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Review

Generalized Thermodynamic Optimization for Iron and Steel Production Processes: Theoretical Exploration and Application Cases

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Abstract: Combining modern thermodynamics theory branches, including finite time thermodynamics or entropy generation minimization, constructal theory and entransy theory, with metallurgical process engineering, this paper provides a new exploration on generalized thermodynamic optimization theory for iron and steel production processes. The theoretical core is to thermodynamically optimize performances of elemental packages, working procedure modules, functional subsystems, and whole process of iron and steel production processes with real finite-resource and/or finite-size constraints with various irreversibilities toward saving energy, decreasing consumption, reducing emission and increasing yield, and to achieve the comprehensive coordination among the material flow, energy flow and environment of the hierarchical process systems. A series of application cases of the theory are reviewed. It can provide a new angle of view for the iron and steel production processes from thermodynamics, and can also provide some guidelines for other process industries.

Keywords: generalized thermodynamic optimization; iron and steel production processes; finite time thermodynamics; constructal theory; entransy theory; metallurgical process engineering

1. Introduction

The iron and steel industry is one of the important pillar industries for China, and its development status has evident influence on the national economy. However, high energy consumption, high resource consumption and high pollution are the characteristics of this industry. The pressures coming from the energy, resources and environment are continuously increasing, and the challenges of saving energy and reducing emissions are huge [1,2].

Various theories and methods have been introduced to realize energy savings and emission reduction, and metallurgical process engineering (MPE) [3–5] and modern thermodynamics [6] play the important roles among them. In the 1950s, investigations of metallurgical processes mainly focused on the transfers of heat, mass and momentum and reactor engineering. Their research objects were small or even micro scale, rather than the whole metallurgical process. MPE can be used to investigate the complex problems of the whole metallurgical process. With the help of MPE, one can easily investigate the physical essences, structures and overall behaviors of the iron and steel production process (ISPP) at macroscopic level. For examples, based on MPE, the incoordination problems between procedures of the ISPP can be solved, and the global optimization results of the ISPP can be obtained, rather than the local optimization results of the procedures. Three representative theories of modern thermodynamics are finite time thermodynamics (FTT) [7–14] or entropy generation minimization (EGM) [15–17], constructal theory [18–23] and entransy theory [24–

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27]. There are many irreversible processes in the ISPP. Classical thermodynamics cannot faithfully describe these processes, such as the finite heat transfer rate between waste gas and steam in waste heat boiler, the time factor of the heat releasing process in waste heat recovery gas turbine, etc. The introduction of FTT mainly helps to describe the irreversibilities caused by heat transfer, fluid flow and mass transfer in thermodynamic systems of ISPP. The corresponding models based on FTT are closer to practical ones of ISPP. Moreover, based on FTT and generalized thermodynamics [28], the generalized thermodynamic optimization was proposed by Chen et al. [8,10,29]. Compared with FTT, this optimization procedure is more generalized; therefore, the applications of generalized thermodynamic optimization into the optimizations of ISPP are also necessary. Both entropy generation and entransy dissipation can be used to calculate the irreversibilities in various thermodynamic systems and transfer processes. Entropy generation emphasizes the loss reduction of doing work ability, and entransy dissipation emphasizes the optimization of heat transfer ability. There exist various work and heat transfer processes in the ISPP, therefore, the applications of FTT and entransy theory to these processes are urgent. The current process structures in the ISPP are not well organized. Constructal theory has provided important guidelines for the structure designs of various transfer systems in nature and engineering. It is believed that the applications of constructal theory to the structure design of ISPP are meaningful. It is to be emphasized that FTT and constructal theory are two different optimization methods, and their optimization variables are thermodynamic parameters and internal and external structures, respectively. In entransy and exergy analyses, the optimization objectives can be entransy dissipation and exergy output, respectively. Different design guidelines of the ISPP can be provided if the optimization results obtained based on the two optimization objectives are different. Therefore, one can carry out performance optimization of the ISPP based on different optimization methods and specified optimization objective simultaneously.

In this review, the emergences and developments of FTT or EGM, generalized thermodynamic optimization, constructal theory, entransy theory and MPE will be reviewed in Sections 2 to 6, respectively. Generalized thermodynamic optimization theory for ISPP and its applications will be reviewed in Section 7, which is the major body of this review. There are four parts in this section. Combining modern thermodynamics theory and MPE, a generalized thermodynamic optimization theory for ISPP will be proposed in Section 7.1. Section 7.2 will introduce the generalized thermodynamic optimizations for elemental and working procedure modules of ISPP. The blast furnace iron-making, converter steel-making, slab continuous casting and laminar cooling elemental packages as well as coking, sintering, iron-making, steel-making, continuous casting and rolling procedures will be taken as the research objects, respectively. Constructal theory, entransy theory and FTT will be applied into the optimizations of these elemental packages and procedures. Section 7.3 will introduce the generalized thermodynamic optimizations for functional subsystems of ISPP. The residual energy and heat will be recovered by absorption refrigerator, waste heat boiler, tubular thermochemical reactor, gas turbine power plant, solid-gas reactor and thermoelectric device, respectively. FTT, constructal theory and entransy theory will be applied into the optimizations of these subsystems. Section 7.4 will introduce the generalized thermodynamic optimizations for sections and whole process of ISPP. The sintering and iron-making section, blast furnace-continuous casting section and whole process of ISPP will be taken as the research objects, respectively. MPE, FTT and constructal theory will be applied into the optimizations of the sections and ISPP. The applications of generalized thermodynamic optimization theory into the optimal designs of ISPP provide new angle of view for the ISPP from thermodynamics.

2. Emergence and Development of the Finite Time Thermodynamics

In 1824, the French engineer Carnot [30], obtained the efficiency of the heat engine between the high- and low-temperature heat reservoirs (T_H and T_L):

$$\eta_C = 1 - T_L / T_H \tag{1}$$

This equation gives the upper limit of the heat engine's efficiency between two heat reservoirs. It also laid the theoretical foundation for second law of thermodynamics, and provided the direction of efficiency improvement for various thermodynamic cycles. However, Carnot efficiency of the heat engine was obtained based on completely reversible conditions, which required an infinite heat transfer time, and the corresponding power output of the heat engine was zero. Therefore, this result could not provide good guidelines for real thermodynamic cycles.

To solve the problem of zero power output, a finite heat exchange rate between the hot and cold fluids was considered by the many scholars. In 1929, Reitlinger [31] firstly considered temperature differences between hot and cold streams, and derived the efficiency at maximum power of a heat engine as follow:

$$\eta_0 = \frac{\sqrt{T_1} - \sqrt{T_2}}{\sqrt{T_1}} \tag{2}$$

where T_1 and T_2 are the hot and cold entrance stream temperatures, respectively. Subsequently, Novikov [32], Chambadal [33] and Curzon and Ahlborn [34] further investigated in depth this problem, and deduced the efficiency at maximum power of an endreversible Carnot heat engine, respectively, as follows:

$$\eta_{CA} = 1 - \sqrt{T_L / T_H} \tag{3}$$

Different from Equation (1), Equation (3) is a new performance limit for a Carnot heat engine, which was obtained with the constraints of finite rate, finite duration and finite-size. It was obtained both by the engineers [32,33] and physical scientists [34]. The corresponding researches about the performance limits and optimizations of various thermodynamic processes and cycles were made great progress. It was named as finite time thermodynamics by Berry et al. in physics, and entropy generation minimization (EGM) by Bejan et al. in engineering. Actually, both of them show good consistency. They are characterized by promoting the development of thermodynamics by combining thermodynamics, heat transfer and fluid mechanics simultaneously. The major purpose is to reduce the irreversibility of the system with the constraints of finite-time and/or finite-size. The performance of the real thermodynamic system with the irreversibilities caused by heat transfer, fluid flow and mass transfer are optimized [10]. This kind of works was named as "finite time thermodynamics" in this review.

The research field of FTT includes various thermodynamic cycles (such as heat engines, refrigerators and heat pumps), various transfer processes (such as fluid flow processes, heat transfer processes, heat exchanger processes, mass transfer processes, chemical reaction processes and time-dependent processes), as well as conventional and unconventional transfer systems (such as quantum thermodynamic systems, micro- and nano-devices, direct energy conversion systems, thermal isolation systems and thermal energy storage systems). Nowadays, the study object of FTT is still being expanded, which promotes the development of FTT.

3. Emergence and Development of the Generalized Thermodynamic Optimization

In the conventional research object of FTT, the temperature and entropy are taken as the driving force and displacement, respectively. Radcenco [28] declared that the processes of conservation and dissipation in the physical systems existing in Nature could be uniformly described by the generalized polytropic processes, i.e., $YX^n = Constant$ ($n > 0$) or $Y = Constant \cdot X^n$, where n, Y and X are the polytropic exponent, generalized driving force and displacement, respectively. Based on this conclusion, the theory of FTT applied in the conventional thermodynamic cycles, processes and systems was extended to the generalized thermodynamic systems. The endreversible model was adopted to emphasize the analyses of the major irreversibilities in the systems, and an optimization theory about the designs and operations of the generalized thermodynamic systems was built. Because all the generalized thermodynamic systems were treated by the uniform idea and method adopted in the thermodynamic systems, this theory was named as "generalized thermodynamic optimization theory" (GTOT) [8,10,29]. GTOT is the new development of FTT, and its research field is also wider than that of FTT. The research field of GTOT includes not only the

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conventional thermodynamic systems, but also more generalized systems, such as the mechanical, electrical, magnetic, chemical, economic and life systems, etc.

4. Emergence and Development of the Constructal Theory

In 1996, Bejan [35] proposed constructal theory [80–98] after deeply analyzing the formation of the city street network. He firstly applied constructal theory to the cooling problem of electronic devices [36], and described the constructal law. It can be stated as [36]: "For a finite-size flow system to persist in time (to live), its configuration must change in time such that it provides easier and easier access to its currents." It also can be simply stated as [20]: "The structures of matters come from their optimal performances."

Constructal theory was proposed based on thermodynamic optimization, which could be defined as the thermodynamics of configuration problems in non-equilibrium systems. Constructal theory provided a theoretical basis for the uniform explanation of various flow structures' formations in Nature, and also provided guidelines for the structure designs of various flow structures in engineering. It can be viewed as a new geometric philosophy. Since constructal theory was proposed, various optimization researches have been carried out based on this theory.

The research contents of constructal theory are abundant, such as natural problems (veins, roots, blood vessels, fluvial landforms, river networks, lightning, ocean currents, cracks), social problems (residential area distributions, civil engineering, peace processes, historical processes, human ages), security and sustainable problems (securities of traffic networks, optimal placements of the waste water with nuclear radiation) and engineering problems (heat and mass transfers, fluid flows, electricity, magnetism, tube networks, economic transports, product platforms), etc. The corresponding discipline fields include thermodynamics, heat transfer, fluid mechanics, engineering mechanics, structural mechanics, electromagnetism, chemical reaction engineering, physical chemistry, sociology, biology, geophysics, economics, etc. Most of the corresponding optimization objectives are single objectives. For engineering problems, the major optimization objectives include maximum temperature difference, maximum pressure difference, minimum thermal resistance, minimum flow resistance, maximum heat flow rate, minimum heat loss rate, maximum power output, maximum field synergy number, minimum entropy generation rate, minimum entransy dissipation rate, etc. Multi-objective optimizations are also introduced. The research scales cover from microcosmic and mesoscopic systems to macroscopic ones, and the research objects are also multi-scale systems. Therefore, multi- disciplinary, multi-objective and multi-scale constructal optimizations are the development tendencies of constructal theory.

5. Emergence and Development of the Entransy Theory

To solve the absence of the basic physical quantity in the heat transfer optimizations, Guo et al. [24] used a new physical quantity, "entransy", to describe the heat transfer ability:

$$E_{vh} = \frac{1}{2} Q_{vh} T \tag{4}$$

where Q_{Vh} is the heat capacity with constant volume and T is the temperature. The entransy dissipation function $\dot{E}_{h\phi}$ can be defined as:

$$\dot{E}_{h\phi} = -\dot{q} \cdot \nabla T = k(\nabla T)^2 \tag{5}$$

where $\dot{q}$, ∇T and k are the heat flux vector, temperature gradient and thermal conductivity, respectively.

The entransy dissipation rate $\dot{E}_{vh\phi}$ of an object can be given as:

$$\dot{E}_{vh\phi} = \int_v \dot{E}_{h\phi} dv = \int_v |\dot{q} \cdot \nabla T| dv \tag{6}$$

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where v the volume of the object. The equivalent thermal resistance of a multi-dimensional heat conduction object can be given as:

$$R_h = \dot{E}_{vh\phi} / \dot{Q}_h^2 \tag{7}$$

The definition of entransy above mainly focuses on heat transfer processes. For diffusion mass transfer process, Chen et al. [37,38] defined the mass entransy dissipation rate per unit volume as:

$$\phi_m = -q_m \cdot \nabla Y = \varrho D |\nabla Y|^2 \tag{8}$$

where q_m, ∇Y, ϱ and D are the mass flow rate, mass fraction gradient of the component, density and diffusive mass transfer coefficient, respectively. Liu et al. [39] further extended the entransy concept to transport process, and defined the mass entransy dissipation rate of a transport process as:

$$\dot{J}_{vm\phi} = \dot{m}^* \Delta \overline{P} \tag{9}$$

where $\dot{m}^*$ is the pure mass flow rate, and $\Delta \overline{P}$ is the average potential difference. Based on the definition in Equation (5), Chen et al. [40] applied it into the constructal optimization of porous medium, and expressed the mass entransy dissipation rate in unit volume of the porous medium as:

$$\dot{J}_{m\phi} = \dot{m}''' \Delta P \tag{10}$$

where $\dot{m}'''$ is the volumetric mass flow rate, and ΔP is the potential difference. The mass entransy dissipation rate in porous medium can be given as:

$$\dot{J}_{vm\phi} = \int_v \dot{J}_{m\phi} dv \tag{11}$$

Cheng et al. [41] further extended the thermal entransy and mass entransy concept to generalized flow process, and defined a series of concepts, such as potential entransy, potential entransy flow and potential entransy dissipation in generalized flow processes.

Based on the definition of entransy dissipation rate, the entransy dissipation extremum principle for heat conduction process was stated as [24]: "For the specified heat flow boundary condition, the heat conduction process reaches its optimal when the entransy dissipation is minimized (minimum average temperature difference); for the specified temperature boundary condition, this process reaches its optimal when the entransy dissipation is maximized (maximum average heat flow)". For the thermal insulation process, mass transfer process and generalized flow process, Feng et al. [42], Chen et al. [37,38] and Cheng et al. [41] further defined entransy dissipation extremum principles for the three processes, respectively.

Entransy theory has been vigorously developed since it was put forward. Lots of scholars have carried out various studies based on entransy theory, such as heat conduction problems, heat convection problems, radiation heat transfer problems, heat exchanger design problems, heat-work conversion problems and constructal design problems, etc. These works illustrate that the research outcomes in the optimizations of various transfer processes and systems based on entransy theory have made great progresses, which enrich the connotation of entransy theory.

6. Emergence and Development of the Metallurgical Process Engineering

At the beginning of 20th century, the research objects of metallurgical process were unit operations. The microcosmic and closed systems were investigated based on chemical reaction, thermodynamics and dynamics. The research purpose was to understand and illustrate the possibilities, rationalities, validities and limitations of the reactions and conversions in various unit operations. At the middle of 20th century, the research objects of metallurgical process were unit procedures and equipment. Medium-scale and open systems were investigated based on energy, mass and momentum transfers and reactor engineering. The research purpose was to optimize the functions and design the structures of the unit procedures and equipment. Traditional investigations

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of the metallurgical engineering mainly focus on the performance improvements of the processes and procedures. Cascade utilizations of waste heat for processes [43], energy-saving theories of waste heat for procedures and process integrations [44] were used in these investigations. Nowadays, the high level, large scale and global structure investigations aimed to the whole metallurgical process are carried out, which forms a new engineering science —metallurgical process engineering (MPE), by Yin et al. [3–5]. MPE is an integration theory aimed at investigating the production process on a large scale. It is the engineering science and technology knowledge about metallurgical production process based on material and energy conversions. Its research objects are the open, non-equilibrium and irreversible complex process systems. The research purpose is to solve the orderliness, compatibility, continuity and compactness of the metallurgical production process.

With the development of MPE, its knowledge system became more and more complex. The research fields of MPE include not only the basic science, technology science and engineering science, but also the corresponding technologies [4]. The research contents of MPE include not only the structures and functions of the unit procedures and equipment, but also those of the whole MPE metallurgical production process. The current MPE studies mainly focus on the efficiency improvements of the material, energy and information flows of the whole process, even optimizations of process time and space. The future extension of MPE is to build an ecological process system, which has the open, circular and easily controlled characteristics. It is believed that the cross-discipline and cross-field investigations in macroscopic scale of the MPE will be further carried out, and the problems about production, environment, ecological coordination and economic rationality of the large and open system about MPE will be solved.

7. Generalized Thermodynamic Optimization Theory for ISPP and Its Applications

An ISPP is an important research object for MPE. ISPPs are an open, far away from equilibrium and irreversible complex process systems. How to carry out optimizations for the complex process systems and which optimization theory is more suitable for the investigations of this system are the hot issues for the scholars and engineers.

7.1. Generalized Thermodynamic Optimization Theory for ISPP

Figure 1 shows the schematic diagram of an ISPP. The whole production process includes the working procedures of coking, sintering, iron-making, steel-making, continuous casting and steel-rolling. It can be seen that the coking and sintering procedures are connected in parallel, and the other procedures are connected in series. Higher energy consumption and higher pollution are two characteristics of the ISPP. An ISPP with lower energy consumption, lower emission and higher yield is chased. Steams and coal gases are generated in several procedures, and they can also be consumed in the other procedures. The surplus energies and waste heats of the flue and waste gases are emitted into the environment. There exist many chances to optimize the structures of the ISPP and the distributions of various resources in the ISPP. The optimizations of ISPP will be more systematically and easily carried out when some advanced theories are introduced.

The authors of this review have being applied the FTT, constructal theory, entransy theory and MPE into the optimizations of ISPP, and provided generalized thermodynamic optimization theory for ISPP [23]. It was stated as [23]: "Combining modern thermodynamics theory branches, including finite time thermodynamics or entropy generation minimization, constructal theory and entransy theory, with metallurgical process engineering, the performances of elemental packages, working procedure modules, functional subsystems, and whole process of the ISPP with various irreversibilities are thermodynamically optimized. The real finite-resource and/or finite-size constraints are considered, and saving energy, decreasing consumption, reducing emission and increasing yield are taken as the major optimization objectives, respectively, to achieve the comprehensive coordination among the material flow, energy flow and environment of the hierarchical process systems." This theory provides a new angle of view for the ISPP from thermodynamics, and its applications on the working procedure modules (including elemental packages), functional subsystems and whole process of the ISPP will be specifically illustrated in the following sections, respectively.

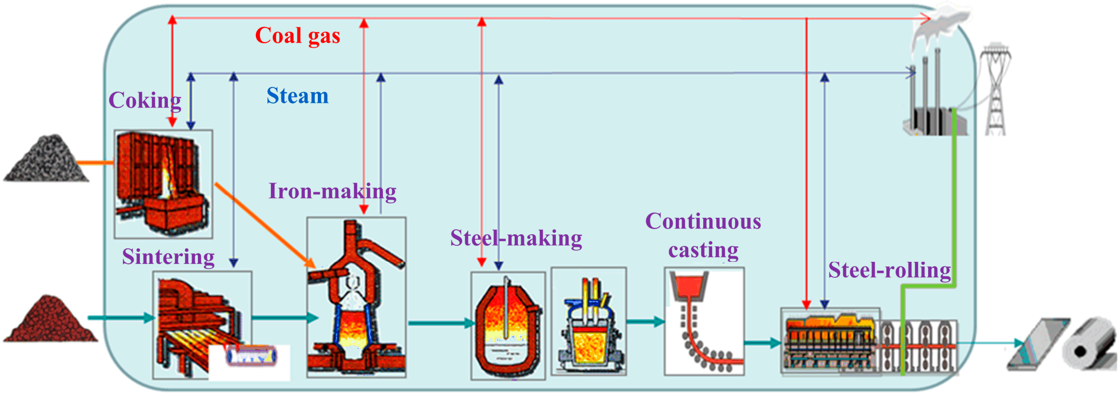

Figure 1. Schematic diagram of iron and steel production process.

7.2. Generalized Thermodynamic Optimizations for Elemental and Working Procedure Modules of ISPP

The ISPP is composed of various elemental packages and working procedure modules, and they have evident influences on the performance of the whole ISPP. It is significant to carry out performance analyses and optimizations of the elemental packages and working procedure modules in ISPP, and generalized thermodynamic optimization is also implemented in these investigations.

7.2.1. Investigations for Coking Procedures

Coking procedures consume about 6% of the energy and discharge 9% of the CO_2 of the whole ISPP, so the energy saving and emission reduction potentials of this procedure are great. Chen et al. [45] analyzed the energy conversion and energy level based on energy conservation and production process energy flow graph, and analyzed various energy consumption and energy efficiency on unit. Xu et al. [46] built a CO_2 emission calculation model based on the practical production data of an iron and steel production enterprise, and the effects of the carbon's import and output on CO_2 emission in coking process were analyzed. Analyses of the energy flow of the coking process (see Figure 2) were conducted, and the energy consumption model and CO_2 emission model of the coking process were built [47], based on universal material and heat balances. Various energy consumption materials (washed coal, blast furnace gas, desalting water, etc.), various products (tar, coarse benzene, coke oven gas, etc.) and the recycling energy consumption (steam) were taken into consideration in the models. The energy consumption per ton of product and the corresponding CO_2 emission of the coking process were calculated. The effects of coke dry quenching and coal moisture control on the energy consumption per ton of product of the coking procedure and the corresponding CO_2 emissions were analyzed (see Figure 3). The results showed that in a practical production process, precisely controlling the technologic parameters, such as the end-state temperature of red coke cooling and the end-state moisture of coal, were of great significance for improving the economic and environmental benefits. Numerical examples showed that the sensible heat from red coke accounts for 47.85% of the total heat output, and energy savings of 34.94 kgce/t could be achieved by power generation using a waste heat boiler. When the moisture content of the coal decreased from 9% to 7%, the amount of CO_2 emissions linearly decreased from 689.00 kg/t to 592.44 kg/t.

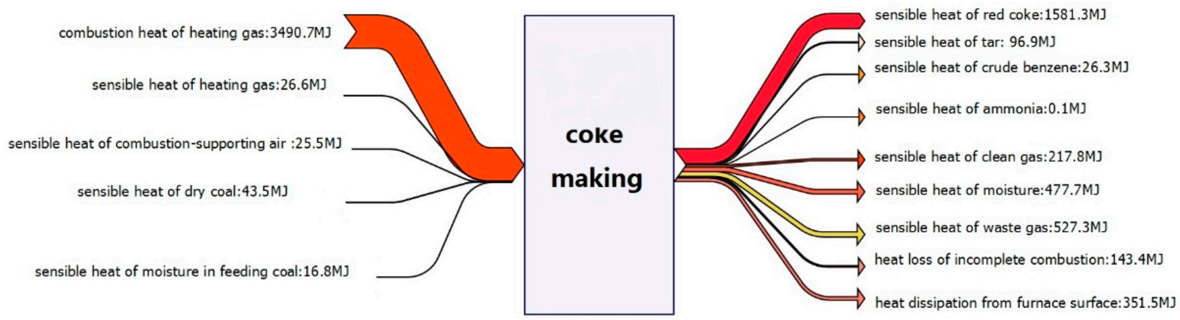

Figure 2. Energy flow of coking procedure.

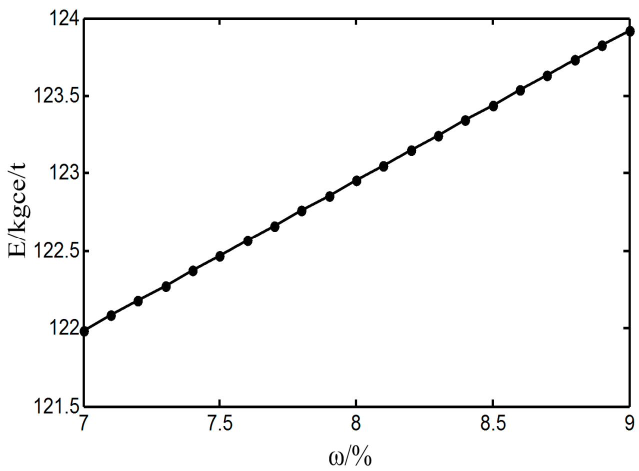

Figure 3. Effect of final moisture content on the energy consumption per ton product.

7.2.2. Investigations of Sintering Procedures

Optimization of Sintering Proportioning

The energy consumption of sintering processes is the second largest in an integrated iron and steel plant and during the past 11 years, China's sinter production has increased by 257%. The proportioning procedure is the source of sintering and it has a great influence on the global energy consumption of the whole sintering process. In most current research on proportioning optimization, the lowest cost or the best quality of sinter has been taken as the optimization objective. Little attention has been paid to the energy contained in iron ore and auxiliary materials in the current models for energy consumption of sintering process.

As shown in Figure 4, on the basis of material and energy balances, a sintering proportioning optimization model was built with system energy saving theory. In the model, the minimum energy value of sinter was taken as an objective [48]. The constraint conditions included the quality requirements of sinter, the consumption constraints of coke and the recovery efficiency of the residual heat and energy. The optimization problem was solved by linear programming with practical data. As shown in Figure 5, the effect of coke on the minimum energy value of sinter was analyzed. The results showed that Chengchao ore, Carajas ore, coke and CaO evidently affected the optimal result. When taking the minimum energy value of sinter as the optimization objective, the energy consumption and CO_2 emission would decrease by 4.92%, but the cost would increase by 6.85%.

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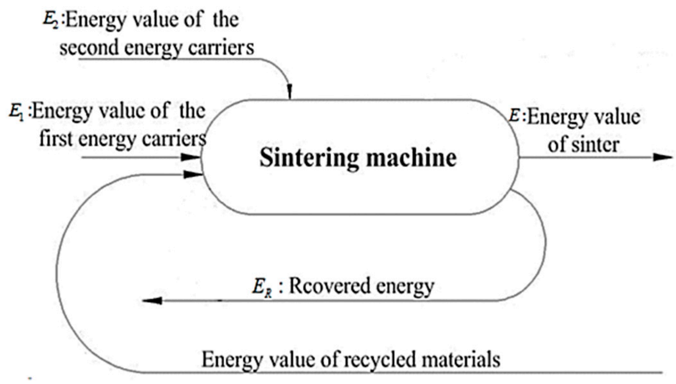

Figure 4. Energy value balance of the sintering process.

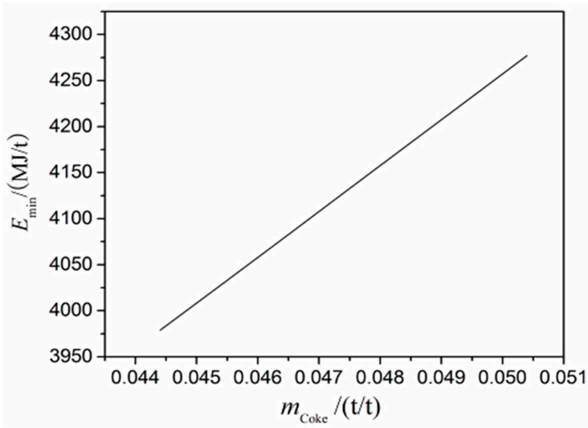

Figure 5. Effect of coke on the minimum energy value of sinter.

Analyses of Heat Transfer in Sinter Cooling Processes

With the developing modern technology approaches, some researchers have conducted numerical simulations of the sinter cooling process. Different dimensional models, including 1-dimensional, 2-dimensional and 3-dimensional ones, heat exchanger model and two energy equations model have been applied to simulate the cross-flow and heat exchange process. As shown in Figure 6 [49], a two-dimensional unsteady model for heat transfer process in annular cooler is established based on the reference coordinate system. Unlike previous researches which only accounted for gas-solid convection, the heat conduction inside the sinter particles and radiation were involved in the model. The equivalent coefficient h_c and heat transfer ratio e were introduced to eliminate the influences of heat conduction and radiation, respectively. A numerical simulation to calculate the distributions of the flow, pressure and temperature fields was conducted, and the effect of heat ratio on the sinter cooling process was analyzed (see Figure 7). The results indicated that the enhancement of heat transfer between the hot sinter ore and cooling air at the first two stages led to an efficient recovery of the residual heat.

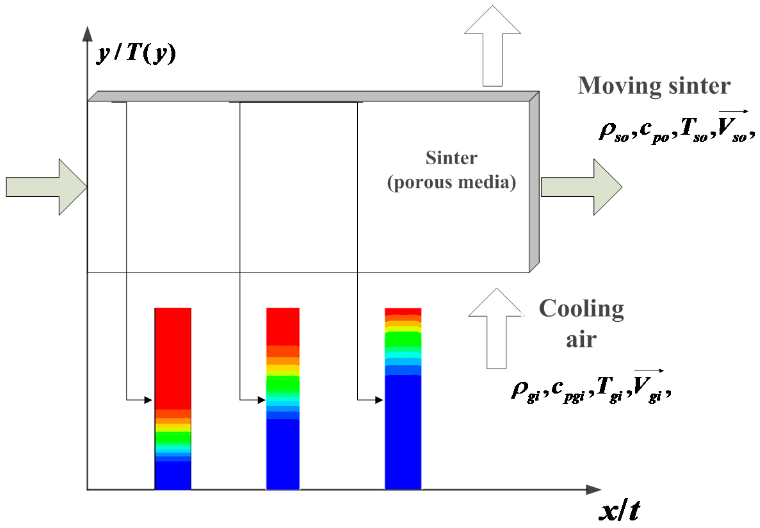

Figure 6. Two-dimensional unsteady model of continuous cooling process of sintered ore.

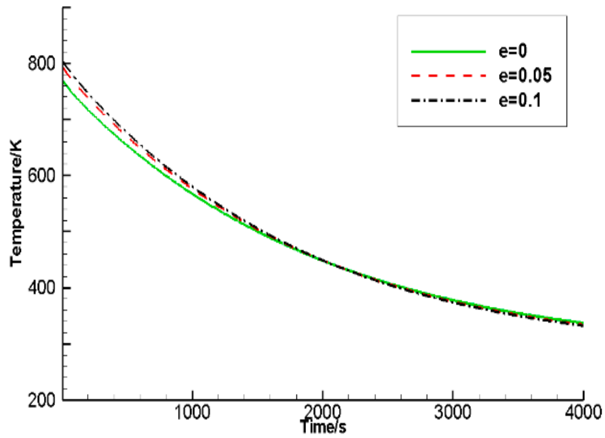

Figure 7. Effect of heat transfer ratio on temperature of waste gas.

Constructal Optimization of Sinter Cooling Processes Based on Exergy Output Maximization

The shape of the sinter layer has an evident influence on the performance of the sinter cooling process. With this situation in mind, a sinter cooling process with variable cross-section of the sinter layer was considered (see Figure 8) [50]. Constructal optimization of this process was performed by taking exhausted gas's exergy output as optimization objective. The volume of the sinter layer was taken as the constraint, and the layer shape was optimized. The optimal construct of sinter layer and maximum exergy output were obtained. The effects of the porosity (see Figure 9), equivalent diameter and air velocity on the optimal constructs were analyzed. The exergy output after optimization was increased by 22.80% compared with that before optimization.

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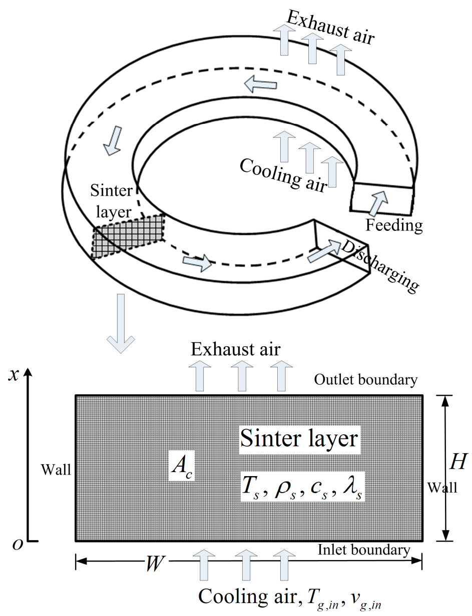

Figure 8. Schematic diagram of sinter cooling process.

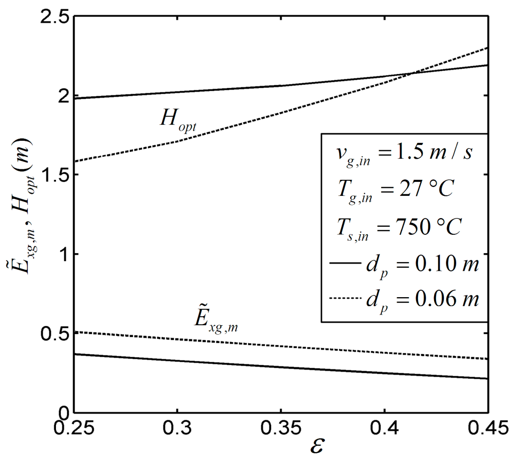

Figure 9. Effect of the porosity on the optimization result.

Field Synergy Analyses of Sinter Cooling Processes in Annular Coolers and Vertical Tanks

As shown in Figure 10 [52], after a comparison between the heat transfer process in annular coolers and vertical tanks, two-dimensional unsteady models for the flow and heat transfer were established. The sinter cooling processes in the annular cooler and vertical tank were considered as continuous cross-flow and counter-flow heat convection processes, respectively. Both cooling systems were viewed as two forms of heat exchangers. Besides convection, the heat conduction inside the sinter particles and radiation were also involved in the calculations. The field synergy theory was introduced to perform analyses and comparisons of the two sinter cooling modes. Because the field synergy number of former was increased by 12.22% and useful residual heat was increased by 134% compared with those of the latter one, the cooling performance in the vertical tank was much better than that in the annular cooler. Moreover, the optimal structure and operation parameters for the vertical tank were proposed by the investigations of effects of major parameters on the performance of the sinter cooling process (see Figure 11).

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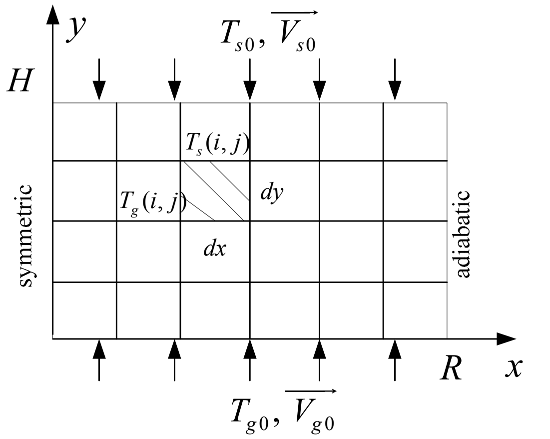

Figure 10. Flow and heat transfer model in vertical tank.

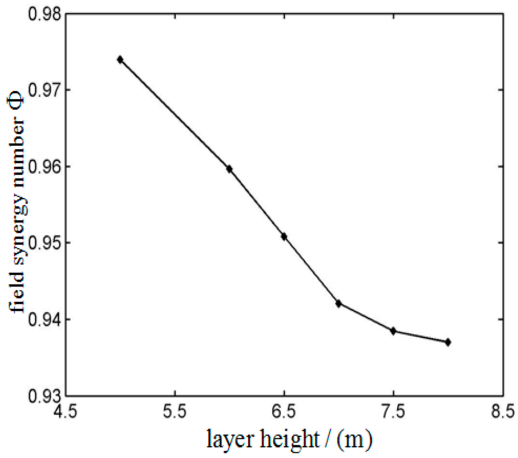

Figure 11. Effects of layer height on the field synergy number.

7.2.3. Investigations of Iron-Making Procedure

Constructal Optimization of Thermal Insulation Processes for Blast Furnace Walls

The shape of the blast furnace wall affects its heat transfer performance, and some scholars have shown great interests in this aspect. As shown in Figure 12 [52], a blast furnace wall with variable cross-sections of the cooling pipes was taken as the research object.

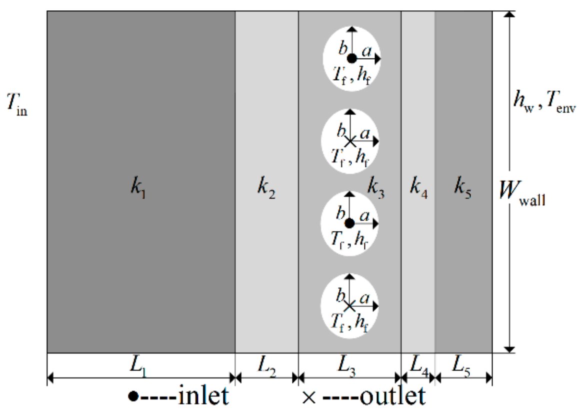

Figure 12. Heat transfer model of a blast furnace wall.

The cross-section of the cooling pipes was taken as the constraint, and the pipe shape was optimized. Constructal design for the cooling pipes of a cooling stave in the blast furnace wall was

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performed by taking entransy dissipation rate minimization as objective. The optimal construct of the cooling pipes was obtained and the entransy dissipation rate was reduced by 2.73%.

Optimizations for Blast Furnace Iron-Making Elemental Packages Based on Nonlinear Programming Methods

Some researchers established some optimization models for blast furnace iron-making elemental packages and working procedures by using linear programming methods [53]. As shown in Figure 13, an optimization model for a blast furnace was established based on nonlinear programming theory [54,55]. This model was based on the material balance and energy balance of a blast furnace iron-making process. Thirty two constraint conditions (mass balance, heat balance of high temperature region, carbon-oxygen balance, slag basicity, coke load and bosh gas index, etc.) and 10 optimization variables (sinter ore ratio, pellet ore ratio, lump ore ratio, coal ratio, coke ratio, blast volume, blast temperature, blast oxygen enrichment, blast humidity, and top gas pressure) were considered in the model, and nine parameters (carbon emissions, energy consumption and exergy loss, etc.) were taken as the optimization objectives. The optimization results were obtained by using the SQP algorithm. The effects of major operating parameters on the optimization results are analyzed [54,55], and the energy flow and exergy flow before and after the optimizations for the coke ratio minimization objective and exergy loss minimization objective were analyzed comparatively [56]. Some guidelines for iron-making production were provided.

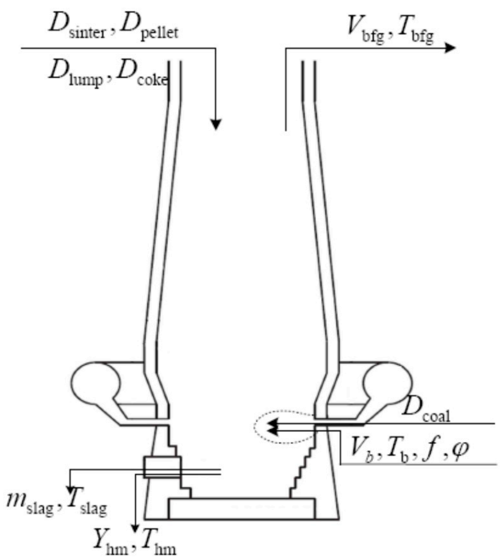

Figure 13. Physical model of blast furnace iron-making elemental package.

Optimizations for Blast Furnace Iron-Making Procedures Based on Nonlinear Programming Methods

As shown in Figure 14, based on the works in [54–56], an optimization model for a blast furnace iron-making procedure including blast furnace, TRT, blower and hot blast stove was established [57,58], and the energy consumption, cost, carbon emissions and exergy loss were taken as optimization objectives, respectively. Similar to the model of blast furnace iron-making elemental package, based on material balance and energy balance, 32 constraint conditions and 10 optimization variables were considered in the model. The effects of major operating parameters on the optimization results were analyzed. The results showed that the energy consumption, carbon emissions, cost and exergy loss were reduced by 3.2%, 5.26%, 9.26% and 16.85%, respectively.

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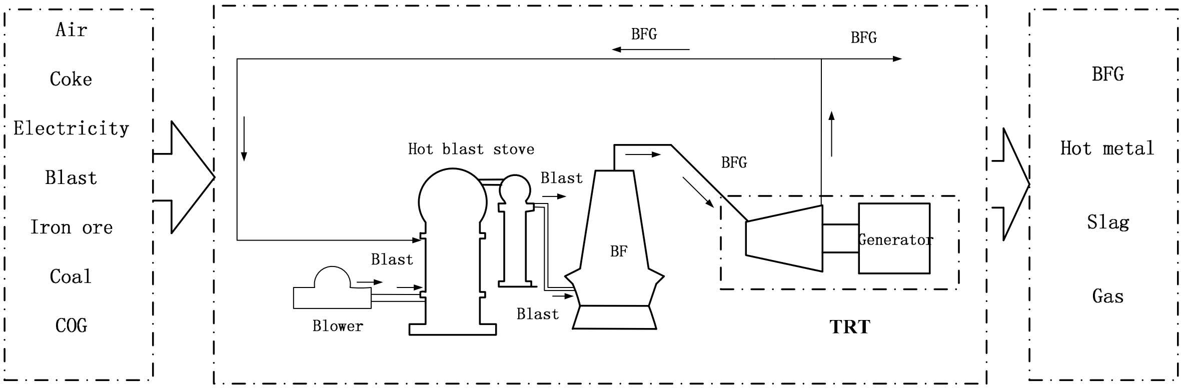

Figure 14. Physical model of blast furnace iron-making procedure.

Generalized Constructal Optimization for a Blast Furnace Iron-Making Elemental Package

Charge composition is an important factor of a blast furnace, and its optimization has become one of hot issues to be investigated. A blast furnace iron-making process considering variable charge composition was taken as research object [59]. For the fixed total raw material cost, generalized constructal optimization for a blast furnace iron-making process was performed by taking the maximum hot metal yield as objective. The optimal cost distribution for the raw materials, namely "generalized optimal construct" was obtained (see Figure 15). The effects of major operating parameters on the optimization results were analyzed. After optimization, the hot metal yield was increased by 2.64%.

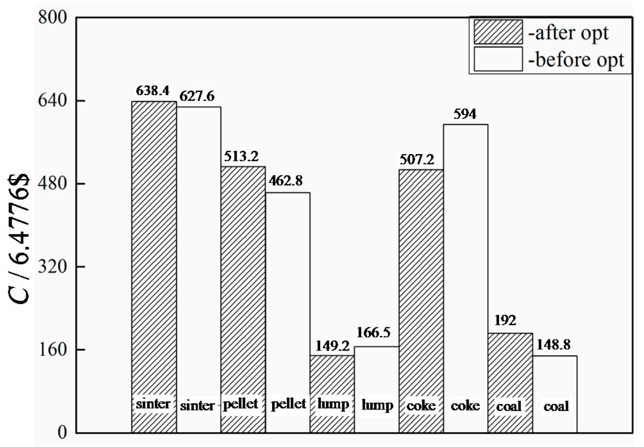

Figure 15. Optimal cost distribution for a blast furnace iron-making process

Generalized Constructal Optimization for a Blast Furnace Iron-Making Procedure

As shown in Figure 16 [60], a blast furnace iron-making procedure was taken as research object. This procedure included the blast furnace, hot blast stoves, blower, top gas recovery turbine, open simple Brayton power plant (OSBPP) and slag heat recovery equipment, etc. The gas recovery turbine was driven by the high pressure of the blast furnace gas (BFG). As shown in Figure 17, BFG is compressed by the gas compressor of the OSBPP first, and then changed into high temperature gas to drive the gas turbine. The waste heat and residual energy are hot metal sensible heat, electric work generated by TRT and OSBPP and the slag heat, which were named as useful energy [60]. The complex function, integrated by hot metal yield and useful energy, was taken as the optimization objective, which compromised the yield and heat and energy recoveries simultaneously. To obtain the maximum complex function, the total raw material cost was taken as the constraint, and the raw material structure of the sinter ore, pellet ore, lump ore, pulverized coal and coke as well as the pressure ratio and relative pressure drop of the OSBPP were optimized. One can see that the raw material structure optimizations meant the introduction of constructal theory, and the parameter

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optimizations of the OSBPP meant the introduction of FTT. Therefore, the combination of constructal theory and FTT was adopted in the work, and general constructal optimization for a blast furnace iron-making procedure was carried out based on these two theories. The optimal cost distribution for the raw materials is obtained with fixed total raw material cost, and the distribution was also called as "generalized optimal construct" (Figure 18). One could see that the optimization was carried out from thermodynamic and economic points of views. The effects of major operating parameters on the optimization results were analyzed. After optimization, the complex function, hot metal yield and useful energy were increased by 3.13%, 2.66% and 2.90%, respectively. These results were obtained by the combination of constructal theory and FTT, and could not be obtained only by constructal theory.

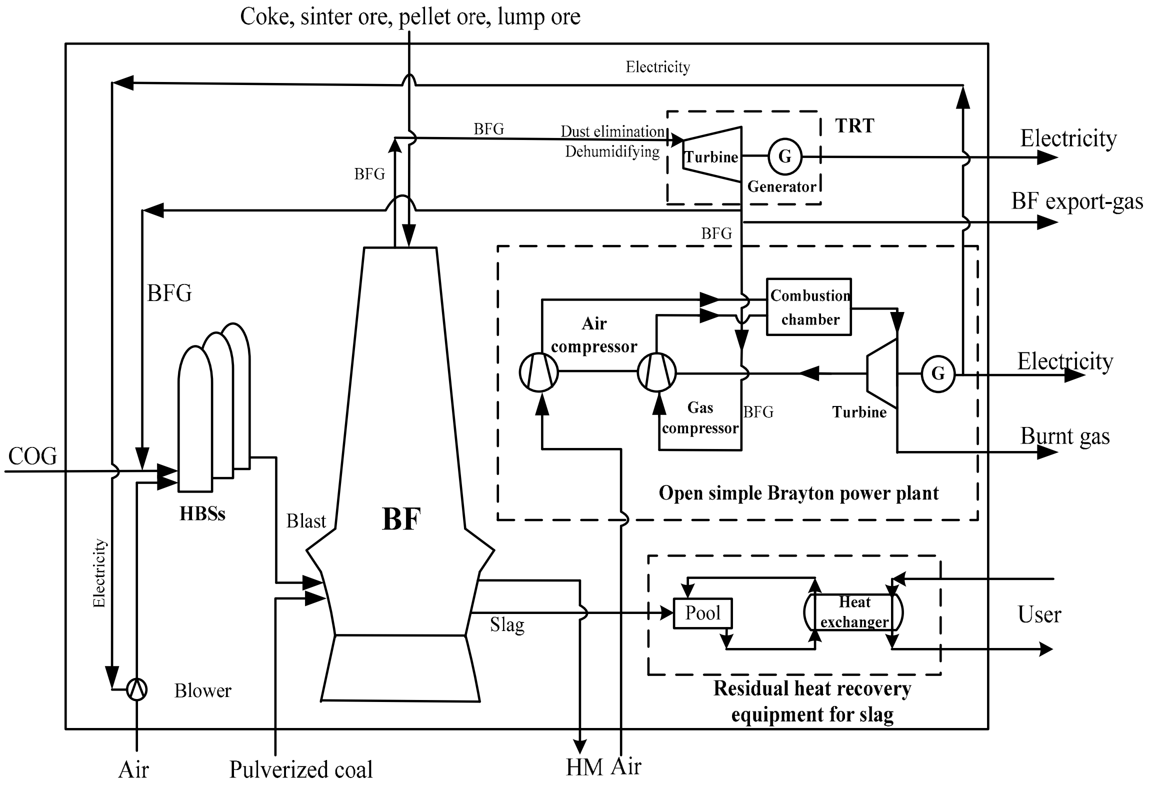

Figure 16. Physical model of blast furnace iron-making procedure.

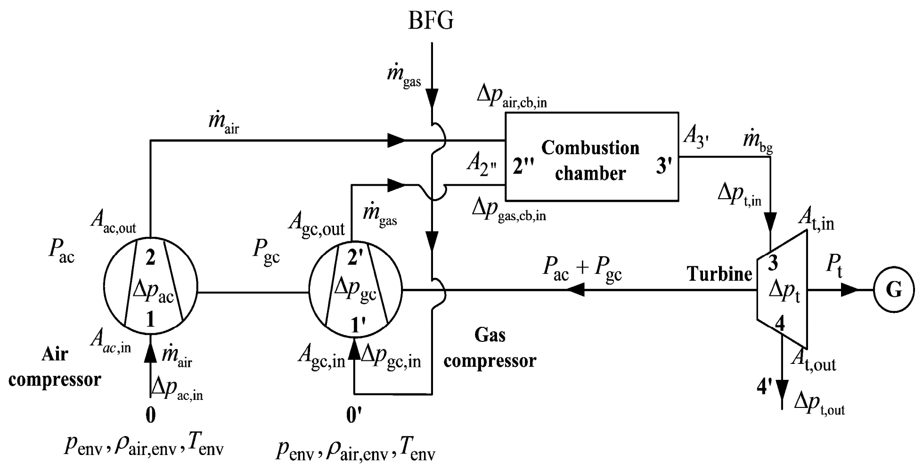

Figure 17. The schematic diagram of the open simple Brayton power plant model.

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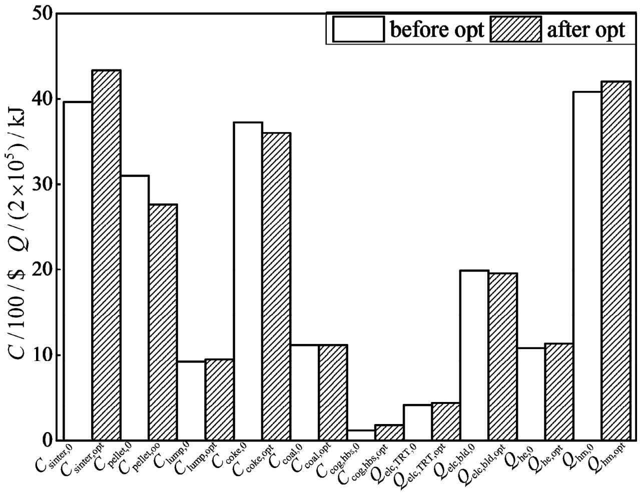

Figure 18. Optimal cost distribution and useful energy distribution.

7.2.4. Steel-Making Procedure Investigations

Generalized Constructal Optimization for a Converter Steel-Making Elemental Package

The optimizations of an steel-making procedure can lead to its metallurgical performance improvement and some other benefits [61–63]. da Costa et al. [61] investigated the CO_2 emissions of a hydrogen steel-making process, and reduced the CO_2 emissions by 80% when the breakthrough hydrogen technology was applied. Lu et al. [62] implemented operation optimization of a converter by experiment programs, and optimized the operation parameters of the steel-making process. Rajashekar et al. [63] used the iron ore slime as the coolant of the steel-making procedure, and obtained the economic and ecological-resource benefits from this innovative practice. Similar to the works in [59], constructal theory was introduced into the optimization for the converter steel-making elemental package [64]. As shown in Figure 19, a converter was taken as research object, generalized constructal optimization for a converter steel-making process was performed by taking the maximum molten steel yield as objective.

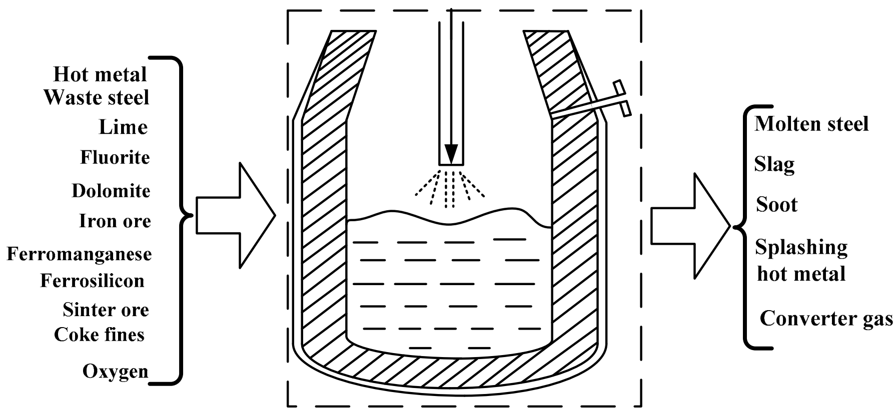

Figure 19. Physical model for a converter steel-making process.

The optimal cost distribution of the materials was obtained with fixed total raw material cost, and was also called as "generalized optimal construct". The molten steel yields were 4748.27 kg and 5008.32 kg before and after optimization, respectively, and the molten steel yield increased by 5.48%. Compared the optimal results with the initial results, less amount of waste steel was used in the coolants. For the fixed total raw material cost, it led to the decrease in the cost of the coolants and the increase in the cost of the hot metal, which finally led to an increase in the molten steel yield. The effects of some parameters on the optimization results were analyzed (see Figure 20). In Figure 20,

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the maximum dimensionless molten steel yields $\tilde{Y}_{steel,ct.max}$ were 0.992 and 1.089 when the Si contents $\omega_{Si,hm}$ were 0.80 and 0.20, respectively. When the Si content in the hot metal decreased, the heat to be absorbed by the coolants also decreased, and less amount of waste steel was used in the coolants. The subsequent reason of the increment in molten steel yield was the same as that of the comparison result above.

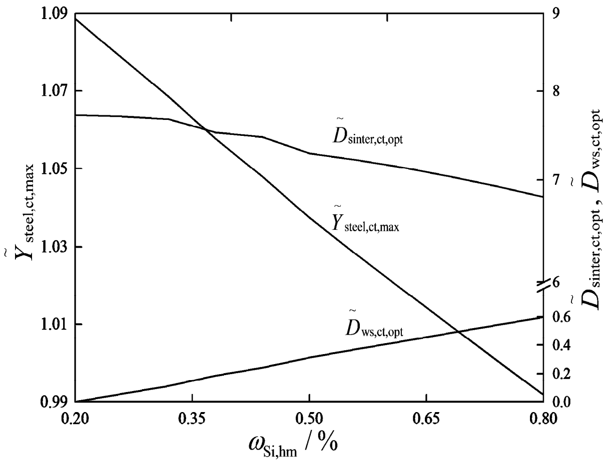

Figure 20. Effect of Si content on the optimal results.

Generalized Constructal Optimization for a Converter Steel-Making Procedure

Similar to the work in [60], constructal theory and finite time thermodynamics were introduced into the optimization for the converter steel-making procedure [65]. As shown in Figure 21, a converter steel-making procedure was taken as research object.

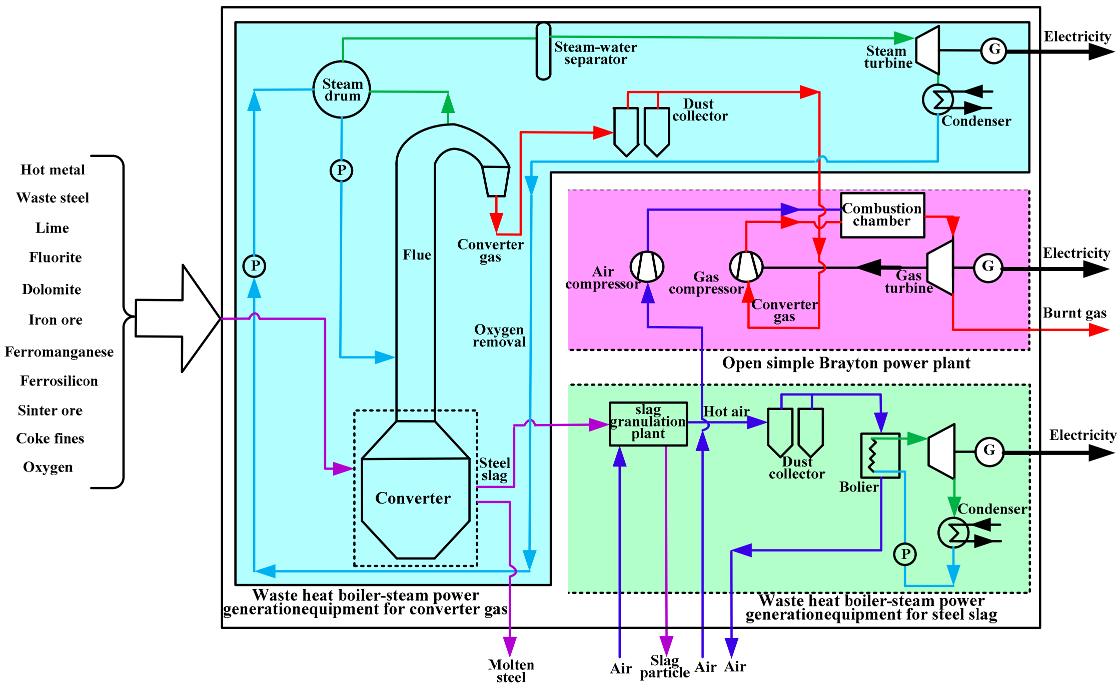

Figure 21. Physical model for a converter steel-making procedure.

Based on constructal theory and FTT, generalized constructal optimization for a converter steel-making procedure was performed by taking a complex function, integrated by molten steel yield and useful energy, as optimization objective. The coolant dosage and total raw material cost were taken as the optimization variable and constraint, respectively. The optimal cost distribution for raw materials was obtained, which was also called as “generalized optimal construct”. One could see that

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the optimization was carried out from thermodynamic and economic points of views. The effects of some parameters on the optimization results were analyzed (see Figure 22). After optimization, the complex function, molten steel yield and useful energy increased by 2.67%, 2.21% and 3.12%, respectively.

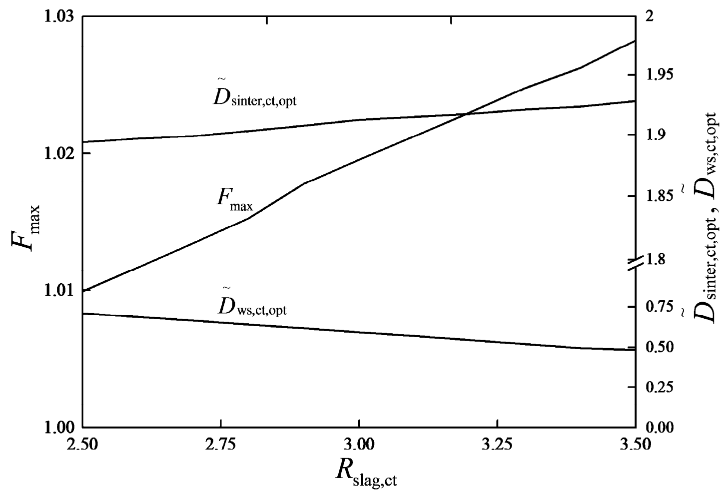

Figure 22. Effect of steel slag basicity on the optimal results.

7.2.5. Investigations of Continuous Casting and Rolling Procedures

Temperature Field Investigation of Thin Slab Continuous Casting and Rolling Procedures

The temperature distributions of the steel in continuous casting and rolling procedures directly affect its quality, and it is important to carry out investigations about this aspect. The schematic diagram of thin slab continuous casting and rolling procedures is shown in Figure 23 [66].

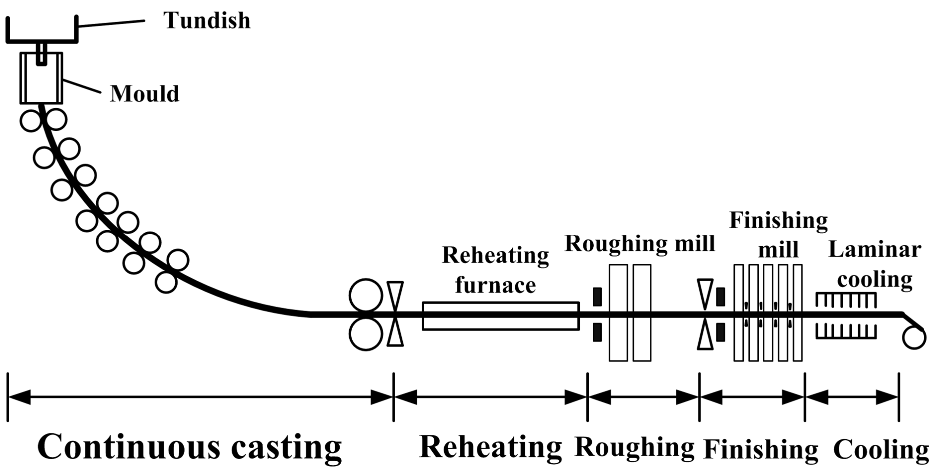

Figure 23. Schematic diagram of thin slab continuous casting and rolling procedures.

The temperature field of thin slab in the four processes was obtained after numerical calculations. The effects of water flow distribution in the secondary cooling zone on the final rolling temperature and final cooling temperature are shown in Figure 24, from where with the increase in water flow distribution f_{s4} (or f_{s5}) of the secondary cooling zone, both the final rolling temperature and final cooling temperature decreases first and then increases. A lower final cooling temperature can be obtained by adjusting the water flow distribution, and a smaller amount of the cooling water is required with the appropriate water flow distribution. From this point of view, the dosage of the cooling water can be reduced. The final rolling temperature is influenced by the water flow distribution, and a reasonable temperature distribution of the strip can be obtained by adjusting the

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water flow distribution. A reasonable temperature can lead to a higher quality of the strip; therefore, the improvement of the strip quality can be realized by adjusting the water flow distribution in the secondary cooling zone.

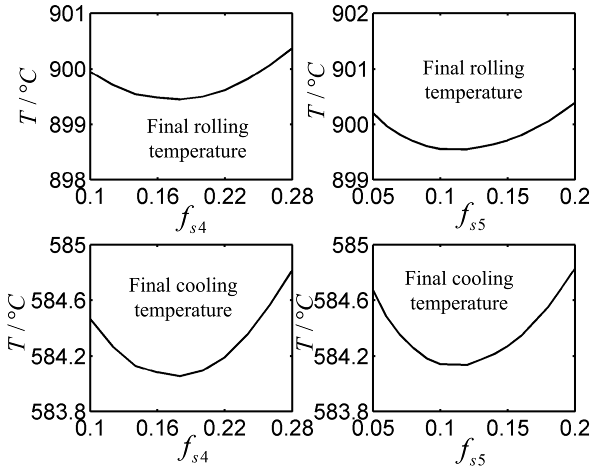

Figure 24. Effect of water flow distribution in the secondary cooling zoneon the final rolling temperature and final cooling temperature.

Generalized constructal optimization of slab continuous casting elemental packages

The water distribution in the secondary cooling zone of the continuous casting process directly affects the quality of the steel, and many scholars have shown great interest in this aspect. The idea of generalized constructal optimization was proposed [67]. This idea and entransy theory were introduced into the optimizations of slab continuous casting process (see Figure 25).

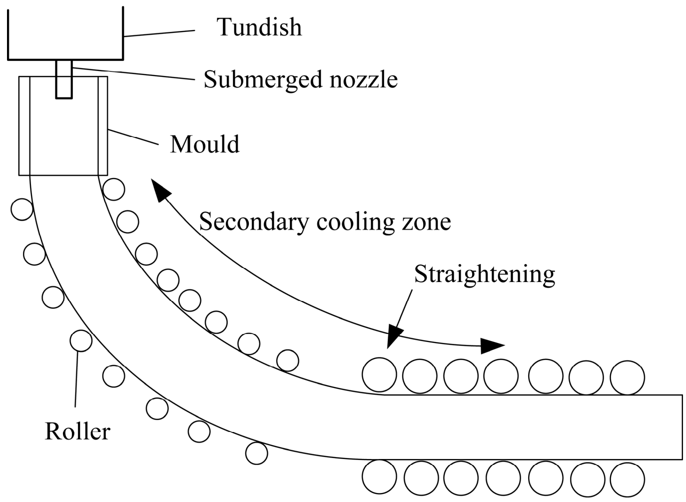

Figure 25. Schematic diagram of slab continuous casting process.

Based on the constructal analyses of this process [68], generalized constructal optimizations of this elemental package were carried out by taking two complex functions as optimization objectives [67,69]. The two complex functions were composed of heat loss and surface temperature gradient function [67], as well as entransy dissipation and surface temperature gradient function [69], respectively. The water flow amount of the secondary cooling zone was taken as the constraint. The optimal construct of the water flow distribution in the secondary cooling zone considering internal and surface temperature gradients of the slab was obtained (see Figure 26). In Figure 26, L is the distance between the mould's meniscus and calculation point, and the end of the secondary cooling zone is located at the right side of the figure. One can see that the temperature drop of the optimal

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water flow distribution at the end of the secondary cooling zone is smaller than that of the initial water flow distribution.

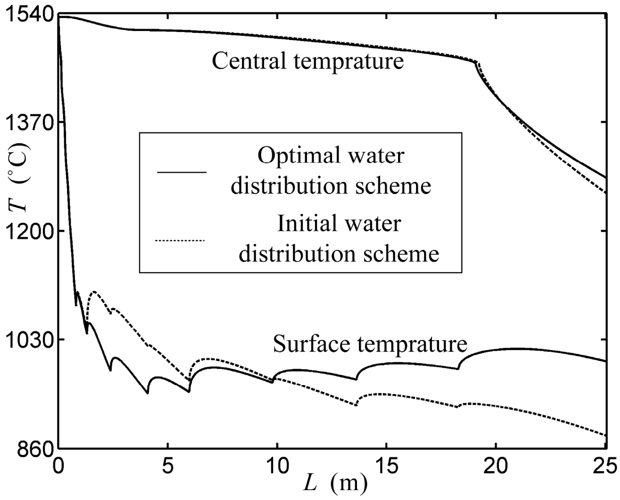

Figure 26. Temperature distributions of the slab for initial and optimal schedules.

Constructal Optimizations for Thermal Insulation Processes of Steel Rolling Reheating Furnace Walls

The steel rolling reheating furnace is an important equipment in the steel rolling procedure, and a reasonable structure of the furnace helps to reduce heat loss and the consumption of gas fuel [70]. Analogy with the entransy dissipation extremum principle (EDEP) for enhanced heat transfer processes [24], the EDEP for thermal insulation processes was proposed [71]. Constructal designs of the thermal insulation structures of four steel rolling reheating furnace walls (see Figure 27) at different boundary conditions were implemented by taking the minimizations of heat loss rate and entransy dissipation rate as optimization objectives, respectively [71–75]. The results showed that the optimal constructs of the insulation layers based on the former two optimization objectives were different (see Figure 28). The thermal insulation performances could be improved by adopting the optimal constructal designs of the insulation layers with variable cross-section and variable thickness.

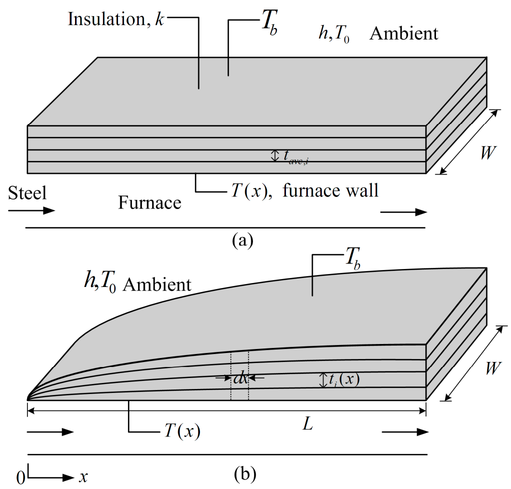

Figure 27. Model of a reheating furnace wall with multi-layer insulation structures.

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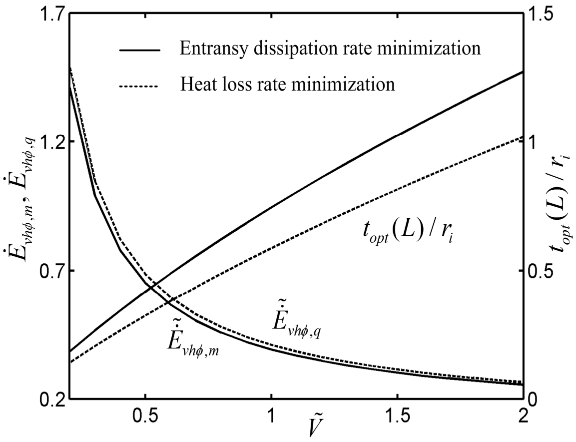

Figure 28. Comparisons of the optimal results based on different optimization objectives.

Constructal Optimizations for Laminar Cooling Elemental Packages

The water distribution in the laminar zone also affects the quality of the steel [76], and it is significant to carry out investigations about this aspect. Generalized constructal optimizations of the strip laminar cooling process (see Figure 29) was carried out by the complex function as optimization objective [77]. The complex function was composed of entransy dissipation and maximum temperature difference, and the total water flow amount in the laminar cooling zone was taken as the constraint.

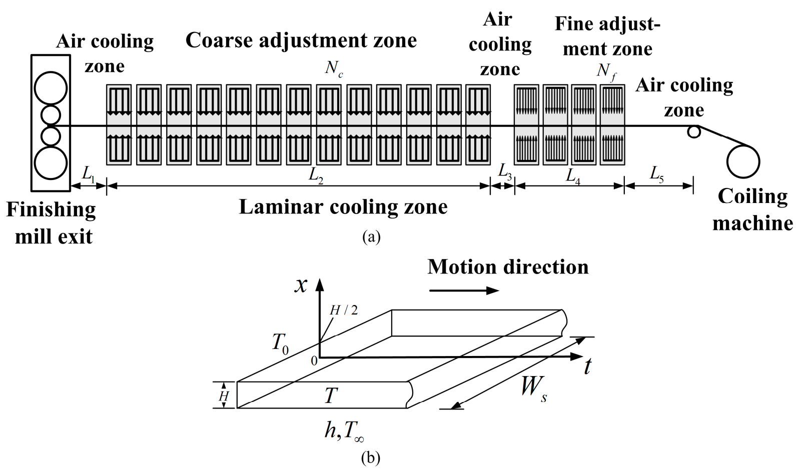

Figure 29. Schematic diagram of a strip laminar cooling process.

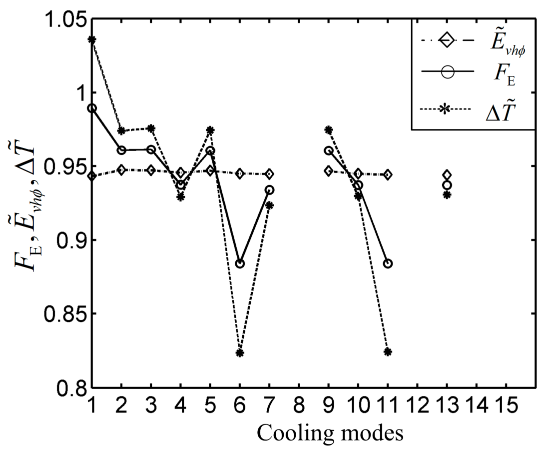

Figure 30. Effect of cooling mode on the complex function.

The optimal water flow distribution of the headers in the laminar cooling zone was obtained. Compared with initial cooling scheme, the complex function, entransy dissipation and maximum temperature difference after optimization were decreased by 11.59%, 5.59% and 17.58%, respectively (see Figure 30).

7.3. Generalized Thermodynamic Optimizations for Functional Subsystems of ISPP

Waste heats and residual energies are important additional resources of ISPP. The systems to make use of waste heats and residual energies are functional subsystems of ISPP. How to improve the heat and energy recovery efficiencies of these functional subsystems is the hot issue of their performance optimizations, and generalized thermodynamic optimizations play important roles in these investigations.

7.3.1. Potential Analyses of Thermodynamic Optimizations in Waste Heat and Residual Energy Recoveries of China's Iron and Steel Industry

The iron and steel industry is an important study object of energy saving and emission reduction. Many researchers have performed analyses and optimizations of materials flows and energy flows in iron and steel industry via various methods, and have proposed effective ways for energy saving and emission reduction. A case study of hot blast stove flue gas sensible heat recovery and utilization (see Figure 31) was presented by Chen et al. [78]. The results showed that before the heat conductance distribution optimization, the system could realize energy savings of 76.2 kgce/h, profit of 68.9 yuan/h, and CO_2 emission reductions of 187.2 kg/h, while after the heat conductance distribution optimization, the system could realize energy savings of 88.8 kgce/h, profit of 92.5 yuan/h, and CO_2 emission reductions of 218.2 kg/h, which were, respectively 16.5%, 34.2% and 16.5% better than before optimization.

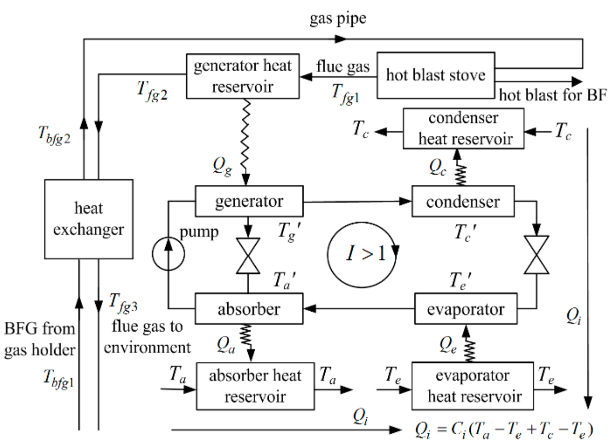

Figure 31. Flow chart of hot blast stove flue gas sensible heat recovery and utilization.

7.3.2. Recovery and Utilization of Residual Energy and Heat for Sintering Procedure: A Case Study

In the iron and steel industry, the recovery and utilization of residual energy and heat plays an important role for energy savings and CO_2 emission reduction. The energy consumption of sintering procedures accounts for 10%-20% in the total energy consumption. Taking three sintering machines in a steel plant as an example [78], on the basis of utilization of the high temperature part of cooling machine flue gas for power generation through steam generated by waste heat boiler, a further scheme (see Figure 32) was proposed that the medium temperature part of cooling machine flue gas was used for hot air sintering or ignition furnace combustion-supporting air. The flue gas of sinter machine discharge end was used for absorption refrigeration. The flue gas flowing out of refrigerator and the low temperature part of cooling machine flue gas were used for preheating of sinter mixture.

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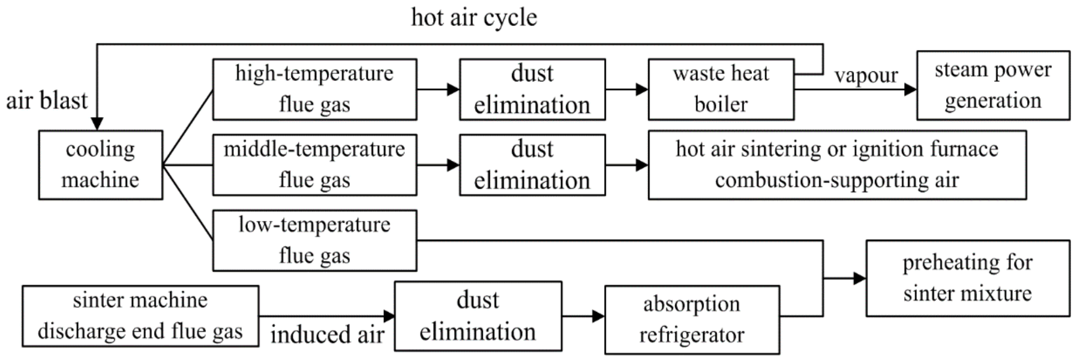

Figure 32. Flow chart for the sintering waste heat utilization.

The energy savings and emission reduction performance of the system were investigated. The results showed that it could provide cooling 369630 GJ every year through recovery of sintering machine high temperature flue gas sensible heat, and could realize energy savings of 14000 ton kgce, and CO_2 emission reductions of 34000 ton. Also, it could realize energy savings of 92000 ton kgce, and CO_2 emission reductions of 226000 ton through recovery of sensible heat from the flue gas flowing out of refrigerator and the low temperature part of cooling machine flue gas which was used for preheating the sinter mixture.

7.3.3. Heat Recovery and Utilization of High Temperature BOG based on Thermochemical Method

Thermochemical recycling methods of methane reforming reactions have been proposed to recycle and utilize the residual heat resources in the ISPP for years. The methane reforming with carbon dioxide is affected by the structures, operation parameters as well as heat transfer laws. Based on efficient heat recovery and utilization of high-temperature BOG, a thermochemical recycling system through methane reforming with carbon dioxide in a tubular plug flow reactor was proposed (see Figure 33) [79].

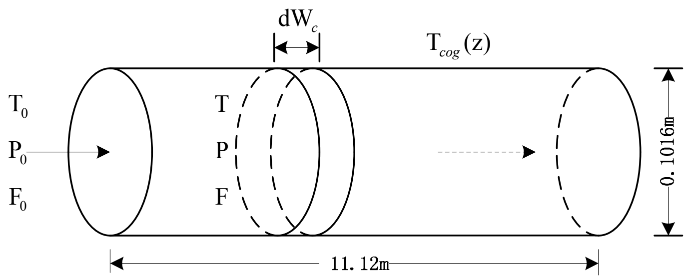

Figure 33. Model of tubular plug flow reactor.

A mixture of CH_4, CO_2 and H_2 in a certain proportion flowed into the reactor filled with Ni/La_2O_3 catalyst granules, and the inlet temperature T_0, pressure P_0 and molar rate F_0 were set as constants. The distribution characteristics of the reacting rate, temperature and total pressure of mixed gas were obtained under the Newton heat transfer law, and the effects of the inlet temperature, total pressure, molar flow rate of methane and catalyst porosity on the reacting rate were analyzed (see Figure 34).

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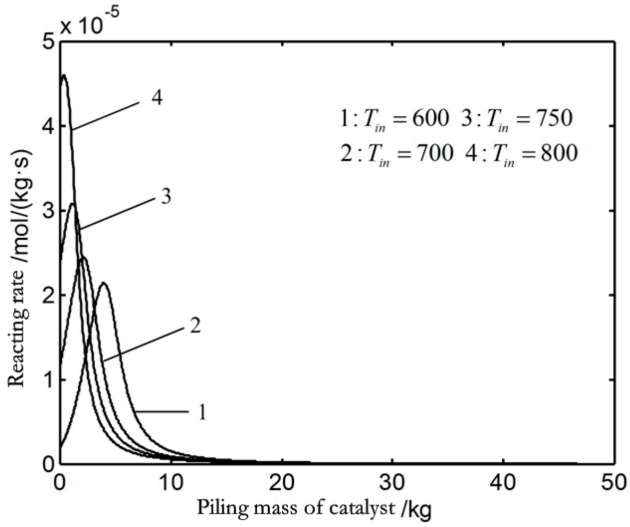

Figure 34. Effect of input temperature on the reacting rate versus piling catalyst mass.

7.3.4. Thermodynamic Optimizations of Residual Energy and Heat Based on Gas Turbine Technology

China's iron and steel industry is one of the pillar industries which consumes energy excessively. The coke oven gas (COG), the blast furnace gas (BFG) and Linz-donawitz process Gas (LDG) are prime fuels that have high heating value. Making good use of the residual COG, BFG and LDG will decrease the energy consumption in steel-making process. Aiming to use steel mill's residual energy and heat (including COG, BFG and LDG's sensible heat and chemical energy, a variety of flue gas and slag sensible heat, etc.) efficiently, a series of thermodynamic optimization researches for utilization of waste heat energy have been carried out based on gas turbine technology. Eighteen kinds of classical thermodynamics and FTT models [80–87], involving simple and complex, closed and open gas turbine power cycles, cogeneration systems and combined cooling heating and power (CCHP) systems, were established.

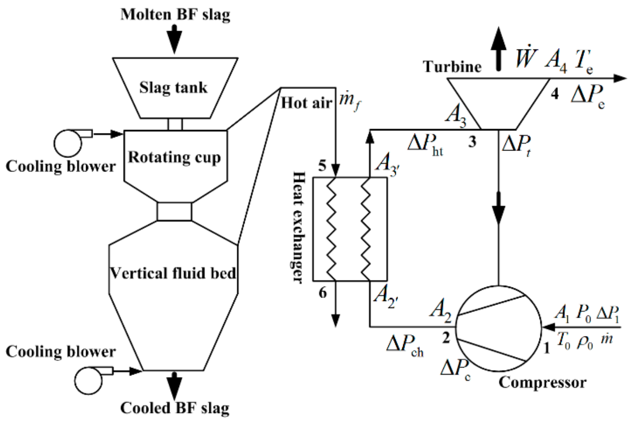

Figure 35. System layout of an air Brayton cycle driven by waste heat of blast furnace slag.

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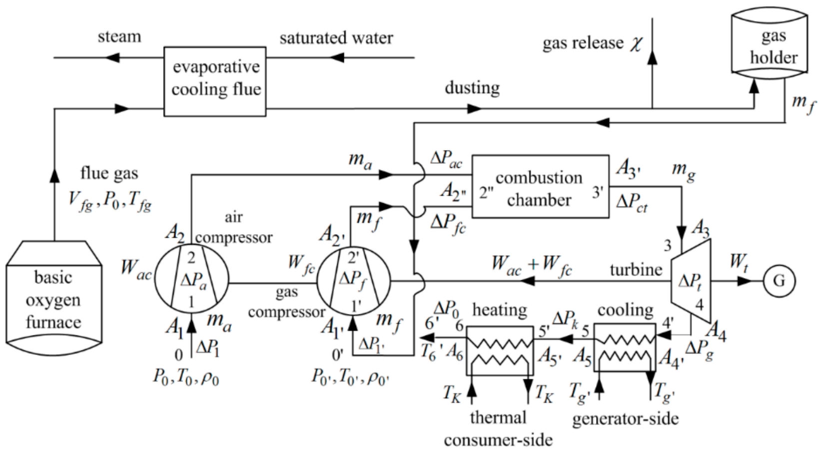

Figure 36. System layout of an open simple Brayton cycle driven by residual energy of converter gas.

Performance analyses and optimizations of the classical thermodynamic model of simple, gas-air, regenerated, regenerative Brayton and inverse Brayton gas turbine power plant, and FTT (endoreversible and irreversible) models of power cycles and cogeneration units (closed gas turbine cycles of regenerated CCHP, intercooled-regenerated combined heat and power (CHP), two-stage intercooled- regenerated- reheated CHP plants, closed simple and regenerated modified Brayton cycle, open gas turbine cycles of simple (see Figure 35) and intercooled, simple CCHP (see Figure 36), regenerated CHP and regenerated CCHP) with constant- and variable-temperature heat reservoirs were implemented by taking the cycle power output, thermal efficiency, power density, total useful energy, useful energy efficiency, exergy output rate, exergy efficiency, profitability and exergoeconomic performance as the optimization objectives, respectively.

7.3.5. Low Temperature Waste Heat Recovery with Constructal Disc-Shaped Solid-Gas Reactors

There exist various low temperature waste heat resources in the ISPP, and solid-gas reactor is one of the pieces of equipment used to recycle the waste heat. As shown in Figure 37, a disc-shaped model of a solid-gas reactor was built [88,89].

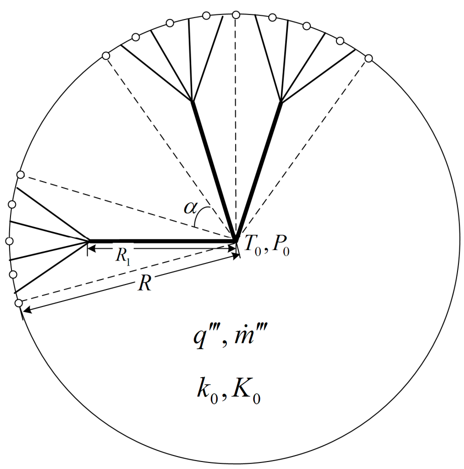

Figure 37. Disc-shaped model of solid-gas reactor.

Tree-shaped integrated collectors were distributed in the disc, and constructal optimizations of this model were implemented by taking the minimizations of entropy generation rate [88] and entransy dissipation rate [89] as optimization objectives, respectively. The volume of the integrated collectors was taken as the constraint, and the radius of the elemental sector was taken as the optimization variable. The optimal constructs of the reactors based on different optimization objectives were obtained. The reverse reaction of model could be used to recycle waste heat, and the positive one could be used to increase the low temperature of the heat source.

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7.3.6. Heat Recovery Based on Thermoelectric Device and Its Evaluation

Waste heat is rich and abundant in the iron and steel industry. The waste water heat not only wastes energy, but also forms urban heat islands causing heat pollution. Taking advantage of the waste heat is of great significance for reducing energy consumption. The low temperature waste heat is mainly used for heating at present. However, heating is only applicable in a few fields. Therefore, to explore the feasibility and economy of power generation from waste heat has become an important topic. In recent years, thermoelectric power generation technology has moved from frontiers towards the industry, and attracts more and more attention. Chen et al. [90] analyzed energy-saving potential of recycling iron and steel industry waste heat based on thermoelectric power generation technology.

Aiming at the characteristics of waste heat of blast furnace slag flashing water and sintering flue gas, a series of waste heat recovery schemes, including water cooling (see Figure 38) and air cooling modes, single stage and two stage combination thermoelectric generator modes were presented [91–94]. The non-equilibrium thermodynamic and FTT models of the thermoelectric devices were established. Trial method was used to translate the boundary value problem into initial value problem that could be solved by numerical method. The key design parameters of the thermoelectric devices, such as thermoelectric element length, effect of thermoelectric module packing factor and effect of fluid channel length, were analyzed by taking the power and efficiency as the optimization objectives. The physical parameters of the commercially available material by Melcor were used for simulation. The generation module specifications were as follows: $A_m = 40 \times 40$ mm², $A = 1.2 \times 1.2$ mm², $L = 2$ m and $N = 127$. It was found that in the various types of waste heat recovery device, the highest efficiency power generation was the flue gas waste heat as the heat source with water cooling, and the efficiency was about 4.5%. The lowest efficiency power generation was waste water as the heat source with air cooling, and the heat efficiency was about 1.28%. When the heat source was flue gas, the temperature of the flue gas decreased rapidly along the flow direction. The channel length of the flue gas should not be too long to avoid the dropping of efficiency. When the heat source was waste water, the waste water temperature dropped slowly. The channel could be longer in order to fully release the waste heat of water.

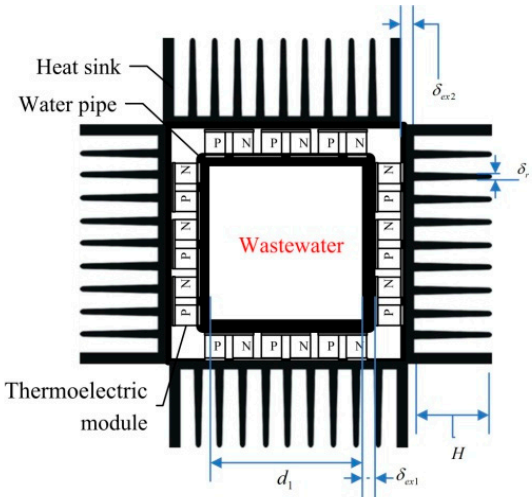

Figure 38. Schematic diagram of a one-stage air-cooling thermoelectric power generator device driven by waste water.

Taking into account the technical implementation difficulty, factory benefit and other factors, the reasonableness of recovery technology cannot be used as a unique evaluation criterion. A waste heat recovery net work in iron and steel factory (see Figure 39) and three indexes, i.e. energy utilization rationality, technical feasibility and investments economics for evaluation, were presented [95]. The waste heat recovery technologies of the iron and steel enterprises were evaluated comprehensively. The basic line of the waste heat utilization technology research was given. Furthermore, the general analytical models of waste heat recovery were established [96]. The

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rationalities of various waste heat utilization process were compared from the viewpoint of thermodynamics. Four kinds of processes, i.e. waste heat heating material, waste heat steam power generation, coal fired heating material and coal-fired steam power generation, were analyzed. The results showed that the thermal analysis method had limitations to judge the rationality of energy utilization. The exergy analysis method could clarify the nature of energy saving. It was pointed out that the maximum exergy efficiency of the whole process of waste heat utilization was the unified index of use of rationality energy utilization. According to this index, some guiding principles of iron and steel industry heat recovery process were deducted.

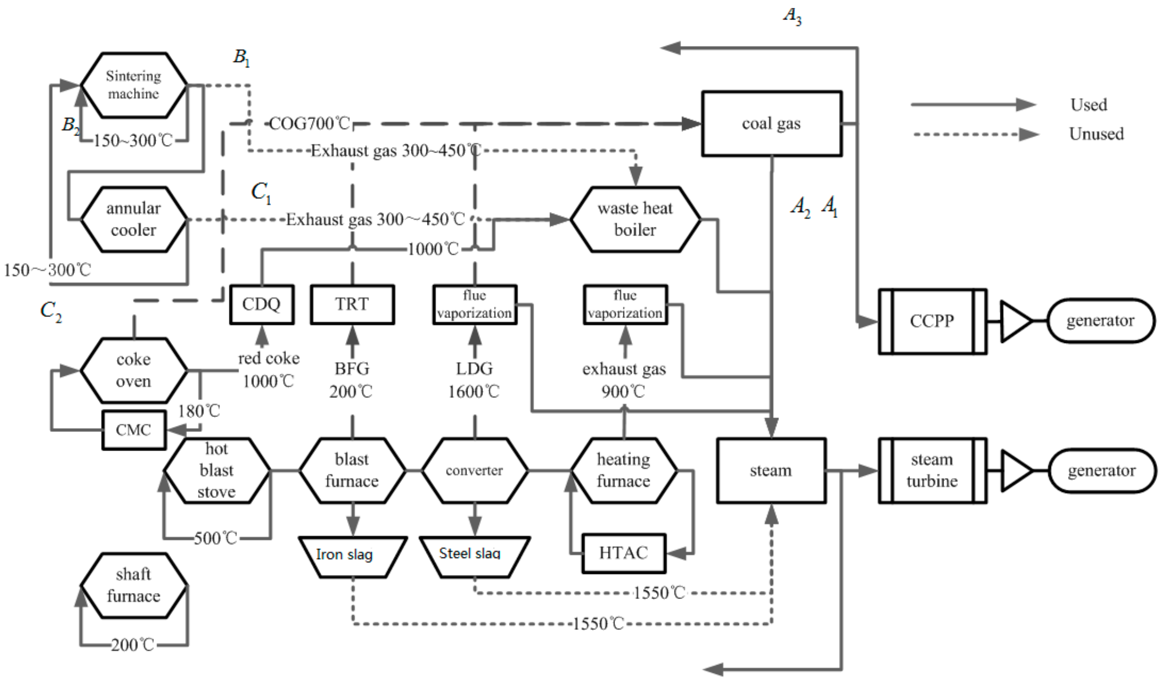

Figure 39. Waste heat recovery net work in iron and steel factory.

7.4. Generalized Thermodynamic Optimizations for Sections and Whole Process of ISPP

Compared with local optimization, global optimization of a system can lead to its global optimal performance, which is also suitable for ISPP. Several sections and the whole process of ISPP have been taken as the research objects, respectively. Some mechanism models and/or half mechanism models combing thermodynamics, heat transfer and dynamics have been built. The transfer and conservation laws of the material and energy flows have been studied, and the global behaviors of the material and energy flows have been explored. Energy savings, decreasing consumptions, reducing emissions and increasing yields of the sections and whole process of ISPP have been implemented based on generalized thermodynamic optimizations.

7.4.1. Performance Optimization of Sintering and Iron-Making Section

Blast furnace iron-making process is an energy intensive and resource consuming process at the core of steel production. Many optimization models have been established to optimize various structures and operation parameters, aiming to achieve different targets, such as yield maximization [59], cost minimization [97] and exergy loss minimization [56], etc. Different methods of mixed integer linear programming (MILP), artificial neural network (ANN), constructal theory [59,60] and other methods have been introduced to solve the relevant problems. Taking minimum energy consumption, CO_2 emission and cost as optimization objectives, an optimization model for iron-making system covering from the sinter ore matching process to the blast furnace was established as shown in Figure 40 [98]. Seventeen optimization variables (material dosages of the sintering process, sinter ore ratio, pellet ore ratio, lump ore ratio, coal ratio, coke ratio, air volume and blast temperature, etc) and 44 constraints (gas balance, hot metal composition, blast pressure, coal injection rate, etc)

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were considered. The combination of linear programming (LP) and nonlinear programming (NLP) methods to solve the problem was applied. The optimal iron ore matching scheme within the given parameters and the optimization results of energy consumption, CO_2 emission and cost minimization were obtained. Effects of sinter ore grade and basicity on the three optimization objectives were analyzed. The results showed that the energy consumption/CO_2 emission of the iron-making system for energy consumption/CO_2 emission minimization and for cost minimization decreased by 2.03% and 1.89%, and the cost decreased by 17.88% and 18.13%, respectively. Taking minimum energy consumption or CO_2 emission of iron-making system as the optimization objective, the minimum energy consumption and the minimum CO_2 emission decreased by 0.71 kgce/t and 1.92 kg/t when the sinter grade (TFe) increased by 1%. Taking the minimum cost of iron-making system as the optimization objective, the minimum energy consumption and the minimum CO_2 emission decreased by 0.63–0.76 kgce/t and 1.70–2.05 kg/t when the sinter grade (TFe) increased by 1%. Moreover, the increases in lump, coal powder injection and blast temperature, and the decrease in coke ratio were effective ways to achieve the energy conservation, CO_2 emission reduction and cost reduction of the iron-making system.

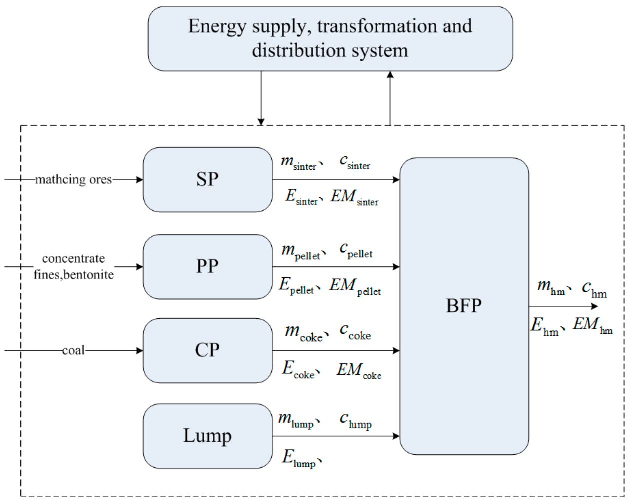

Figure 40. Input-output relationship of iron-making system.

7.4.2. Study of Reasonable Process Route for BF-CC Section Based on the MPE

Based on the MPE theory, a physical model of blast furnace-continuous casting (BF-CC) section accounting for the function of product manufacture in the ISPP was established. In the model, function of each process was dissected, and coordinative optimization was conducted between processes with the same function. This “dissection-optimization-integration” method contributed to reasonable process routes was applicable to various typical steel products manufacture. The results mainly indicated that [99]:

(1) The most reasonable process route for plain construction steel production is “small BF-KR desulphurization ([S] > 0.03%) -small converter - ladle argon stirring and wire feeding/(CAS-OB) -billet caster”.
(2) The reasonable process route for machinery steel production is “small BF-KR desulphurization-small BOF-LF-VD/RH-billet caster, adding process carburetion of catching carbon at blowing endpoint of converter ([C] ≥ 0.6%)”.
(3) The reasonable process route for HR thin slab production is “large BF-KR desulphurization (full hot metal pretreatment, namely KR desulphurization and dephosphorization BOF)-large decarburization converter-(CAS-OB)/RH (ladle argon stirring for plain carbon steel, LF-RH for pipe line steel)-thin slab caster”.
(4) The reasonable process route for CR thin slab production is “large BF-KR desulphurization (full hot metal pretreatment, namely KR desulphurization and dephosphorization BOF)-large decarburization converter-RH (CAS-OB for plain carbon steel)-thin slab caster”.

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Moreover, the RH light treatment should be applied in the low carbon Al-killed steel production with RH refining.

(5) The reasonable process route for plain construction steel production is "medium sized BF-KR desulphurization-medium sized converter-LF-VD or RH-slab caster".

7.4.3. Calculations of Theoretical Minimum Energy Consumption and CO_2 Emission and Exergy Analysis for ISPP

The minimum energy consumption of each procedure and the whole process of ISPP were studied. The result was compared with the practical energy consumption. It was helpful to find out the weak links of energy consumption in the procedures and the whole process, analyze the energy saving potential, and then determine the reasonable energy saving measures [100]. The system and equipment energy utilization could be comprehensively and reasonably analyzed by exergy analysis method, and it was also important for the energy consumption condition analysis of the practical production process of iron and steel industry [101]. Fruehan et al. [100] put forward the concept of theoretical minimum energy consumption based on the basic physical changes and chemical reactions of iron and steel production, and calculated the theoretical minimum energy consumption and the corresponding CO_2 emission of each production process under several given conditions. Qiu et al. [102] further established a mathematical model of process energy consumption per ton of steel, and developed a computing platform. Four manufacturing processes: sintering process, iron-making process, basic oxygen furnace steel-making process and electric arc furnace steel-making process (see Figure 41) were considered. The theoretical minimum energy consumption model and the exergy analysis model were established [103], with which the effect of the values of the technological parameters on the theoretical minimum energy consumption, the internal exergy loss, the external exergy loss and the exergy efficiency under different conditions were studied. For the rolling process, considering the energy consumption of heating and shaping, the theoretical minimum energy consumptions of four kinds of steels under five conditions were calculated and analyzed.

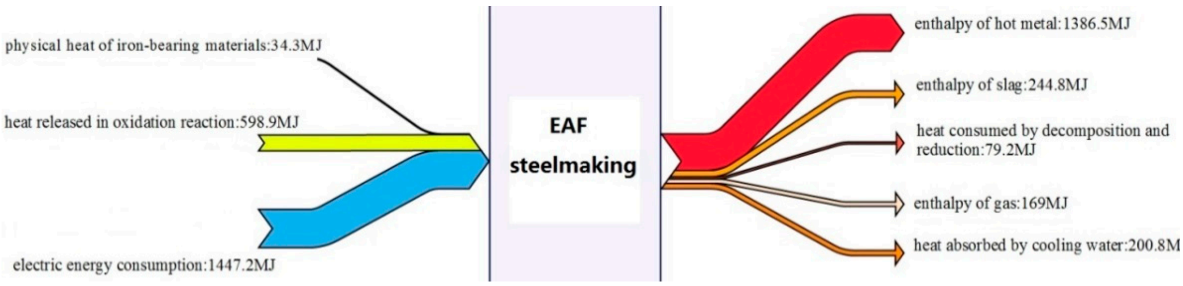

Figure 41. Diagram of energy flow for electric arc furnace steel-making process.

The CO_2 emission and fuel consumption of the coking process, sintering process, ironmaking process, basic oxygen furnace steelmaking process, electric arc furnace steelmaking process and rolling process were calculated when the process used single or multiple kinds of fuels with the theoretical minimum energy consumption. The results showed that the energy consumption reduction of sintering process had a significant effect on the reduction of coke consumption. The recovery of the enthalpy of the sinter, blast furnace gas, converter gas and electric arc furnace gas should be enhanced to reduce the energy consumption. The effect of reducing heating energy consumption on the reduction the total energy consumption of steel rolling was remarkable, and the effect of billet initial size was smaller. The exergy efficiency of sintering process was lower, and the exergy efficiencies of blast furnace iron-making, converter steel-making and arc steel-making process were higher.

7.4.4. Investigations of the Dynamic Characteristics of Iron Flow for ISPP

System dynamics can be used effectively to study complex systems with the methods of macroscopic and microscopic analyses, qualitative and quantitative analyses. Many scholars have

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built system dynamic models to simulate and analyze the dynamics of energy systems. Based on material and energy balances, the dynamic model of each procedure in ISPP was established at relatively macroscopic level using the methods of causal loop diagrams and stock-flow diagrams [104]. Then, a dynamic model for iron-flow network of the ISPP (see Figure 42) was built with system dynamics by connecting the input and output relations of sintering, blast furnace, iron-making, converter steel-making and rolling procedures [105]. The dynamic characteristics of the iron flow in each procedure and the whole process were analyzed. The response characteristics of the global iron-flow network to returned iron-flow of each procedure were studied.

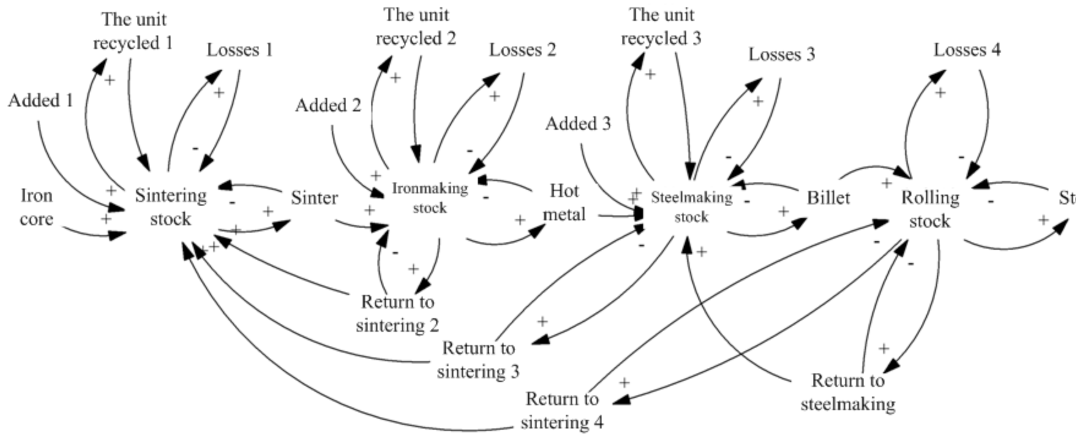

Figure 42. Causal loop diagram of ISPP.

Taking the rolling procedure as an example, the response characteristics of the global iron-flow network to returned iron-flow of rolling procedure were studied under five different recycle situations (see Figure 43). The results showed that the more behind the procedure was, the longer the time was taken for the procedure to reach the steady output state again. The variation ranges of the iron flow of products decreased in turn.

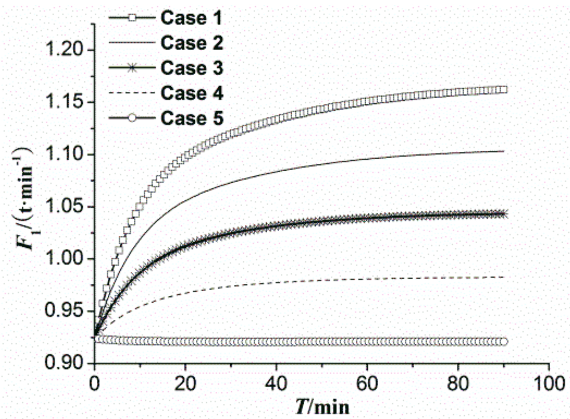

Figure 43. Response characteristic of the global iron-flow network to returned iron-flow of rolling procedure.

7.4.5. Generalized Energy Consumption Structure Analysis and Systematic Optimization for ISPP

The energy consumption structure can be dissected into certain functional subsystems and then specific processes, as shown in Figure 44. The functional subsystems included the subsystems before the blast furnace, blast furnace subsystem, BOF subsystem, hot and cold rolling subsystems and supply subsystem, etc. Analyses of the material and energy flows for each process within the ISPP, and integration of various advanced energy-saving and emission reducing technologies make the

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calculation of energy consumption and emission available. It is significant to optimize the distributions of the resources and energy flows in the ISPP.

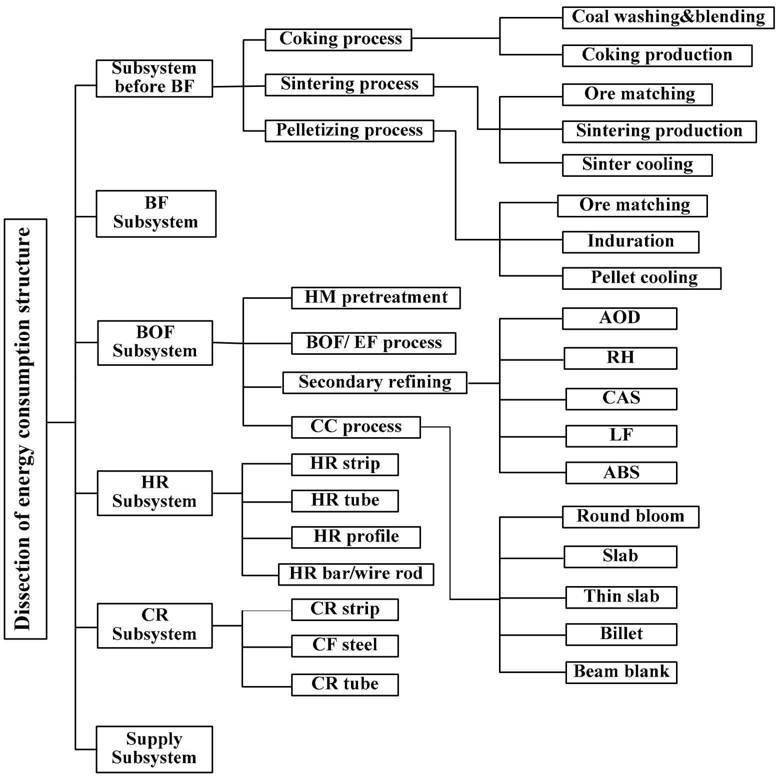

Figure 44. Dissection of energy consumption structure for ISPP.

7.4.6. Generalized Constructal Optimization for ISPP

Based on the constructal optimization investigations in the procedures mentioned above, one could consider the constructal optimization of the whole ISPP (see Figure 45) [23,106], which was connected by the coking and sintering procedures in parallel, and iron-making, steel-making, continuous casting and steel-rolling procedures in series. A complex function to evaluate the performance of the whole ISPP was built, which was composed of energy consumption per unit steel, temperature difference of the slab surface and center as well as temperature difference of the strip surface and center. The raw material dosages of the sintering, iron-making and steel-making procedures and the water dosage distributions of the continuous casting and steel-rolling procedures were taken as the optimization variables. The total cost of the raw materials in the ISPP was taken as the constraint. After optimization, the energy consumption per unit steel was reduced by 7.24%. The corresponding iron element flow could easily go through the production process system, more energy flows were recycled, and lower influences on the environment were obtained. The generalized multi-objective constructal optimization synthetically considering yield, waste heat and residual energy as well as environmental influence were realized [23,106,107]. The generalized optimal constructs of production process structures and resource distributions were obtained. The purposes of increasing yield, saving energy and reducing emission were reached, and the obtained results provided some new guidelines for the global optimal designs and operations of a real ISPP.

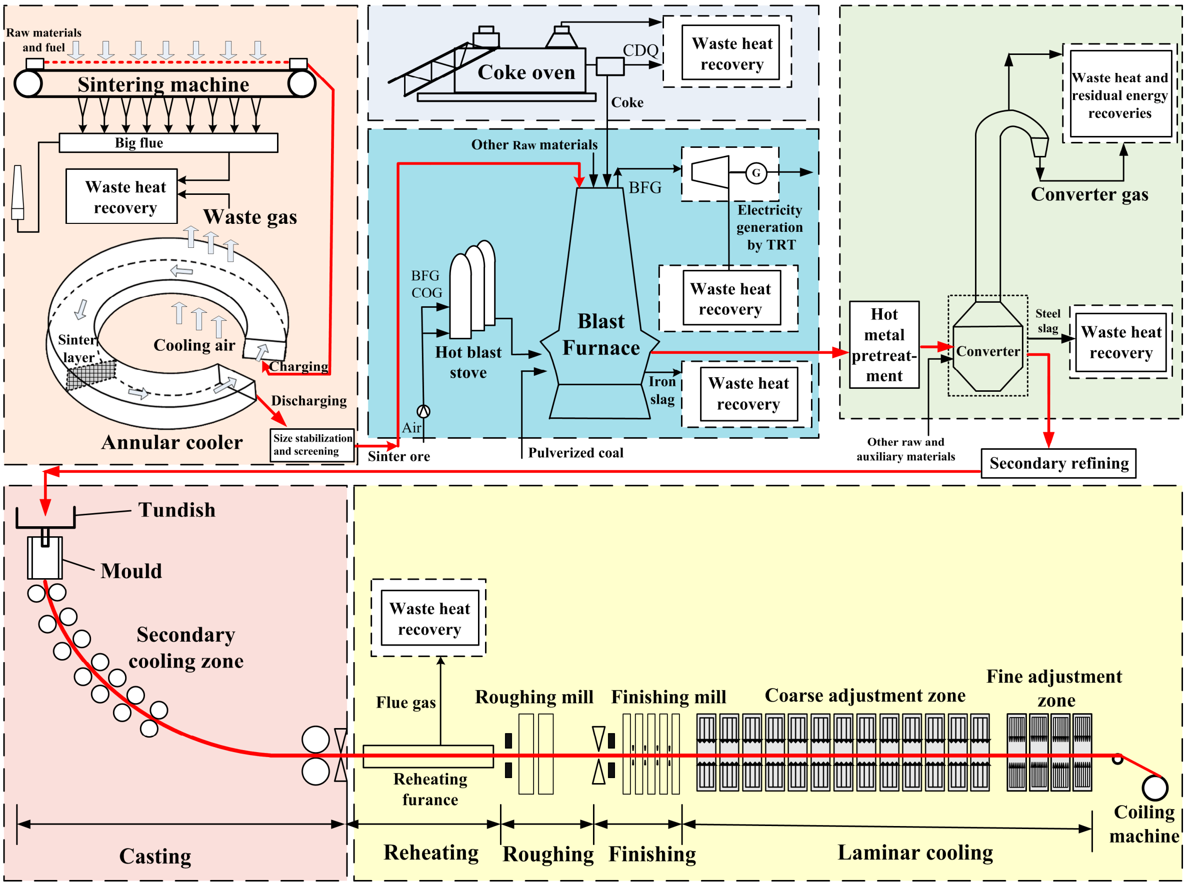

Figure 45. Schematic diagram of the ISPP for constructal optimization.

8. Conclusions

The generalized thermodynamic optimization theory provides a new theoretical basis for the performance analyses and optimizations of elemental packages, working procedure modules, functional subsystems and whole process of ISPP. For the investigation of procedure modules, coking, sintering, iron-making, steel-making, continuous casting and rolling procedures are taken as the research objects, respectively. Some theories of modern thermodynamics, such as constructal theory, entransy theory, field synergy theory and FTT are applied into the optimizations of these procedures. Some new results different from those obtained based on traditional methods are obtained. For the investigations of functional subsystems, waste heats and residual energies in each procedure are considered to be recycled. FTT, constructal theory and entransy theory are introduced into the optimizations of these functional subsystems. Their heat and energy recovery efficiencies are improved after optimizations. For the investigations of sections and whole process of ISPP, the sintering and iron-making section, BF-CC section and the whole process are taken as the research objects, respectively. FTT, constructal theory and MPE are introduced into the optimizations of these objects. Their global optimal performances are obtained by using global optimizations. After optimizations, energy savings, consumption decrements, emission reductions and yield increments of the hierarchical process systems are realized, and the corresponding comprehensive coordination among the material flow, energy flow and environment are achieved.

The generalized thermodynamic optimization theory has preliminarily been applied to elemental packages, working procedure modules, functional subsystems and whole process of ISPP. For coking and sintering procedures, sensible heat of the red coke and residual heat of the exhausted gas were recovered, which realized energy savings of the two procedures. For iron-making and steel-making procedures, the yields of the hot metal and molten steel were increased and waste heats and residual energies were recovered, which realized energy savings and yield increments of the two procedures. For continuous casting and rolling procedures, the heat losses and surface temperature functions of the slab and strip were reduced simultaneously, which realized the improvements of energy retention and quality simultaneously. For ISPP, the energy consumption per unit steel and the corresponding carbon dioxide emission were reduced, which realized the energy saving and emission reduction of the whole process of ISPP. These applications have greatly extended the application ranges of the generalized thermodynamic optimization theory, and also enriched its connotation. Specially, the applications of constructal theory, entransy theory and FTT into the optimal designs of ISPP, provide new angles of views for the ISPP from thermodynamics and heat transfer enhancement, which can be brought into the optimizations of other process industries. Moreover, thermo-economics [108–110] and exergy are important indexes for the performance evaluations of the ISPP, and many local optimizations of the elemental packages and procedures are theoretically carried out. Therefore, one can further implement global performance optimizations of the more practical ISPP based on thermo-economic and exergy indexes.

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