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A Study on the Essence of Process Manufacturing Industry

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Abstract: Process manufacturing industry is an important pillar of China's economic development, and its orderly and healthy development is of great significance to both China's economic and social development. However, the development of process manufacturing industry is constrained by its enormous consumption of resources and energy and its serious environmental impact. To reach a deeper understanding of the future development of process manufacturing industry, this study extends an analytical perspective from a single industry to all forms of the process manufacturing industry. Based on the concepts of thermodynamics and entropy, this study analyzes the essence of process manufacturing. Three groups of key factors are used to build the analysis framework: flow and process; material, energy, and information; and scale and efficiency. A chemical engineering process and a phosphorus chemical process are then analyzed using this framework. The results show that the fundamental direction of the development of process manufacturing is to minimize the entropy increments of the whole system, rather than only those of the process system, while ignoring the entropy increments of the system of the external environment. In order to minimize the entropy increments of the whole system, it is necessary to not only pay attention to the economic benefits of the process system, but also to improve resource, energy, and environmental efficiency. To improve efficiency, the technology involved requires improvement, upgrading, and innovation. Improving and upgrading the technology can slightly improve the efficiency of a process system, while revolutionary innovation in the technology may greatly improve the efficiency.
Keywords: process manufacturing industry; entropy; process system; essence; essential characteristic

1 Introduction

The process manufacturing industry, also known as process industry, involves putting raw materials through mixing, separation, molding, or chemical reaction, and causing a series of changes in the physical and chemical properties, which add value, so that the materials acquire physical and chemical properties, and gain specific uses as industrial products.

A typical process manufacturing industry, such as the chemical industry, is in continuous operation in terms of time and space. The input of raw materials and production of products are continuous and without interruption, except for regular equipment maintenance and accidents. A continuous production process usually only produces a few kinds of products. Only after technological innovation is it possible to change the type of product, process parameters, and the raw materials in the production process.

The process manufacturing industry, which includes iron and steel, nonferrous metals, chemicals, building materials, etc., is an important pillar of economic development in China. The yield and the output value of China's process manufacturing are large, and account for considerable proportions of those worldwide, respectively. For example, China's crude steel output was 8.04×10^8 tons in 2015, accounting for 49.5% of the world's crude steel

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output, and China's aluminum production was 3.111×10^7 tons, accounting for 54.6% of the world's aluminum production. Additionally, China's cement output was 2.348×10^9 tons, accounting for 57.3% of the world's cement production. The healthy development of the process manufacturing industry is of great significance to the stable development of the economy and society.

2 Common features of the process manufacturing industry

The process manufacturing industry incorporates many other industries, such as steel, nonferrous metals, chemicals, and building materials. Most of them focus on the orderly and healthy development of the process manufacturing industry, focusing on the development of a particular industry, including its development direction and development strategy. For example, the development direction and development strategy of a typical process manufacturing industry, such as the steel industry, the non-ferrous industry, or the building material industry, have been thoroughly analyzed and researched. The steel industry in China is large in scale and large in net exports. It faces many problems, such as high resource and energy consumption, and heavy environmental load [1]. The future development of the steel industry needs to realize green development, bring into play the three major functions of the iron and steel industry, and cooperate with other industries and society to build ecological links [2–4]. Also, as a typical manufacturing industry, the non-ferrous industry faces similar problems. The future development of the non-ferrous industry needs technological innovation at its core [5], promoting pollution prevention and control in the non-ferrous industry, comprehensively utilizing waste and cleaner production through technical progress [6], realizing the green, circular and low-carbon development of the nonferrous industry [7]. Technological development to promote the green development of the industry, along with a sustainable development strategy, also apply to the typical process manufacturing industry–the building material industry [8–9]. In particular, the development of technologies related to green building materials, and improvement of standards and systems has important significance.

The research on how to develop a single industry is more mature, but few studies are conducted from the point of view of the whole process manufacturing industry. By analyzing the common features of each industry in the process manufacturing industry, this paper explores the essence of the process manufacturing industry, recognizing its essential characteristics, and further analyzing the essence of the process manufacturing industry to put forward the development strategy of the process manufacturing industry based on the essential analysis.

The common features of various industries within the process manufacturing industry can be summarized as follows:

(1) In the production process, the process manufacturing industry mainly uses bulk natural resources (such as mineral resources and water resources) as raw materials for production;

(2) In the production process, large amounts of material and energy flows are transformed into desired products people need through physical or chemical changes;

(3) The production process of the flow manufacturing industry mainly involves a series or parallel operation of unit operations (or processes) with different functions and coordinated operations to achieve continuous or quasi-continuous production.

(4) A large amount of material and energy is input into the production process and, at the same time, materials and energy are exported from the production process through various forms of emission and waste processes;

(5) People control the production process by getting the information (such as equipment operating parameters) from the production process and injecting information into the production process (such as market demand, process technical parameters, policy requirements, etc.) to ensure that they comply with the target sequence operation;

(6) For the process manufacturing industry, economies of scale can increase production efficiency and reduce production costs. As a result, the process manufacturing industry is large at this stage and still scaling up.

According to the above general characteristics, the production processes of all industries can be summed up conceptually. (Fig. 1)

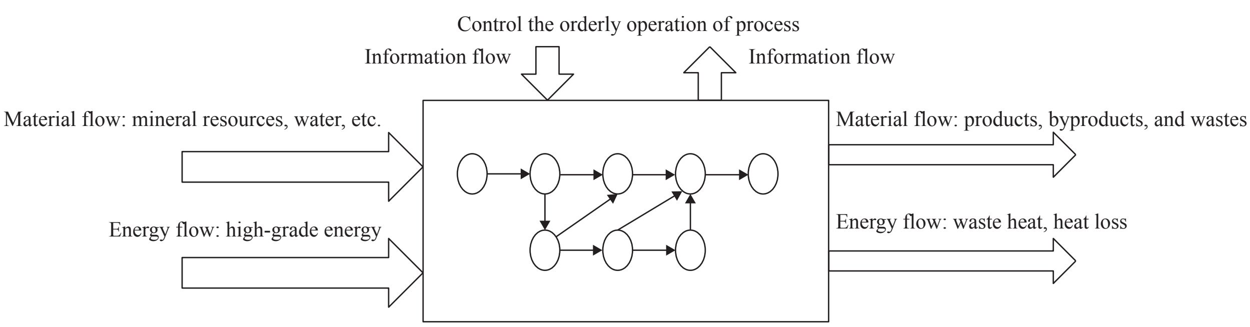

Fig. 1. Diagram of manufacturing process.

The common characteristics of the process manufacturing industry mean that all industries face similar problems and challenges at present, such as resource, energy, and environmental constraints. To solve these problems and challenges, the development direction and development strategy of each industry must have a common ground. Therefore, expanding the analytic perspective from a single industry perspective to the entire process manufacturing industry can help explore the essence and essential features of the process manufacturing industry, allowing us to better grasp the the development direction and the future development strategy of the process manufacturing industry.

3 The essence and the essential features of the process

The production process is at the core of the process manufacturing industry, and to understand the essence of the process manufacturing industry, a clear and in-depth appreciation of the essence and the essential features of the production process.

Thermodynamics can be used to study the nature and law of matter from a macroscopic point of view. The production processes of industries covered by the process manufacturing industry can all be regarded as thermodynamic systems. Therefore, the essence of the process can be described most clearly and completely from the viewpoint of a thermodynamic system. That is, a process is an open, unbalanced, irreversible, complex system of non-linear couplings operated by elements of different structures and functions. In this system, material flow, driven by energy flow, under the guidance of information flow, runs in a dynamic and orderly manner along the flow network system according to a pre-set program, and the operation process includes a series of chemical reactions and physical changes.

Entropy is an important parameter in thermodynamics to describe the state of the system. To clearly describe the essential characteristics of the process, we can start from the perspective of entropy. From the essence of the process, we can know that the process is an open, non-equilibrium, irreversible system, and, in fact, the process system can be seen as a typical dissipative system as it constantly exchanges material, energy, and information with the outside world. The material flow, the energy flow, and the information flow are transformed in the process system, and then act on the external environment. After the change to the external environment reaches a certain threshold, it transforms from the disordered state to the normalized and ordered state. Because the process system is a dissipative system, constantly regulating the direction of development, the process system is an entropy reduction system.

The main focus of attention has previously been how to make the process system more orderly, that is to say the entropy reduction of the process system, because people's vision is limited to the process system itself and ignores the same important external environment system, resulting in the process manufacturing industry facing environmental pollution, resource, and energy constraints, as well as other issues. In studying the future development of the process manufacturing industry, the process system and the external environment system should be regarded as a whole system, and, thus from an overall prospective and in a more comprehensive and thorough manner, the essential features of the process can be analyzed, and the development strategy of the process manufacturing industry can be formulated.

The operation and development of the process system cannot be separated from the external environment system. The external environment system provides material flow, energy flow, and information flow to the process system, and the driving force of the flow system movement mainly comes from the energy flow provided by the external environment system. In order to make the process system more orderly and achieve the objective of entropy reduction, the external environment system provides energy to the process system, or can be understood as the external environment system, to work on the process system by injecting energy flow, thus, the external environment system generates entropy increase. Because all the heat cannot be transformed into work, the absolute value of the entropy increase of the external environment system is greater than the absolute value of the entropy reduction of the process system. For the whole system, the entropy change is equal to the sum of the entropy change of the system of the process and the external environment, meaning the overall system is in a state of entropy increase. This is the essential feature of the process. If the whole system is in a state of great entropy increase for a long time, then the overall system will gradually enter a state of chaos and disorder, although the flow system is developing in a stable and orderly direction.

In order to allow the process manufacturing industry to continue a steady development, the fundamental development direction of process manufacturing industry should mean that the overall value of the unit entropy increase is greater in the overall system formed by the process system and the external environment system. That is, under the premise of people's material needs, the entropy increment of the overall system is getting smaller and smaller. In this way, the overall system of entropy increase can be maintained within a certain range, and will not see too much entropy in a state of chaotic disorder.

In the continuous development of the process, the improvement of technology, the upgrading of technology, and the influx of information flow can increase the efficiency of thermal conversion into work when the external environment system provides the driving force to the process system, meaning entropy reduction. The price paid (that is, the increase of the entropy of the external environment system) continues to decrease, and the entropy increase of the overall system also decreases. Therefore, the evolution of the process manufacturing industry is inseparable from technological innovation, and cannot be done without more efficient use of information flow.

4 The essential analysis of the process manufacturing industry

4.1 The frame of the essential analysis

In order to conduct a more in-depth analysis of the evolution of the process manufacturing industry, and to propose a future development strategy of the process manufacturing industry, we should start from a much easier and more understandable perspective. Therefore, the key elements in the three flow couples of flow–process, material–energy, and scale–efficiency are selected to make up the the frame of essential analysis (Fig. 2).

"Flow" is the main body of the operation of the process system. Material flow is the core of the operation of the process system. Making raw materials into finished products is the most important function of the process system. The energy flow is the driving force of the process system and promotes the material flow, and physical changes and chemical reactions in the process system. The information flow is the guarantee of the orderly operation of the process system. It ensures that the material flow and the energy flow along the established route in the system and guarantees high efficiency of the process of "three transfers and one reaction."

"Process" can be understood as the "hardware" of the process system. "Process" is a set formed by the nonlinear coupling of unit operations, and the individual unit operations can be regarded as a collection of multiple technologies. Therefore, "process" can be regarded as a collection of multiple physical, chemical, and biological phenomena, at a deeper level, a collection of technologies that control, integrate, and apply technologies that are non-linearly coupled and integrated to create products that meet the needs of humanity (Fig. 3).

In the process system, "flow" and "process" lead each other to make changes and innovations. At the level of "flow," the material flow and the energy flow each follow the basic principle of "three transfers and one reaction." The development of "flow" mainly manifests in continuously improving the efficiency of "three transfers and one reaction" of material flow and energy flow. The improvement of the efficiency of "three transfers and one reaction" relies on the improvement and upgrading of existing technologies and the introduction of new technologies, all of which are a collection of technologies–the elements of "process" having changed. Therefore, the evolution of "process" has provided support for the evolution of "flow." The evolution of "flow" has also resulted in the changing direction in the evolution of the new "process." In the process of continuous interaction between the two, the process system continues to evolve in a more efficient and orderly way.

With the development of the process manufacturing industry, when the focus of people is not limited to the process system itself, and the external environment system has also entered the category of concern, it is necessary to sort out the relationship between the external environment system and the process system.

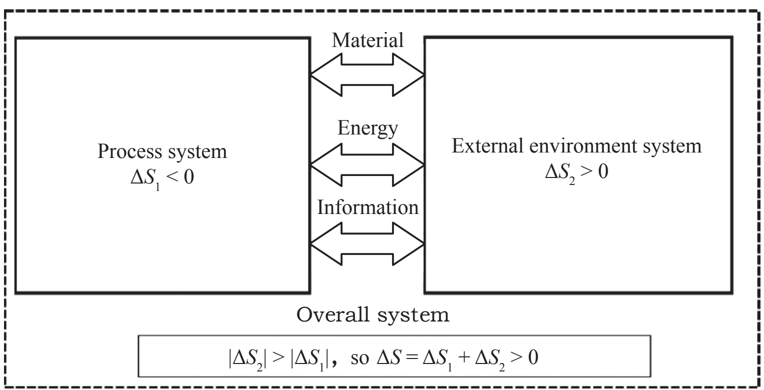

Fig. 2. The essential characteristics of process.

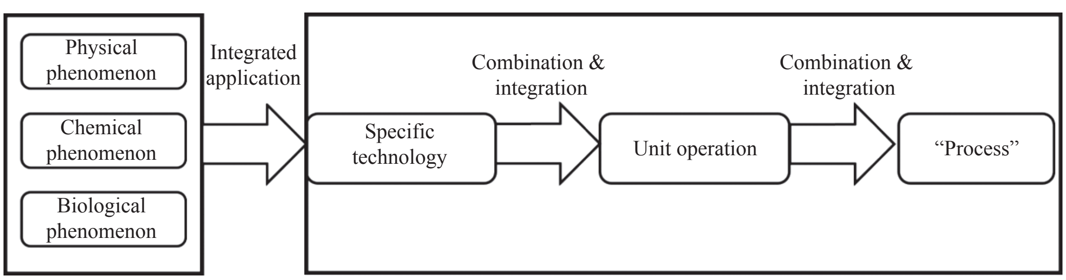

Fig. 3. Conceptual diagram of "process".

Material, energy, and information are closely linked to the external environment system and the process system, and the external environment system and the process system are undergoing the process whereby information is continuously communicated between the process system and the external environment system, along with the reaction (conversion) process. Most of the material and energy are input from the external environment system into the process system in physical form (such as raw material input, fuel input, etc.), reacted (or converted) in the process system, and then in the form of entities (such as product output, residual heat and pressure, etc.), output from the process system to the external environment. Information mainly acts on the flow system in a non-substantive manner, governing the scope of the unit operations or technologies involved in the "process" collection, as well as the manner in which the technical or unit operations are coupled together (Fig. 4).

As people gradually begins to measure the pros and cons of development from the perspective of the overall system entropy change, in order to reduce the entropy increment of the whole system, it is necessary to increase the transfer and conversion efficiency of material flow, energy flow, and information flow between the external environment system and the process system, making the process manufacturing head in a green and intelligent direction.

In the development process of process manufacturing industry, there are two important factors that measure the development status of the process manufacturing industry, namely, "scale" and "efficiency."

"Scale" refers to the volume of the process system. For example, people are familiar with the gross output value, total resource consumption, total discharge of pollutants, total inventory of pollutants, and other indicators of the total amount, which can be used to characterize the scale. The expansion of the scale of the process system will bring a scale effect, which will improve the efficiency and increase the profit to a certain extent. However, when the scale expands to a certain volume, the continued expansion of the scale may cause the supply of resources to reach the upper limit, resulting in the shortage of resources or an environmental impact that is greater than the flow system external environment system carrying capacity.

"Efficiency" includes resource efficiency, energy efficiency, environmental efficiency, etc. For example, people are familiar with a variety of intensity indicators of resource productivity, such as energy consumption per million GDP. Processes are always moving in the direction of increasing efficiency, but at different stages of development, the focus shifts to different types of efficiency. In the initial stage, people pay more attention to the economic benefits (such as gross output value and total profit) of the process system. With the increase of resources and environmental pressure, people gradually begin to pursue higher resource efficiency and environment effectiveness under the circumstance of ensuring economic benefits.

These three key factors can be combined with the timeline to build an essential analytical framework to clearly sort out the evolution of the process manufacturing industry, providing a reference for development in the process manufacturing industry.

4.2 Analysis of the historical development of the chemical industry

The chemical industry is a typical process manufacturing industry. The general characteristics of the process manufacturing industry are obviously reflected in the chemical industry. This article analyzes the historical development of the chemical industry and examines the essential characteristics of the process over a long time span.

The development of the chemical industry can be divided into three periods: the seed stage, the budding stage, and the great development period.

In the seed stage of chemical industry development (before the eighteenth century), typical chemical processes would include sunning, brewing, and smelting. In the seed stage, the "process" of the chemical process system was relatively simple, the number of processes was small, and the process structure was simple and chain-like. At the same time, people's understanding of technology was not profound, and they mainly depended on

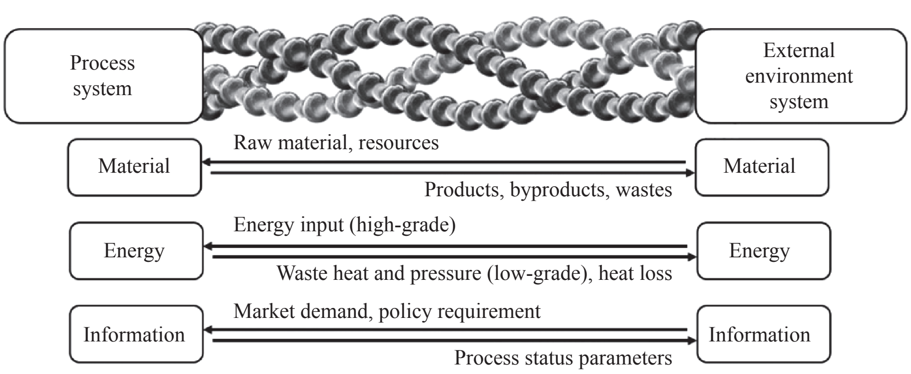

Fig. 4. Interactions between the process system and the external environment system.

experience to support the operation of the process system. At the level of “flow,” there were fewer types of material flow in and out of the flow system, and the resulting products were more singular. Energy flow was dominated by biomass energy and solar energy. Information flow was mainly the practical experience that people got from the flow system. Summary analysis would be performed and then applied to the process system. Due to the limitations of external factors, such as technical conditions and economic development at that time, it was difficult for the process system to reach a certain scale. Therefore, most of the seed flow systems were on a smaller scale or could be called “family-owned workshop” scale. Also, due to technical constraints, both resource efficiency and energy efficiency were low. However, due to the small scale, the environmental impact was very small (i.e., the entropy increase of the external environment system was small), and the environmental efficiency was at a moderate level.

In the infancy of the chemical industry (from the late 18th to the 19th century), typical chemical processes included sulfuric acid, hydrochloric acid, organic dyes, and synthetic polymer materials. In the budding period, the complexity of “process” gradually increased. The structure of the process was no longer straightforward. The concept of unit operation had been established. People were beginning to recognize the importance of technological innovation in enhancing process efficiency and promoting the development of process manufacturing. At the level of “flow”, the types of material flow in and out of the flow system increased, the main products and the by-products were obtained at the same time; the energy flow was dominated by fossil fuels; the flow of information inputted new technology and market demand into the flow system, so that the process evolved. With the improvement of the level of social and economic development and the continuous improvement of technology, the scale of the process system in the budding period expanded and a large number of chemical plants emerged. The expansion of scale brought about economic benefits. Technological innovations increased resources and energy efficiency. However, since people were still not aware of resource, energy, and environmental problems, resource efficiency and energy efficiency were still at medium levels, the scale of environmental impact increased, and environmental efficiency was at a low level.

By the early 20th century, the chemical industry entered a period of great development. The level of “process” rapidly developed with the rapid development of technology to promote the evolution of the process, and the industry chain continued to extend through the coupling of co-production and other ways to mesh development. At the level of “flow,” the amount of material flow in and out of the system was large, with a great variety of diversified products. The energy flow was dominated by fossil fuels. In recent years, in order to deal with the supply of fossil fuels, new energies, such as solar energy and biomass energy have also emerged. The flow system inputs new energy flow; the volume of information flow exponentially increases with the development of automation and informatization, and people have evolved the flow system to be more stable and orderly through the efficient use of information flow. The scale of the process system in the great development period saw financial support brought on by the advancement of technology and there was marked improvement in the economic level. Many large-scale and even world-class enterprises emerged, such as the ultra-large-scale refining and chemical base. The leap in scale led to a substantial increase in economic benefits. Resource efficiency and energy efficiency further increased with the development of related technologies. However, the larger scale also meant greater environmental impact and the environmental efficiency was not greatly improved and there remains room for improvement.

After the chemical industry’s historical development process has been clearly and qualitatively sorted out, three key sets of essential analytical frameworks can be used to perform an essential analysis of the evolution of the chemical industry. The result is shown in Table 1.

At the “process” level, technology continues to develop, with the continued optimization and upgrading of existing technolo-

Table 1. Essential analysis of the evolution of the chemical industry.

Key factor		Seed stage	Germination stage	Rapid development stage
Process	Technological advancement	*	***	****
	Process structural complexity	*	**	****
Flow	Efficiency of "three-trans-one-react"	*	***	****
	Utilization of information	*	**	***
Scale	Process scale	*	**	****
	Overall economic benefits	*	**	****
	Environmental impact	*	***	****
Efficiency	Resource efficiency	*	**	***
	Energy efficiency	*	**	***
	Environmental efficiency	**	*	**

Note:*denotes different levels.

gy, but new technology is also joining the process system, and the process system is also becoming structurally more complex, while the industrial chain gradually extends, and a number of industrial chains couple to form the industrial chain network.

At the level of "flow," technological change increases the efficiency in material flow and energy flow in the process of "three transfers and one reaction." The information flow is based on the application of related technologies in the chemical industry. The basics are unutilized and gradually developed to play an important role in the regulation and control of the process system, and the information flow undergoes leaping changes from both the utilization volume and efficiency.

At the "scale" level, thanks to the evolution of technology and the continuous development at the overall social and economic levels, the scale of the process system is continuously expanding and the economic benefits of its creation are constantly increasing. With the expansion of scale and the flow system, the environmental impact is also on the rise.

At the "efficiency" level, the optimization and upgrading of technologies have resulted in the continuous improvement of resource efficiency and energy efficiency. In the period from the seed stage to the budding stage, environmental efficiency has sprouted due to the neglect of the environmental impact and the substantial expansion of the scale of the process system period to a very low level. In the great development period, as people gradually pay attention to the environmental impact and the process technology continues to be cleaner and greener, the environmental efficiency of the process system can be greatly improved, but there is still a large room for improvement.

From the evolution of the chemical industry, it can be seen that the fundamental driving force for the evolution of the process is the development and innovation of technology. Innovation promotes the continuous evolution of the process, the gradual expansion of its scale, the continuous improvement of efficiency, and the steady and orderly entropy reduction. At this stage, people have begun to pursue the overall system with smaller increments of entropy to pursue higher resource efficiency and environmental efficiency, as well as more reasonable and efficient use of information flow. These important requirements are satisfied by the future development of the process manufacturing industry.

5 Evolution analysis of the phosphorus chemical industry

The chemical industry contains a large number of sub-sectors. In this study, the phosphorus chemical industry was specifically selected for its essential analysis. The phosphorus chemical industry is a typical chemical industry, it is central to the development of industry and agriculture. With the economic development of China and the rapid growth of industrial and agricultural demand for phosphorus chemical products, the sharp and prominent problem of a shortage of phosphorus resources has become one of the bottlenecks in the development of China's phosphorus chemical industry. With the population growth, urbanization, and phosphate rock depletion in China, the reserves of phosphate rock can only last for a few decades. The phosphorus chemical industry has far-reaching strategic significance as a typical resource-based chemical industry, which can be studied to show how to make full use of resources, improve resource efficiency, and the external environment system to offer long-term protection to the national economy.

Phosphorus in nature mainly exists in the form of phosphate minerals, but it is also one of the most important components for life. People are currently mining a large amount of phosphate ore in a rough and inefficient manner to bring the natural elements of phosphorus into the lives of animals and plants, while a large amount of phosphorus is lost to the soil and water and is no longer used. The phosphorus chemical industry has gradually led to the problem of scarce resources.

The phosphorus chemical industry faces scarce resources, but also bears the enormous pressure caused by overcapacity. Due to the repeated construction of low-level phosphate fertilizer products in China, the concentrated capacity release has caused serious overcapacity.

In regards to the application of phosphate fertilizer, soil compaction caused by excessive fertilization directly threatens soil environmental safety. Unreasonable application leads to a low fertilizer utilization rate. Excess nutrient components in the soil are washed away by rain and concentrated in natural water, resulting in eutrophication of water bodies; a large amount of phosphogypsum is produced during production in the phosphorus chemical industry, and a large amount of concentrated phosphogypsum poses a serious threat to the environment.

Wet-process phosphoric acid and thermal process phosphoric acid are the two main technical process routes of the phosphorus chemical industry in China. In order to describe the state of the process system more clearly, the process system is divided into the wet process phosphoric acid subsystem and the thermal process phosphoric acid subsystem. In terms of time, the evolution process of the phosphorus chemical process system is divided into the primary resource processing stage, large-scale whole-process production stage, and the cross-industry cycle linking stage. There are three stages in the process of the phosphorus chemical process system. Resource efficiency, energy efficiency, and environmental efficiency were calculated and analyzed.

First of all, we look at the phosphorus chemical industry "flow" and "process" level analysis. In terms of the primary resource processing stage, the development of the phosphorus chemical industry is in its infancy. At the "process" level, the process structure is relatively simple. The main production processes include phosphoric acid leaching from sulfuric acid leaching, phosphoric acid, ammonia synthesis, and stone yellow phosphorus. At the "flow" level, the material flowing to the input process system is primarily phosphate rock, sulfuric acid, ammonia, water, coal, and silica. The material flows output from the process system include an annual output of 6×10^4 tons of ammonium phosphate, 2×10^3 tons of yellow phosphorus, and phosphorus gypsum, phosphorus slag, iron phosphate, phosphorus, and other solid waste, as well as electric furnace exhaust and dust (Fig.5). The total energy input for the process system is 4,097 tons of standard coal per year.

Regarding the scale of the whole process of the production stage, in the "process" level, the process structure did not change significantly, the process technology underwent upgrading and innovation, and people have begun to understand the thermal method of phosphoric acid technology, and the high energy consumption disadvantage resulting from the phosphorus chemical industry's gradual move away from the heat of phosphoric acid. With regards to the dominant development of the thermal method and its wet coexistence, at the "flow" level, due to the expansion of the process system, the input and output of material flow and energy fluid greatly increased compared to the first stage, the output of ammonium phosphate reached 1.5×10^5 tons / year, the output of yellow phosphorus reached 5×10^3 tons / year, but at the same time, a large amount of solid waste, such as phosphogypsum and phosphorus slag were produced, and the production of solid waste was much larger than that of the product. A large amount of solid waste brought a series of environmental problems, and the development of the formation of constraints.

In the cross-industry cycle stage, at the "process" level, compared to the first two stages, the process structure has undergone major changes, in order to absorb waste and reduce environmental constraints from the phosphorus chemical process system of the salt chemical industry and building materials industry. The construction of industrial recycling links utilizes phosphogypsum and phosphorus slag resources. In the wet process, phosphogypsum and salt chemical industry waste salt gypsum are used as raw materials, adding materials (such as coke, bauxite, etc.) to produce cement and sulfuric acid; phosphorus residue in the thermal system is used as raw materials for the building materials industry, adding auxiliary materials (such as quartz, dolomite, etc.) for the production of glass and artificial wollastonite. At the "flow" level, as the "process" changes, the material flows to and from the inputs also change, the constraints imposed by solid waste are weakened and the size of the process system is further expanded. The major products, ammonium phosphate production reached 3×10^5 tons / year, yellow phosphorus production reached 7×10^3 tons / year (Fig.6), the and input flow system energy is as high as 15,780 tons of standard coal / year. The comparison in scale level is shown in Table 2.

The scale of the process system is gradually expanding in these three stages. This trend can be reflected in the changes of product output, resource consumption, energy consumption, and output value. In the second stage to the third stage, product output rose sharply, significantly reducing the amount of waste generated, because industrial recycling links are formed among the phosphorus chemical industry, the salt chemical industry, and the building material industry in the third stage, and the bulk of phosphorus chemical wastes–phosphogypsum and phosphorus residues were used as resources in the production of cement, glass, and artificial wollastonite, resulting in increased product categories, product output increases, reduction in the amount of waste generated, and a substantial increase in output value.

An analysis of "efficiency" levels requires there to be a clear definition of indicators that measure resource efficiency, energy efficiency, and environmental efficiency. The definition of efficiency index is shown in Table 3.

The comparison of efficiency levels is shown in Table 4. It can be seen that the resource efficiency, energy efficiency, and environmental efficiency of the phosphorus chemical process system are slightly increased from the first stage to the second stage, mainly due to the scale effect and technological upgrading caused by the scale expansion. From the second stage to the third stage, resource efficiency, energy efficiency, and environmental efficiency both rose sharply. As for the cross-sectoral recycling linkages, the wet-process phosphoric acid subsystem salt chemical industry establishes an industrial recycling link

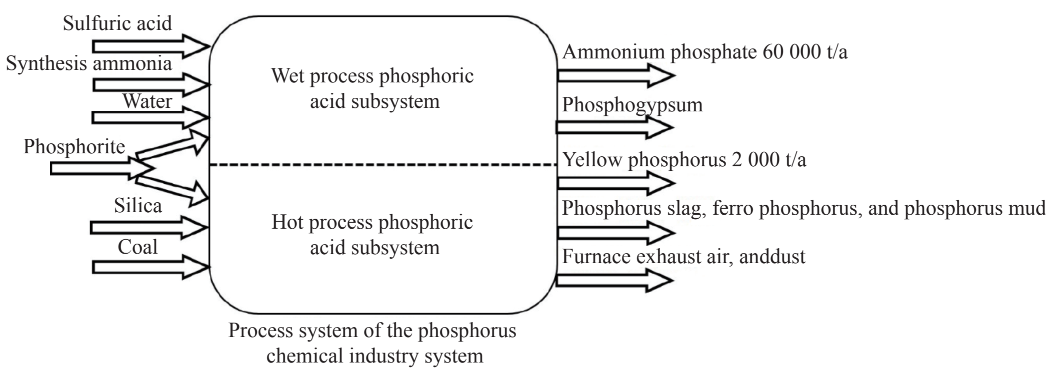

Fig. 5. Process system of the phosphorus chemical industry (primary stage).

and uses phosphogypsum as a raw material for sulfuric acid and cement production, reducing the amount of waste generated, while at the same time, the production of sulfuric acid is used for the wet-process phosphoric acid production process, reducing resource consumption, and the production of a large number of cement products increases the output and wet system output.

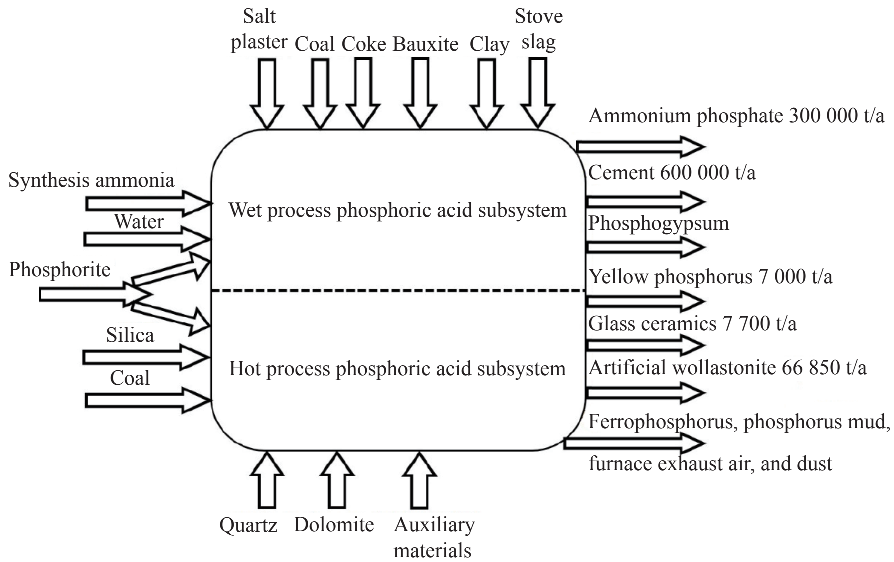

Fig. 6. Process system of the phosphorous chemical industry (cross-industry cycling link stage).

Table 2. Comparison in scale levels of three stages.

Scale	Stage 1	Stage 2	Stage 3
Products (tons)	62 000	155 000	981 550
Waste (tons)	190 998	443 955	375 230
Resource consumption (tons)	369 349	705 660	1 482 270
Water consumption (tons)	184 445	372 400	649 850
Energy consumption (tce)	4 097	9 618	15 780
Output value ($\times 10^4$ yuan)	14 900	37 250	95 161

Table 3. Definition of efficiency index.

Type	Index	Calculation method
Resource efficiency	Resource utilization	Product yield / resource consumption
	Unit output resource consumption	Resource consumption / 10000 yuan output value
	Unit output water consumption	Water consumption / 10000 yuan output value
Energy efficiency	Unit output energy consumption	Energy consumption / 10000 yuan output value
	Energy consumption per ton	Energy consumption / product yield
Environmental efficiency	Unit output waste generated	Amount of waste generated / 10000 yuan output value

Table 4. Comparison of efficiency levels of three stages.

Type		Stage 1	Stage 2	Stage 3
Resource efficiency	Resource utilization	17%	22%	66%
	Unit output resource consumption	24.8	18.9	15.6
	Unit output water consumption	12.4	10.0	6.8
Energy efficiency	Unit output energy consumption	0.27	0.26	0.17
	Energy consumption per ton	0.066	0.062	0.016
Environmental efficiency	Unit output waste generated	12.82	11.92	3.94

For the thermal method phosphoric acid subsystem and building materials industry, the establishment of industrial recycling links, the use of phosphorus slag production of glass and artificial wollastonite, reduced the amount of waste generated, with the production of products creating considerable output. Through the resource utilization of solid waste at this stage, the process system drastically reduced the amount of waste generated and the output and output value of products, so that resource efficiency, energy efficiency, and environmental efficiency could be greatly enhanced.

The improvement of efficiency relies on the establishment of industrial recycling links, and the establishment of industrial recycling links requires the mature application of relevant technological processes in the process system. The "process" in the process system is a collection of technologies, and the changes in the elements contained in the collection drive the evolution of the process. Changes to existing elements of the collection (that is, technological improvements and upgrades) can make the process slightly more efficient, and adding new elements to the collection (that is, introducing new technology into the process system) can make the process much more efficient.

6 Conclusions

The process can be regarded as a complex system composed of nonlinear couplings of different unit operations. The material flow, energy flow, and information flow enter the process system from the external environment system, and then transform in the process system to act on the external environment system. The process system is a dissipative system, which is entrusted to a more stable and orderly direction through the injection of energy flow and information flow. At the same time, the external environment system must bear the cost of entropy increase, and the increment of entropy is greater than the entropy reduction, so the overall system is an entropy increase. The basic direction of the process manufacturing industry is to cause the gradual reduction of the entropy increase of the overall system. The overall system can run steadily. Instead of focusing on the entropy reduction of the process system itself, the entropy increase of the external environment system should be neglected.

Through the historical development of the chemical industry and the essential analysis of the evolution of the case of the phosphorus chemical industry, it can be seen that the process manufacturing industry needs to develop in a direction of smaller entropy of the overall system, instead of merely focusing on expanding the scale and increasing economic benefits. The improvement and upgrading of technology can slightly improve the efficiency of the process system. However, disruptive and innovative technologies may significantly improve the efficiency of the process system, thereby drastically reducing the entropy increase of the overall system and enabling the overall system to operate in a stable and orderly manner.

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