parameters are discussed in the following sections.

Table 1 Values of the base operation conditions

Name	Values	Name	Values	Name	Values
α_2	1.1	η_1 (%)	92	η_{p1} (%)	96
α_3	0.3	η_2 (%)	6.25	η_{p2} (%)	90
α_4	1.2	η_3 (%)	0.2	K (kgce/t)	72.4
α_5	1.4	η_4 (%)	0.5		
β_2	0.8	η_5 (%)	5		

5.2 Influence of operating rate

Fig. 6 shows the variation of energy intensity in a rolling process under different operating rate. And evergy operating rate is changed from 0 % to 100 % in Fig. 6.

The process energy intensity exhibits an approximately linear relationship with the operating rates of normal production, abnormal production, abnormal production transition, and stop production transition, and it exhibits a nonlinear relationship with the stop production operating rate. it's proportional to the operating rates of abnormal production, stop production, abnormal production transition, and stop production transition and inversely proportional to the normal production operating rate (shown in Fig. 6).

The influence of change in the normal production operating rate on the process energy intensity is relatively small (for every 1 % increase, it decreases approximately 0.4 kgce/t), which is primarily because any change in normal production is converted into an abnormal production state; this is why Fig. 6(a) and Fig. 6(b) are symmetric to each other.

The influence of the abnormal production transition operating rate (for every 1 % increase, the process energy intensity increases 0.96 kgce/t) and stop production transition operating rate (for every 1 % increase, the process energy intensity increases 1.16 kgce/t) on the process energy intensity is relatively large, which is primarily caused by a higher energy consumption when the production is in a transition process in which the production equipment is at the start-up stage. Moreover, compared with the abnormal production transition, the stop production transition state has a lower starting point and longer duration and thus, has a larger influence on the process energy intensity.

Relative to the other operating rates, the influence of the stop production operating rate on the process energy intensity is extremely prominent, and this influence will gradually increase with the increase of the stop production operating rate. When the stop production operating rate is lower than 50 %, its influence on the process energy intensity is relatively small; when it is at 50-75 %, the influence increases significantly, and when it is at 75-100 %, the increase in the influence is extremely prominent. The primary reason for this changing influence is that as the stop production operating rate increases, the production volume continuously decreases. It is known from Eq. 2 that the production volume has an inversely proportional functional relation with the process energy intensity such that when the stop production operating rate reaches 75 %, abrupt changes in the process energy intensity will occur. Overall, for every 1 % increase in the stop production operating rate, the process energy intensity will increase 4.1 kgce/t in average.

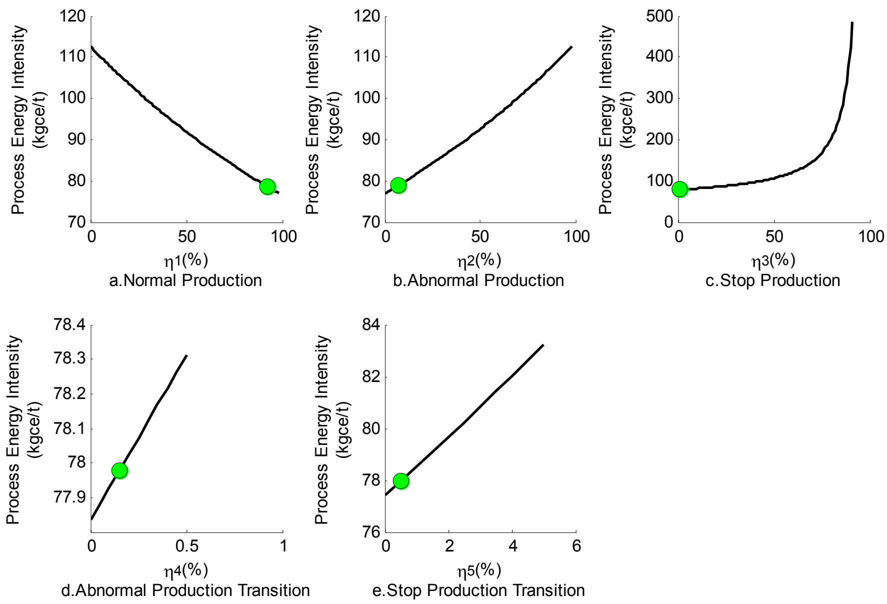

Fig. 6 Variation of energy intensity in a rolling process under different operating rate

5.3 Influence of qualification rate

Fig. 7 shows the variation of energy intensity in a rolling process under different qualification rate. And evergy qualification rate is changed from 0 % to 100 % in Fig. 7.

The process energy intensity is inversely proportion to the normal production qualification rate, and the relation is nonlinear; it's also inversely proportional to the abnormal production qualification rate, where the relation is essentially linear (shown in Fig. 7).

The influence of the normal production qualification rate on the process energy intensity is much larger than that of the abnormal production qualification rate primarily because the products produced in an abnormal production state within a statistical cycle are limited, and thus, the influence of its qualification rate is also limited. Moreover, as the normal production qualification rate gradually increases, its influence will gradually decrease; when the qualification rate is between 0-25 %, the influence is extremely prominent. As the normal production qualification rate continues to increase, the influence is significantly reduced, although it remains large compared with that of the abnormal production qualification rate. Overall, for every 1 % increase in the normal production qualification rate, the process energy intensity will decrease 12.8 kgce/t in averaged.

In summary, the influence of the stop production operating rate and normal production qualification rate on the process energy intensity is extremely prominent. Thus, these two indexes should be strictly controlled in actual production.

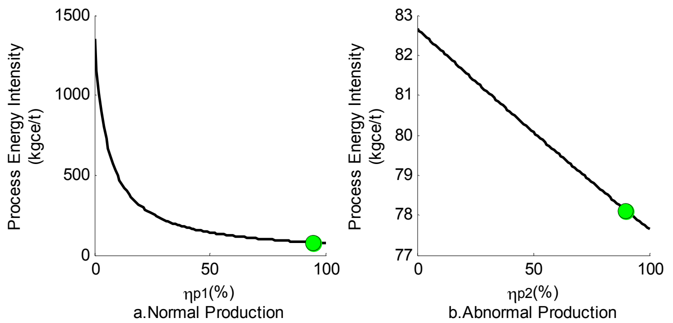

Fig. 7 Variation of energy intensity in a rolling process under different qualification rate

6. Discussion

Through above analysis, operating rate and qualification rate (especially the stop production operating rate and normal production qualification rate) are main parameters of production fluctuation. The prime factors, which bring about them change, are analyzed. And then, some management suggestions, which can improve these two parameters, are put forward.

6.1 Analysis of operating rate

The main impacts of operating rate are as follows in practical production.

1) Equipment failure or overhaul of research object

Equipment failure is the event or phenomenon that the equipment can't complete its regulation function, and it bears the characteristic of sudden. Meanwhile, it can be divided into slight fault and serious fault according to its consequences. Slight fault, which can result in decreasing of production, is generally partial functional deterioration of auxiliary equipment. This situation can be considered as abnormal production state because failure generally doesn't occur in the main production line, and equipment replacement or maintenance time is very short. Serious fault, which can bring about temporary stop production, generally occur in key equipment of the main production line. For instance, steel billets preserve heat by reducing the fuel supply in furnace when rolling mill function goes down. In any case, equipment needs to be urgent repaired, and production resumes as short as possible. In order to reduce the probability of equipment failure, what needs doing is specified as follows:

- The regulations of daily inspection tour and spot inspection should be formulated. That is, the entire production line needs to be regularly inspected, and the focal equipment should be checked carefully.
- Some parameters, which can represent equipment state, should be detected online, such as temperature, pressure, flow, voltage etc. And on-line diagnosis system should be established.
- Fault is strictly classified; fault maintenance project and strategy should be formulated. Once the failure occurs, maintenance personnel can operate in accordance with the regulations, and maintenance time can be further reduced.
- Maintenance personnel are regularly trained to enhance their professional skills.

Overhaul is the regular repair or replacement of equipment after the disintegration of all or most of the components. And then, the whole production process will be discontinued (planned shutdowns), it is characterized by a longer duration. For instance, the ironmaking process will be shut down in blast furnace overhaul. In order to shorten the overhaul time and resume production as soon as possible, some measures should be adopted, as shown in the following.

- Reasonable repair scheme, such as maintenance content determination and task allocation, is laid down before overhaul.
- Departments carry out their duties, and cooperate with each other in overhaul.

2) Equipment failure or overhaul of up-downstream production process

With the equipment failure or overhaul in up-downstream production process, the supply/demand of research object will decrease. In this paper, the relationship between the upstream production process and the research object is descried, because the influence of the up-downstream processes on the research process is consistent. There are obvious characteristics of series between the upstream production process and the research object, as shown in Fig. 8.

There is only one upstream production process in Fig. 8(a) and Fig. 8(b), so supply decreased slightly when slight fault occurs. And the inventory is adjusted dynamically to ensure the stability of the research object. When the upstream production process has a serious fault or overhaul, research object production can be kept stable if $I \geq R_s \cdot T$ (I: inventory level, metric ton; R_s: normal supply of upstream production process, metric ton/hour; T:shutdown time, hour). The demand for raw materials of the research object, that is R_s, is actively reduced in order to keep the production stability if $I \leq R_s \cdot T$, and research object is in abnormal production state at this moment. From the foregoing analysis, abnormal production is far superior to the stop production in the energy intensity. Where, it can only be discontinued if production decrease still una-

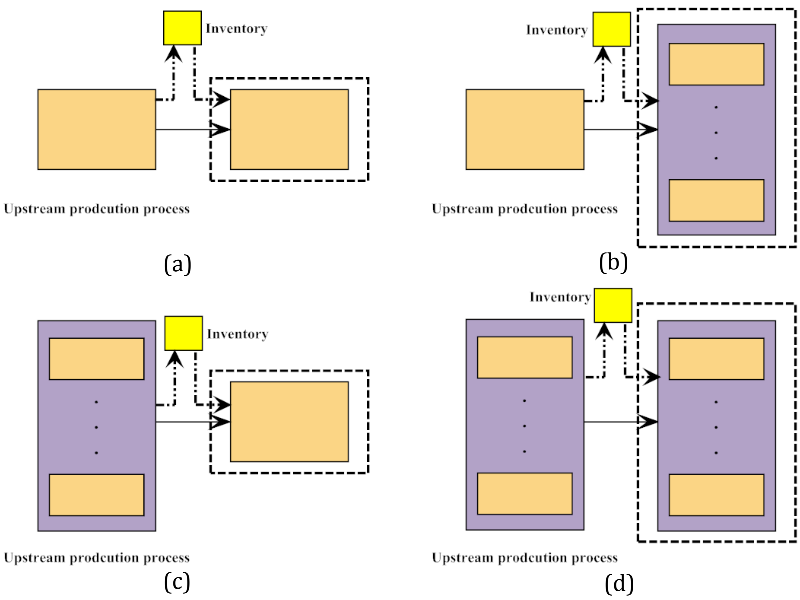

Fig. 8 The structure between production processes

ble to ensure continuous production. There are many production units in the upstream production process in Fig. 8(c) and Fig. 8(d), and there are characteristics of parallel between units. The research object will not stop production if one or a few units are discontinued (Not all). So the upstream production process also needs to formulate strict equipment maintenance regulations and reasonable repair schedules to minimize the probability of the occurrence and time of stop production. In addition, the establishment of the buffer unit (that is inventory) is beneficial to reduce the fluctuation of production.

3) The lack of market demand

Iron and steel enterprise need to reduce production because the shortage in market need. And the production capacity of iron and steel enterprise can't be fully released. So some measures should be done in order to make the production can be operated smoothly, such as readjusting product structure and remaking production schedule, according to changes in market demand.

6.2 Analysis of qualification rate

The main impacts of qualification rate are as follows in practical production.

1) The quality of raw material and fuel

The quality of raw materials is critical to the qualification rate of product. The impurity content of iron ore, which is the main raw material for iron and steel enterprise, will directly affect the quality of molten iron; even affect product quality of the subsequent process. For example, Sulfur and phosphorus are typical harmful elements in iron ores. High content of sulfur will cause the steel hot brittleness; reduce the ductility and toughness of the steel, and cracks are formed in forging and rolling. Meanwhile, sulfur is also detrimental to the welding performance and reduces corrosion resistance. In addition, High content of phosphorus will increase the cold brittleness of steel, deteriorate the welding performance and cold-bending property, and reduce the plasticity. The influence of fuel quality can't be ignored. For instance, the poor permeability of blast furnace and the furnace condition stability are affected when ash and sulfur content increase. Moreover, COG (Coke oven gas) is the major source of energy for heating furnace, some performance of steel will be poor, such as hot brittleness, if it contains high sulfur content.

2) Operating parameters of production process

Operating rules and regulations must be set up to strictly control the parameters in order to guarantee the quality of product. Otherwise, scrap rate will increase, and even cause stop production. For example, the blast kinetic energy determines the size and shape of the combustion zone in the furnace. If the blast kinetic energy is small, the gas distributes in the edge area. And conversely the center of the gas flow is disturbed. These two kinds of conditions can lead to poor quality of molten iron. Meanwhile, the billet is easy to produce surface crack and columnar crystal if the pouring temperature of the continuous casting machine is too high. Conversely inclusion can't float. Moreover, the billet is over heated and oxide scale of steel will increase if the heating furnace gas flow is too large. Conversely the billet can't be fully heated and can't be rolled.

3) Aging of equipment or backward production techniques

Inferior efficiency will happen due to aging of equipment or backward production techniques. Furthermore, qualification rate will reduce. So aging equipment and backward production techniques should be replaced or eliminated promptly.

7. Conclusions and suggestions

According to above-mentioned analysis, the following achievement can be obtained:

- This paper divides the process production state into five conditions: normal production, abnormal production, stop production, abnormal production transition, and stop production transition through analysing (E-P) method of cleaner production; and then, the process energy intensity model is constructed.

- Operating rate and qualification rate (especially the stop production operating rate and normal production qualification rate) are important index of production fluctuation on process energy intensity through case study.

Meanwhile, operating rate and qualification rate are analysed in order to reduce the impact of production volatility on process energy intensity. And some suggestions are proposed.

- Rules and regulations is a prerequisite to ensure the normal operation of equipment, and consummate rules should be formulated, such as daily inspection tour, spot inspection and fault treatment plans and so on. In addition, on-line fault diagnosis system also helps to reduce the probability of failure of equipment.
- Operation and maintenance personnel are the executive of the rules and regulations, so they need to be trained and assessed regularly to improve vocational skills.
- Buffer unit, which is conducive to reducing the volatility of production, should be adopted between production processes in iron and steel enterprise.
- The high-grade of raw/fuel and advanced production techniques favors to improve qualification rate of the product.
- Readjusting product structure and remaking production schedule can avoid production halt or abnormal production according to changes in market demand.

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Reference

[1] Du, T., Shi, T., Liu, Y., Ye, J.-B. (2013). Energy consumption and its influencing factors of iron and steel enterprise, *Journal of Iron and Steel Research, International*, Vol. 20, No. 8, 8-13, doi: 10.1016/S1006-706X(13)60134-X.

[2] Rasul, M.G., Tanty, B.S., Mohanty, B. (2007). Modelling and analysis of blast furnace performance for efficient utilization of energy, *Applied Thermal Engineering*, Vol. 27, No. 1, 78-88, doi: 10.1016/j.applthermaleng. 2006. 04.026.

[3] Zheng, L. (2012). A system dynamics based study of polocies on reducing energy use and energy expense for Chinese steel industry, *Foreign Investment in China*, No. 8, 156-157.

[4] Hasanbeigi, A., Price, L., Chunxia, Z., Aden, N., Xiuping, L., Fangqin, S. (2014). Comparison of iron and steel production energy use and energy intensity in China and the U.S, *Journal of Cleaner Production*, Vol. 65, 108-119, doi: 10.1016/j.jclepro.2013.09.047.

[5] Dong, L., Zhang, H., Fujita, T., Ohnishi, S., Li, H., Fujii, M., Dong, H. (2013). Environmental and economic gain of industrial symbiosis for Chinese iron/steel industry: Kawasaki's experience and practice in Liuzhou an Jinan, *Journal of Cleaner Production*, Vol. 59, 226-238, doi: 10.1016/j.jclepro.2013.06.048.

[6] Zhang, C.-X., Shangguan, F.-Q., Hu, C.-Q., Qi, Y.-H., Yin, R.-Y. (2010). Steel process structure and its impact on CO2 emission, *Iron and Steel*, Vol. 45, No. 5, 1-6, doi: 10.13228/j.boyuan.issn0449-749x.2010.05.021.

[7] Fysikopoulos, A., Papacharalampopoulos, A., Pastras, G., Stavropoulos, P., Chryssolouris, G. (2013). Energy efficiency of manufacturing processes: A critical review, *Procedia CIRP 7 – Forty Sixth CIRP Conference on Manufacturing Systems 2013*, Vol. 7, 628-633, doi: 10.1016/j.procir.2013.06.044.

[8] Worrell, E., Price, L., Martin, N. (2001). Energy efficiency and carbon dioxide emissions reduction opportunities in the US iron and steel sector, *Energy*, Vol. 26, No. 5, 513-536, doi: 10.1016/S0360-5442(01)00017-2.

[9] Arens, M., Worrell, E., Schleich, J. (2012). Energy intensity development of the German iron and steel industry between 1991 and 2007, *Energy*, Vol. 45, No. 1, 786-797, doi: 10.1016/j.energy.2012.07.012.

[10] Li, Z.-P., Fan, X.-H., Yang, G.-M., Wei, J.-C., Sun, Y., Wang, M. (2015), Life cycle assessment of iron ore sintering process, *Journal of Iron and Steel Research, International*, Vol. 22, No. 6, 473-477, doi: 10.1016/S1006-706X(15) 30029-7.

[11] Zhou, H., Cheng, M., Zhou, M., Liu, Z., Liu, R., Cen, K. (2016). Influence of sintering parameters of different sintering layers on NOx emission in iron ore sintering process, *Applied Thermal Engineering*, Vol. 94, 786-798, doi: 10.1016 /j.applthermaleng.2015.09.059.

[12] Zhang, S., Worrell, E., Crijns-Graus, W., Wagner, F., Cofala, J. (2014). Co-benefits of energy efficiency improvement and air pollution abatement in the Chinese iron and steel industry, *Energy*, Vol. 78, 333-345, doi: 10.1016/ j.energy.2014.10.018.

[13] Liu, X., Chen, L., Qin, X., Sun, F. (2015). Exergy loss minimization for a blast furnace with comparative analyses for energy flows and exergy flows, *Energy*, Vol. 93, Part 1, 10-19, doi: 10.1016/j.energy.2015.09.008.

[14] Zhu, R., Zhu, J., Li, J. (2010). Development of and exploration on large-scale blast furnaces, *World Iron & Steel*, Vol. 10, No. 5, 33-39, doi: 10.3969/j.issn.1672-9587.2010.05.007.
[15] Zhang, F.-M., Mao, Q.-W., Mei, C.-H., Li, X., Hu, Z.-R. (2012). Dome combustion hot blast stove for huge blast furnace, *Journal of Iron and Steel Research, International*, Vol. 19, No. 9, 1-7, doi: 10.1016/S1006-706X(13)60001-1.
[16] Napp, T.A., Gambhir, A., Hills, T.P., Florin, N., Fennell, P.S. (2014). A review of the technologies, economics and policy instruments for decarbonising energy-intensive manufacturing industries, *Renewable and Sustainable Energy Reviews*, Vol. 30, 616-640, doi: 10.1016/j.rser.2013.10.036.
[17] Musa, C., Licheri, R., Locci, A.M., Orrù, R., Cao, G., Rodriguez, M.A., Jaworska, L. (2009). Energy efficiency during conventional and novel sintering processes: The case of Ti-Al_2O_3-TiC composites, *Journal of Cleaner Production*, Vol. 17, No. 9, 877-822, doi: 10.1016/j.jclepro.2009.01.012.
[18] Ziebik, A., Lampert, K., Szega, M. (2008). Energy analysis of a blast-furnace system operating with the Corex process and CO2 removal, *Energy*, Vol. 33, No. 2, 199-205, doi: 10.1016/j.energy.2007.09.003.
[19] Shen, Y.S., Zong-Ming, L., Tao, Z., Fu-Sheng, Y., Hong-Ni, X., Rui-Lian, S. (2009). The new technology and the partial thermotechnical computation for air-cooled blast furnace tuyere, *Applied Thermal Engineering*, Vol. 29, No. 5-6, 1232-1238, doi: 10.1016/j.applthermaleng.2008.06.026.
[20] Oliveira, T.L., Assis, P.S., Leal, E.M., Ilídio, J.R. (2015). Study of biomass applied to a cogeneration system: A steelmaking industry case, *Applied Thermal Engineering*, Vol. 80, 269-278, doi: 10.1016/j.applthermaleng.2015.01.002.
[21] Chen, L., Yang, B., Shen, X., Xie, Z., Sun, F. (2015). Thermodynamic optimization opportunities for the recovery and utilization of residual energy and heat in China's iron and steel industry: A case study, *Applied Thermal Engineering*, Vol. 86, 151-160, doi: 10.1016/j.applthermaleng.2015.04.026.
[22] Walsh, C., Thornley, P. (2012). Barriers to improving energy efficiency within the process industries with a focus on low grade heat utilization, *Journal of Cleaner Production*, Vol. 23, No. 1, 138-146, doi: 10.1016/j.jclepro.2011.10.038.
[23] Yin, R. (2011). *Metallurgical process engineering*, Springer, Beijing, Metallurgical Industry Press, Beijing, China, doi: 10.1007/978-3-642-13956-7.
[24] Lu, Z., Cai, J., Yu, Q., Xie, A. (2000). The influences of materials flows in steel manufacturing process on its energy intensity, *Acta Metallurgica Sinica*, Vol. 36, No. 4, 370-378, doi: 10.3321/j.issn:0412-1961.2000.04.008.
[25] Chen, G., Cai, J.-J., Yu, Q.-B., Lu, Z.-W. (2002). The analysis of the influences of materials flows in iron and steel corporation on its energy consumption, *Journal of Northeastern University (Natural Science)*, Vol. 23, No. 5, 459-462, doi: 10.3321/j.issn:1005-3026.2002.05.014.
[26] Yu, Q.-B., Lu, Z.-W., Cai, J.-J. (2007). Calculating method for influence of material flow on energy consumption in steel manufacturing process, *Journal of Iron and Steel Research, International*, Vol. 14, No. 2, 46-51, doi: 10.1016/S1006-706X(07)60026-0.
[27] Chae, S.H., Kim, S.H., Yoon, S.-G., Park, S. (2010). Optimization of a waste heat utilization network in an eco-industrial park, *Applied Energy*, Vol. 87, No. 6, 1978-1988, doi: 10.1016/j.apenergy.2009.12.003.
[28] Gu, C., Leveneur, S., Estel, L., Yassine, A. (2013). Modeling and optimization of material/energy flow exchanges in an eco-industrial park, *Energy Procedia*, Vol. 36, 243-252, doi: 10.1016/j.egypro.2013.07.028.
[29] Schulze, M., Nehler, H., Ottosson, M., Thollander, P. (2016). Energy management in industry – A systematic review of previous findings and an integrative conceptual framework, *Journal of Cleaner Production*, Vol. 112, Part 5, 3692-3708, doi: 10.1016/j.jclepro.2015.06.060.
[30] Wang, Y., Li, H., Song, Q., Qi, Y. (2015). The consequence of energy policies in China: A case study of the iron and steel sector, *Resources, Conservation and Recycling*, Vol. 117, Part A, 66-73, doi:10.1016/j.resconrec.2015.07.007.
[31] Brunke, J.-C., Johansson, M., Thollander, P. (2014). Empirical investigation of barriers and drivers to the adoption of energy conservation measures, energy management practices and energy services in the Swedish iron and steel industry, *Journal of Cleaner Production*, Vol. 84, 509-525, doi: 10.1016/j.jclepro.2014.04.078.
[32] Tang, E., Shao, Y.-J., Fan, X.-G., Ye, L.-D., Wang, J. (2014). Application of energy efficiency optimization technology in steel industry, *Journal of Iron and Steel Research, International,* Vol. 21, Supplement 1, 82-86, doi: 10.1016/S1006-706X(14)60126-6.
[33] Liu, X., Niu, D., Bao, C., Suk, S., Shishime, T. (2012). A survey study of energy saving activities of industrial companies in Taicang, China, *Journal of Cleaner Production*, Vol. 26, 79-89, doi: 10.1016/j.jclepro.2011.12.030.
[34] Chen, G. (2004). Development of process energy intensity formula under different state variables, *Journal of Harbin Institute of Technology (New Series)*, Vol. 11, No. 6, 694-696, doi: 10.3969/j.issn.1005-9113.2004.06.025.
[35] Yang, L. (2009). Assessment approaches to cleaner production audit with resource and energy as auditing keynote, *Environmental Science and Management*, Vol. 34, No. 7, 153-156, doi: 10.3969/j.issn.1673-1212.2009.07.044.