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Energy and emission analysis of flash ironmaking-powder generation coupling processes with various fuels



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Yiru Yang^a, Zhongjie Shen^a, Xiaochun Wen^b, Haifeng Liu^{a,*}

^a Shanghai Engineering Research Center of Coal Gasification, East China University of Science and Technology, Shanghai 200237, PR China ^b School of Material Science and Engineering, Fujian University of Technology, Fuzhou 350118, PR China

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ABSTRACT

The flash ironmaking-power generation coupling (FIPG) process combines the latest entrained-flow bed ironmaking technology and efficient cycle power generation. Different fuels (hydrogen, methane, coal, and biomass) are adopted to produce the reducing gas components. In this study, the process simulation was established based on the Gibbs free energy minimize principle, and FIPG included the flash ironmaking coupling (FIC), settler heating (SH), and combined cycle power (CCP) processes. The sensitivity analysis determined the optimum conditions (fuel ratio R_{F_1} oxygen ratio R_{O_2} and replenished oxygen ratio R_{OF}), and we compared mass, energy, and exergy flows in different cases. In FIC, the optimized conditions determined using the crossing points of curves temperature T = 1350 °C and reduction degree X = 0.7 are (H₂: $R_F = 0.16$, $R_O = 2.11$), (CH₄: $R_F = 0.43$, $R_O = 1.58$) and (Coal: $R_F = 0.59$, $R_O = 0.88$). Due to the low heating value of biomass, its optimized R_F is higher than others, even with a declined requirement (X = 0.6) (Biomass: $R_F = 4.3$, $R_O = 0.39$). In SH, except that the SH-biomass requires more replenished fuel, the other three cases slightly differ due to the close first stage particle outputs. A suitable replenished oxygen/coal ratio ($R_{OR} = 0.74$) ensures the hot metal's high carburization rate and temperature with fewer fuel amounts. From the energy balance perspective, the fuels account for most heat expenditure, while the electricity produced by CCP accounts for most of the energy benefit. Meanwhile, chemical energy from iron is the third largest expenditure item, with a share ranging from 10.91 % to 21.71 %. Exergy analysis provided a detailed flow chart between processes, showing the highest exergy efficiency (48.6 %) in FIPG-H₂ and the lowest (43.0 %) in FIPG-biomass. Although the ore reduction consumes CO to generate the oxidation product CO₂, the most significant CO₂ generation occurred in the CCP stage. The total CO₂ emissions per energy consumption unit are 71.55 Nm³/MW, 107.56 Nm³/MW, 138.49 Nm³/MW, and 148.63 Nm³/MW in FIPG-H₂, FIPG-CH₄, FIPG-coal, and FIPG-biomass.

1. Introduction

Flash ironmaking technology (FIT) is a novel alternative ironmaking process based on the entrained-flow bed principle [1]. There are serval characteristics of FIT, including high temperature, low particle load, and high reduction potential gas, which lead to excellent gas-particle reactivity. Therefore, it is expected to replace blast furnace ironmaking in the future. The disadvantages of the traditional ironmaking process can be avoided, including environmental pollution, dependence on coke, and high CO₂ emissions. Due to the low gas utilization during the FIT, the flash ironmaking-power generation coupling process is a practical scheme to recover high-quality gas after ore reduction processes [2].

Sohn et al. [1,3] proposed FIT and developed the small-scale flash

ironmaking reactors. Pinegar et al. [4–6] used METSIM to simulate the flash ironmaking process, including mass flow, energy consumption, and CO₂ emission. Methane and hydrogen are chosen as the optional fuels due to their low pollution and CO₂ emission. The oxidant was used to reform fuels or release partial heat, for example, CH₄-H₂O, CH₄-O₂, and H₂-O₂ flame. Yang et al. [2,7] proposed the coal gasification and flash ironmaking coupling process (CG-FI) to realize the gasification and reduction in a single reactor. The CFD simulation was used to figure out gasification and reduction zone distribution. Due to the similar high-temperature conditions, the coupling process simplifies the reactor structure and reduces the material transfer, enhancing energy utilization. Wang et al. [8,9] used biomass steam reforming to produce the qualified syngas to realize flash ironmaking. For new processes,

* Corresponding author. *E-mail address:* hfliu@ecust.edu.cn (H. Liu).

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different subsequent utilization.

industrial practices.

numerical simulations are often used as design aids to provide valuable

information for further research, such as pilot-scale testing. CFD models are used for numerical simulation within a detailed reactor, and product

predictions can be carried out with submodules such as chemical reaction mechanisms and component diffusion transport [10-12]. At the

same time, the process simulation can also be performed based on a

complete process, including many reactors. The single solution of the

reactor is based on various reactor models, such as a rigorous reactor

based on the Gibbs principle or a stoichiometric reactor based on the

known fractional conversion [13,14]. Therefore, the process simulation

can also provide detailed mass, energy, and exergy flow between

fuels resource. However, the focus is different, such as reduction

mechanism [15], thermochemical equilibrium [16,17], reaction kinetics

[18,19], and flow characteristics [20–22]. Whether from experimental

research or industrial practice, the low utilization rate of reducing gas in

the flash ironmaking coupling process is predictable-however, no

relevant research report on the treatment of reduced iron particles and

high-LHV exhaust gas. The subsequent stages will largely determine the

system's energy consumption. For calculating the whole process,

different fuels will affect the flash ironmaking process and lead to

process can store part of the energy in the cogeneration system, thus

improving the utilization efficiency. However, with a high fuel ratio and

high tail gas quality, gas energy recovery will become the key to efficient

smelting. The current research only focuses on the ironmaking process

and does not conduct quantitative research on the subsequent gas

treatment methods. To promote the development of the flash iron-

making process, the full-cycle energy flow and material flow to inves-

tigate the potential of the new process is necessary. In this study, the

flash ironmaking-power generation coupling (FIPG) process simulation

was established based on the full-cycle of flash ironmaking coupling

(FICP), settler heating (SH), and combined cycle power (CCP) processes.

The product prediction is performed by determining the appropriate

material ratio through sensitivity analysis, in which the unified technical

indicators are adopted. The energy evaluation is further conducted

based on the predicted material flow. An exergy evaluation system was

established simultaneously, considering the energy level reduction

during fuel use. Ultimately, the direct CO₂ emissions are compared be-

tween different routes because clean energy fuels will have significant

advantages in this field. Thus, a cross-sectional comparison between

other fuel processes allows us to select the appropriate procedure for

Previous studies have shown that the coal-based flash ironmaking

Researchers have studied the different technical routes using diverse

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2. Methodology

2.1. Process description

There are several routes in the follow-up utilization of exhaust gas, such as power generation, hydrogen preparation, or methanol synthesis. Different utilization methods are related to the final composition of the gas, especially the hydrogen/carbon ratio. The combined cycle power process (CCP) is relatively mature and can be utilized for combustible gas with various components. Therefore, it was chosen as the uniform route in this research. The full-cycle flash ironmaking-power generation process (FIPG) was indicated as following Fig. 1. The entire procedure can be broken into flash ironmaking and gas reform (A) and combined cycle gas turbine (B). The first part of the flash ironmaking coupling process (FIC) included partial fuel combustion with oxygen and ore reduction by reducing gas. Further, the settler heating process (SH) melts the reduced iron and produces hot metal. The second part uses the combined cycle power process (CCP) to recover the heat and combust gas to generate electricity.

The flow chart, including critical reactors and numbered streams, is shown in Fig. 2. In the core coupling reactor, the hematite ore fines (stream#8), fuel (stream#9), and oxidant (stream #6) were mixed. They reacted to generate primary reducing gas and qualified reduced iron particles. When the particles have sufficient residence time, they can be recognized as a thermodynamics equilibrium state. In the steady-state settler, the pulverized coal (stream#11) and oxidant (stream#7) was injected into the hot metal to react with slag and hot metal. Therefore, the three-phase process of gas, iron, and slag is considered a thermodynamic equilibrium process.res The primary gas passing rapidly above the liquid level is supposed not to participate in the reactions.

According to the Gibbs free energy minimization principle, the flash ironmaking and gas reform (A) can be solved by the process simulation in HSC Chemistry 6.0, a thermodynamic software commonly used in metallurgy with an accurate pyrometallurgical database. The component balance module can output the specific components at the reaction temperature by inputting the initial materials. The energy conservation governing equation was used to judge the balance temperature by repeated iterations. Coal and biomass are non-conventional components that cannot be input as pure components. Therefore, the additional converter is also written to decompose the components and correct the energy calculation [16]. While, in the combined cycle gas turbine (B), Aspen Plus is another option to simulate the power generation because of its wide application and high accuracy.

2.2. Assessment definition



There are numerous process indicators in sensitivity analysis, and the quality evaluation of interest must be first defined. Here, we describe the concepts of ore reduction degree (X) and gas utilization (U). The

Fig. 1. The full-cycle flash ironmaking-power generation coupling process.



Fig. 2. The flow chart of critical reactors and numbered streams.

reduction degree is defined as follows:

$$X = \frac{[Oxygen]_{loss}}{[Oxygen]_{ferr}} \times 100\%$$
⁽¹⁾

where $[Oxygen]_{loss}$ is lost oxygen content (*wt.%*), $[Oxygen]_{ferr}$ is the oxygen content in the iron oxides (*wt.%*). Therefore, the reduction degree can also be called as oxygen loss ratio. For the two-stage direct reduction process, such as COREX, FINEX [23,24], or flash ironmaking process in this study, the reduced degree (*X*) of ore in the first stage is also called the primary reduction degree, which will significantly influence the FeO content in the hearth, and leading to the intense corrosion. The primary reduction degree that can be achieved in the pre-reduction stage should be as high as possible to reduce the reduction requirement in the settler.

The gas utilization can be divided into carbon monoxide utilization (U_{CO}) and hydrogen utilization ratio (U_{H2}) , which can be defined as follows:

$$U_{CO} = \frac{[CO_2]}{[CO] + [CO_2]}$$
(2)

$$U_{H2} = \frac{[H_2 O]}{[H_2] + [H_2 O]} \tag{3}$$

where [*i*] is the mole fraction of species *i*, including CO₂, CO, H₂, and H₂O. Gas utilization indicated the oxygen capture capacity during the ore reduction. This ability is limited by the thermodynamic equilibrium at a specific temperature. For example, at 1500 °C, the utilization rate (U_{CO}) of excess CO will not exceed 20 % at most because it cannot further capture oxygen elements from FeO.

The material energy is calculated by the latent chemical heat and sensible physical heat, which can be written as follows:

$$E_i = LHV_i + m_i C_i T \tag{4}$$

where E_i is the total energy of species i (J), *LHV* is the lower heating value (MJ/kg), m_i is the mass (kg), and C_i is the heat capacity (J/kg.°C). The total energy of stream (*E*) was further written as:

$$E = \sum E_i \tag{5}$$

It should be noted that the initial inputs are at atmospheric pressure, and the residual pressure of the final product is directly dissipated, so the energy contained in the pressure is not calculated. The energy calculation in this study is only used for the system balance calculation of input and output, and the pressure-based energy is calculated in the more detailed exergy evaluation.

Exergetic analysis introduces the energy level into the energy evaluation system, representing the energy's available proportion. According to the previous works for the exergy analysis [25,26], both physical and chemical exergy were included in the calculation. Physical exergy mainly refers to the temperature-based component of physical exergy, which can be calculated as followings:

$$Ex_T = (h - h_0) - T_0(s - s_0)$$
(6)

where *h* and *s* denote the specific molar enthalpy and entropy of the materials, h_0 and s_0 are the specific molar enthalpy and entropy under the environmental conditions (room temperature 25 °C).

The physical exergy also included the exergy caused by pressure, which the following formula can calculate:

$$Ex_P = nRT_0Ln(p/p_0) \tag{7}$$

where *p* denotes the absolute pressure, and p_0 is the environmental conditions (atmospheric pressure 101.25 kPa). *n* is the mole number of the species, *R* is the gas constant, and T_0 is the environmental temperature. On the other hand, the pressure-based of physical exergy did not work for the solid or liquid phase because the volume variation is tiny.

The physical exergy can be obtained by the sum of temperaturebased and pressure-based components of physical exergy as followings [27]:

$$Ex_{ph} = Ex_T + Ex_P \tag{8}$$

On the other hand, the chemical exergy of a mixture (gas phase and solid/liquid phase) can be calculated in the following formula:

$$Ex_{ch} = \sum x_i E x_{ch,i}^0 + RT_0 \sum x_i ln x_i$$
(9)

where x_i is the molar fraction of the species i in the mixture, the chemical exergy can be divided into two parts: the exergy caused by the chemical potentials and the species mixture. The chemical potentials were relative to the environment, and the standard chemical exergy $Ex_{ch,i}^0$ was determined by the benchmark substances [28,29].

The chemical exergy of coal $Ex_{ch,coal}$ was measured by early researchers and induced to different expressions [30,31]. In this work, the exergy of coal was calculated by the empirical formula used by previous researchers [32]:

$$Ex_{ch,i} = Q_L(1.0064 + 0.1519[H]/[C] + 0.0616[O]/[C] + 0.0429[N]/[C])$$
(10)

where Q_L means the lower heating value (KJ/kg), [i] denotes the element mass ratio.

Therefore, the exergy efficiency based on all substances was defined to obtain a more suitable evaluation for FIGP. Input materials included oxygen, steam, carrier gas, and coal. Output materials included exhaust gas, hot metal, and molten slag. Both physical exergy and chemical exergy of materials were counted in the evaluation, as shown in the following formula:

$$\varphi = \left(\sum Ex_{ph,j} + \sum Ex_{ch,j}\right) / \left(\sum Ex_{ph,i} + \sum Ex_{ch,i}\right)$$
(11)

where *i* is the raw material, including coal, oxygen, carrier gas, and ore, and *j* is the product, including coal gas, reduced iron, slag, and residual carbon. Also, the exergy efficiency of each unit can be calculated by this method when the input and output of each unit are obtained. Although there may be errors in an ideal Gibbs reactor, this is a reasonable measure for a new type of reactors, such as FIC and SH. More details about the reactors can be founded in the previous CFD works [2,7].

2.3. Process conditions

Due to the lack of practical experience, the composition of optimized materials is not yet determined, and comparisons between different fuels are more difficult to carry out. To eliminate the effect of yield scale, two process parameters, fuel/ore ratio (R_F) and oxygen/fuel ratio (R_O), are used to distinguish between different compositions, which are defined as:

$$R_F = \frac{m_{fuel}}{m_{orr}} \tag{12}$$

$$R_O = \frac{m_{oxygen}}{m_{fuel}} \tag{13}$$

where m_{fiel} is the mass of fuel, m_{oxygen} is the mass of pure oxygen, and m_{ore} is the mass of hematite ore, calculated by the hot metal yield as 100,000 tons per year. Predictably, when the R_F increases, the more reducing components available can improve particles' reduction degree (X) but lead to more energy consumption. When the oxygen/fuel ratio (R_O) increased, more chemical energy was released, but gas reduction potential decreased and suppressed the reduction degree. The summary of process conditions adopted in this study is listed in Table 1. Hydrogen, methane, coal, and biomass were input raw materials. The components

Table 1

The summary of process conditions.

	Hydrogen	Methane	Coal	Biomass
Ore amount (t/h)	21			
Preheated temperature (°C)	180			
Heat dissipation (%)	5			
R _F (-)	0.1-0.6	0.2 - 1.0	0.3 - 1.3	1–7
R ₀ (-)	0.4–1.6	0.4–1.6	0.2 - 1.0	0.1-0.6

of coal and biomass are listed in Table 2.

2.4. Model validation

This study's process simulation used a combination of HSC Chemistry, Aspen Plus, and user-defined codes. Aspen Plus has been widely used in the chemical engineering or energy fields, including the combined cycle power process (CCP) in this study. Therefore, the accuracy can be found in previous research [33–37]. The focus of attention is the flash ironmaking coupling process (FIC), defined by the HSC Chemistry database and the user-defined codes. The values obtained by HSC chemistry can be directly used as the input data for Aspen Plus, and no iteration was needed for the sequential process. As thermodynamic software, their underlying logic is based on the lowest Gibbs free energy minimize principle. Therefore, the reactor is considered an ideal homogeneous system without considering the substance's existence form or transfer mode.

The experimental results of a small-scale test run by Sohn et al. [3] were compared with our thermodynamic simulations. The single reactor for flash reduction and CH₄-O₂ combustion coupling process conforms to the premise of multi-phase mixing and complete reactions. The reduction degree was the final product, as shown in Fig. 3. Five of the six trial records had prediction errors of 20 % or less; three predictions were within 10 %, concentrated in the moderate reduction degree. In an actual reactor, the furnace zone is small, and the gas stream shows significant distribution (e.g., high central flow rate, wall reflux, etc.) with a short residence time of particles. There are two cases where the thermochemical model predictions deviate significantly; the first is that the reduction reaction is slow at low reaction temperatures, and the reactions were not completed in a limited time. The second one is the uneven distribution leading to the high-reduction degree particles. When the highly-reduced particles move into the low reduction potential region, the thermodynamic equilibrium recognizes that the reoxidation reactions will oxidate the metallic iron, decreasing the reduction degree. However, from the kinetics perspective, the reoxidation reaction can hardly occur between metallic iron and oxidant CO₂ or H₂O.

The prediction of a more complex computational fluid dynamics (CFD) model was also included in Fig. 3 as red points. Although the CFD models have more detailed considerations, such as gas-particle flow and reaction kinetics, our thermodynamics model provides a relatively accurate prediction. Furthermore, according to partial blocks in the reactor, the local heat balance model offers the possibility of improvements in thermochemical models. However, this improvement should be based on a deep knowledge of practical experience and can not be conducted.

Table 2

The components of coal and biomass in this study.

	Coal	Biomass
LHV (MJ/kg)	28.50	16.44
Proximate Analysis (wt.%)_		
Moisture	1.90	9.04
Ash	14.30	0.61
Volatiles	28.50	76.70
Fixed carbon	57.20	13.65
Ultimate Analysis, dry (wt.%)		
С	73.30	49.90
Н	4.40	6.40
0	6.20	43.60
N	1.54	0.10
S	0.26	0.00



Fig. 3. The comparison of model prediction and test report.

3. Results & discussion

3.1. Sensitivity analysis

3.1.1. Flash ironmaking coupling process

Since the material ratio has effects on the FIC and different fuels have their optimization conditions, the combinations of fuel/ore ratio (R_F) and oxygen/fuel ratio (R_O) are studied, and the corresponding cloud diagrams of critical indicators, including temperature, reduction and gas are drawn separately.

Fig. 4 shows the sensitivity analysis results of FIC-H₂ as a contour diagram, in which the influence of different R_F and R_O on the indicators can be found. As we can see, the temperature always increases with the increasing R_O , but as not sensible with increasing R_F at low temperatures. However, with the rising R_O , the influence of R_F on temperature becomes more and more apparent. Regarding the ore reduction degree in Fig. 4(b), a rising and falling trend was observed with increasing R_O , and the gradient is more significant with a higher R_F . The peak value existed at the middle and up part of the contour. In Fig. 4(c), the U_{H2} increased from the top left to the bottom right, indicating that the lower R_F and higher R_O help improve the gas utilization. The contour uses the interpolation method to provide additional data outside the measurement points to show the intuitive law.

For other processes based on the different fuels in Fig. 5, 6 and 7, the basic pattern is similar to temperature and reduction degree in FIC-H₂. In contrast, a trend of first rising then falling shows the difference for carbon-hydrogen mixture in gas utilization. An apparent depression existed in U_{H2} and U_{CO} figures, overlapping with the high-reduction degree zone in X figures. At the same time, the slight dislocation between U_{H2} and U_{CO} shows the differences in oxygen capture capacity: H₂ is higher at high temperatures, and CO is more elevated at low temperatures.

Optimum goals must be set to obtain the optimized conditions. First, a high temperature should be adopted to guarantee the rapid reduction in the limited reaction zone, and the value was chosen as 1350 °C according to the previous work [17]. Second, the reduction degree should not be lower than 0.7 in FIC to avoid the erosion of high FeO content slag. Based on these two goals, we can determine the optimum



Fig. 4. Sensitivity analysis of materials ratios based on FIC-H2.



Fig. 5. Sensitivity analysis of materials ratios based on FIC-CH4.

conditions based on the superimposed contours, as shown in Fig. 8. There is an intersection point of two curves, and R_F is the lowest at this time in Fig. 8(a). However, due to the low LHV of biomass, gas reduction potential in higher temperatures can hardly reduce the ore particles. Therefore, there is no intersection point between curves $T = 1350 \degree C$ and X = 0.7 in Fig. 8(b). A declined requirement for X = 0.6 had to be adopted for the subsequent calculations in this study. Even with a lower reduced iron quality, R_F in FIC-biomass is still higher than the others.

Based on the above approach, the optimization conditions (R_F and R_O) were determined in Table 3. The disparity in the mass ratios is relatively large due to significant differences in molecular weight. It is noteworthy that the fuel amount of biomass is significantly higher than the others, while the R_O is much less. The higher oxygen and lower fixed carbon content require fewer oxidants for gasification. In conclusion, the authors believe directly injecting biomass into the FIC reactor to realize gasification is unreasonable. It is difficult for low LHV biomass to reach the high temperature required for flash ironmaking, and the increased oxygen ratio leads to the insufficient reduction potential to reduce ore particles.

However, biomass is still an attractive substitute due to the low price, wide application, and renewable resources. The high-quality syngas or prepared hydrogen after biomass gasification and reforming is more recommended in the FIC process. In this FIC stage, the high R_F increases energy consumption and decreases the reduction degree of particles, but the subsequent calculation can be continued with a higher reduction requirement on the SH.

Fig. 9 shows the gas products at the end of FIC. The highest gas production and percentage of oxidative components were observed as expected. FIC-coal has the second-highest gas production, with the

lowest $\rm H_2$ content. However, $\rm H_2$ occupies a significant part of the exhaust gas for FIC-H_2 and FIC-CH_4 processes.

3.1.2. Settler heating process

Since the equilibrium temperature of the first stage products is set as 1350 °C, only low melting point calcium ferrate melted. Pulverized coal was sprayed into the settler with oxygen and brought the heat to melt the metallic iron. At the same time, the residual carbon carburizes the hot metal, and the melting point is reduced to 1450 °C, which helps to reduce the energy consumption.

In this study, the heat dissipation was calculated using 20 MJ/m²·h as the heat flow density of the typical blast furnace [38]. The square settler was assumed as 5 m \times 3 m \times 3 m, and the heat dissipation occurred at the refractory wall. Therefore, the heat dissipation was determined as 1260 MJ/h.

The SH process's key parameters are the amount of replenished fuel (coal) and the replenished oxygen/fuel ratio (R_{OR}). The sensitivity analysis aims to realize a temperature rise, the hot metal carburization, and the improvement of elemental iron yield. Fig. 10 investigated the effect of R_{OR} on the fuel amount, carbon content, and metal yield in an extensive range from 0.70-to 0.90. With the increasing R_{OR} , the needed fuel amount to reach the temperature was significantly reduced. Also, the carbon content and metal yield declined sharply. As the valuable by-products, the Fe element loss should be avoided. Therefore, the more suitable range should be 0.7–0.75, in which the metal yield can be controlled to over 95 %.

Fig. 11 further provided the optimized parameter for SH, in which the carbon content of 3 % was chosen as a reasonable value. The optimized condition can be obtained in Table 4. We can see similar optimum



Fig. 6. Sensitivity analysis of materials ratios based on FIC-coal.

conditions in SH-H₂, SH-CH₄, and SH-coal because the settler heating only involved the solid product from the FIC, which was already set as the same. The minor difference is mainly due to the introduction of pulverized coal slag and the accuracy of determining the intersection in the first stage. On the other hand, the fuel amount is much higher in the SH-biomass process because the second-class reduced particle brought a higher requirement of smelting in the settler.

The bubbles from the slag surface mixed with the first stage exhaust gas and again reached the thermodynamics equilibrium state. Finally, the main components and equilibrium temperatures under optimal conditions are shown in Fig. 12. Both CO and H₂ in the gas composition under biomass were much higher than in others. For CO outputs, the relationship is hydrogen < methane < coal < biomass, but for H₂ outputs, the relationship is coal < methane < hydrogen < biomass. In terms of oxidizing components, the utilization of H₂ is higher than CO at all equilibrium temperatures. The equilibrium temperature ranking law is hydrogen > methane > coal > biomass. Considering the similar composition and temperature of the gas produced after the settler coal injection, the gas composition in the first stage plays a decisive role in the final gas composition of SH.

3.1.3. Heat recovery & power generation

The heat recovery by steam and gas turbine power generation is considered from streams#16–32 in Fig. 2. The compressor, combustion chamber, and turbine compose the gas turbine power generation, and the heat exchanger, pump, and turbine compose the steam turbine

power generation. The combined cycle power (CCP) process is simulated by Aspen Plus, the details of which can be found in previous work [39]. The reactor efficiency was different in the literature, and we provided the references including the same value. Note that this value will directly affect the final result. As a widely used process, the process simulation of CCP was not repeated, and Aspen Plus can provide robust results. The most critical air amount was also based on the sensitivity analysis, in which the most enormousmentioned heat load can determine. The needed oxygen amount in the compressed air for complete combustion corresponds to the maximum heat output, as shown in Table 5.

According to the calculation, compressors 1-2 and pumps' energy consumption and the mechanical work of turbine 1-2 were as shown in Table 6. The mass in streams #23–32 is circulating water, and the absorbed heat determines its flow rate during the heat recovery. Therefore, the comparison between different fuels can be carried out in the next section.

3.2. Energy assessment

The energy flow is always based on material flow; the inflow and outflow of the entire process system are listed in the following Table 7. The energy consumption for ore mining and crushing was ignored because it was too small and difficult to measure. The energy consumption for oxygen production by cryogenic air separation technology was set as 0.395 kWh/Nm³ (provided by HangZhou oxygen plant group



Fig. 7. Sensitivity analysis of materials ratios based on FIC-biomass.



Fig. 8. Schematic diagram of determining optimization conditions based on sensitivity analysis.

Co., LTD), a suitable value for a large-scale oxygen concentrator. In addition, gas and air compression was considered in the total energy consumption; the optimized values were already presented in Table 6. In heat expenditure, the main items are the sensible heat and

chemical energy of mass flow, including hot metal, molten slag and gas, and the electricity generated by turbines. The physical heat is treated as a valuable heat expenditure item rather than heat loss. It should be noticed that the chemical energy of metallic iron also included the

Table 3

Optimized material ratios in the flash ironmaking coupling process.

	Hydrogen	Methane	Coal	Biomass
Oxygen amount (t/h)	7.09	14.27	10.90	35.42
Oxidant/fuel ratio (kg/kg)	2.11	1.58	0.88	0.39
Fuel amount (t/h)	3.36	9.03	12.39	90.3
Fuel/ore ratio (kg/kg)	0.16	0.43	0.59	4.3
Temperature (°C)	1350	1350	1350	1350
Reduction Degree (-)	0.7	0.7	0.7	0.6
U _{CO} (%)	18.8	19.1	10.8	27.7
U _{H2} (%)	42.3	42.8	39.9	54.9



Fig. 9. The main components output during the FIC.

dissolved carbon amount because carbon can be oxidized exothermally by the oxygen blown.

According to the calculation, the primary heat input and output items in this process are shown in Fig. 13. The fuel in the FIC stage and replenished coal used in the SH stage occupied the most critical roles of more than 80 % of the thermal income items. The output energy goes to the most important two parts: electricity and iron chemical energy. Although there is a possibility of recycling sensible slag heat, the amount ratio is less than 1 %.

The order of total energy input is biomass > methane > hydrogen >

coal, which is consistent with the order of energy yield. The energy utilization shows that the FIPG-H₂, FIPG-CH₄, and FIPG-coal are close, but FIPG-biomass is significantly lower. As the author et al. [16], the advantage of storing partial energy in ferrochemical energy by FIC is improved. Therefore, the higher the overall energy consumption, the lower the energy utilization efficiency because of the fixed storing effect of hot metal.

The energy consumption per ton of iron is often used to evaluate the energy consumption level in ironmaking. We can calculate the energy consumption (only fuel) of four cases as follows: 61.6 GJ/t, 68.0 GJ/t, 58.1 GJ/t, and 148.6 GJ/t for FIGP-H₂, FIGP-CH₄, FIGP-Coal, and FIGPbiomass. If the power generation was considered the minus part, the values could be reduced to 40.2 GJ/t, 36.0 GJ/t, 31.0 GJ/t, and 71.1 GJ/ t separately. As a reference, Li et al. [44] pointed out that the blast furnace exergy is 14.5 GJ/t in a traditional blast furnace, and Pinegar et al. [4] recognized the blast furnace energy consumption as 12.7 GJ/t. Although our research is different from the iron and steel industry in terms of statistical methods, there is no doubt that FICP has no advantages compared with the mature route of the iron and steel industry. A large amount of gas leads to loss during the subsequent power generation process. The energy efficiency of the blast furnace based on iron ore reduction is as high as 90 %, and about half of it will be stored in the form of chemical energy of hot metal [44].

However, when FICP is recognized as a power generation system with by-products of metal iron, adding ore particles helps store the energy and improve efficiency. Integrated Gasification Combined Cycle (IGCC) is a similar multi-generation to generate electricity [45,46], and Descamps et al. [47] report 43.5 % energy efficiency. Also, Giuffrida et al. [48] obtained a value of 48.91 % for IGCC with cold gas clean-up. While in FIGP-coal, the energy efficiency is as high as 51.5 %. Although some advanced technologies can improve the IGCC process, such as supercritical power generation and multi-wheel group cycle, they can also obtain results higher than this value. However, previous studies under the same conditions have also proved the role of thermochemical coupled energy storage in improving system efficiency.

The economic analysis can be conducted briefly according to the material and energy flow. Considering the energy structure and price, the conclusions can vary between countries. Just take China as an example, on the premise of choosing the cost of molten iron 3000 yuan/t, electricity price 1 yuan/kWh, hydrogen 2.1 yuan/Nm³, liquefied natural gas 6000 yuan/t, coal 600 yuan/t, and biomass 480 yuan/t, the economic benefit of power generation is 104 thousand/h, while the molten iron is 41.58 thousand/h, and the additional ore cost is 16.8



Fig. 10. The effect of oxygen/coal ratio on critical indexes.



Fig. 11. The optimum condition determined in the SH process.

Table 4

Summary of optimized material ratio in settler heating process.

	Hydrogen	Methane	Coal	Biomass
Oxidant/fuel ratio (kg/kg)	0.74	0.74	0.74	0.74
Fuel amount (t/h)	16.62	16.82	16.88	21.9



Fig. 12. The outputs of optimized cases during the SH process.

Table 5

The summary of parameters in CCP simulation.

Content	Values
Heat recovery temperature (°C)	215
Compressor pressure (bar)	15.4
Compressor efficiency (-)	0.85(isentropic), 0.95(mechanical)
Combustion temperature (°C)	1300
Chamber heat transfer efficiency (-)	0.95
Heater heat transfer efficiency (-)	0.9[40,41]
Steam initial temprature (°C)	540
Turbine efficiency (-)	0.92(isentropic)[42,43], 0.99(mechanical)
Pump efficiency (-)	0.86

thousand/h. The comparison between different energy sources shows that coal costs are the lowest, biomass is the second, natural gas is the third, and hydrogen is the most expensive. However, in terms of benefit/ cost ratio, the highest to lowest are biomass, pulverized coal, natural gas, and finally hydrogen. Using the residual hydrogen from the exhaust

Table 6	
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Summary of optimized material ratio in CCP.

	Hydrogen	Methane	Coal	Biomass
Air amount (kmol/h)	5288.423	5818.659	4850.742	13275.93
Gas turbine work (MW)	50.87	54.88	44.34	135.10
Compressor1-electricity (MW)	15.72	16.28	12.43	43.04
Compressor2-electricity (MW)	17.88	19.68	16.40	44.89
Steam turbine work (MW)	61.56	68.78	57.93	163.95
Heat recovery (MW)	162.76	181.83	153.17	433.45

Summary o	f inputs and	outputs.
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Fuels	Hydrogen	Methane	Coal	Biomass
Input items				
Ore (t/h)	21	21	21	21
Fuel (t/h)	3.36	9.03	12.39	90.30
Oxygen (kmol/h)	221.55	445.86	340.73	1106.76
Replenish fuel (t/h)	15.59	16.82	15.85	21.90
Replenish oxygen (kmol/h)	365.39	388.96	371.48	506.44
Output items				
Hot metal (t/h)	13.87	13.90	13.86	13.90
Slag (t/h)	3.33	3.46	5.11	4.72
Exhaust gas (kmol/h)	7116.53	7641.90	6149.85	18690.47
Recycle water (kmol/h)	13398.5	14968.46	12609.14	35681.55

gas to power generation is almost unprofitable.

3.3. Exergy analysis

Exergy analysis was used to calculate the detailed exergy flows based on the material flow between units. Figs. 14-17 summarized all results for FIGP-H₂, FIGP-CH₄, FIGP-coal, and FIGP-biomass. The fuel exergy flow occupied the most critical proportion as exergy input, and only hot metal and electricity are considered practical outputs. A strict distinction is not introduced here to divide exergy loss, heat dissipation, and useless materials, all calculated as a loss. It can be seen that the most considerable losses occur in the steam turbine stage, where the exergy efficiency of the turbine is only 55.6 %. Considering that the isentropic efficiency of the turbine set is 0.92 and the mechanical efficiency is 0.99, most of the remaining losses are exergy losses [49].

The exergy efficiency is always lower than the energy efficiency. The exergy efficiency of FIGP-H₂ remains the highest at 46.9 %, while the exergy efficiency of FIGP-biomass remains the lowest at 43.0 %. The energy efficiency of FIGP-coal (51.5 %) is higher than that of FIGP-CH₄



Fig. 13. The energy income and expenditure of different FIGPs: (a) income items (b) expenditure items.

(50.7 %), but the exergy efficiency (45.5 %) is lower than that of FIGP-CH₄ (46.9 %). It should be attributed to the higher quality factor of coal, as shown in **Eq.** (10).

3.4. CO_2 emissions

Compared with traditional fossil energy, one of the initial intentions of using clean fuels, such as H₂, CH₄, or biomass, is to reduce CO₂ emissions. Therefore, the CO2 emissions after three stages (FICP, SH, CCP) were compared in Fig. 18. The uniform use of pulverized coal for settler heating and carburization in the SH stage, and the requirements on the yield of high value-added metallic elements, inevitably increase the corresponding fuel consumption. Therefore, even in the clean energy cases, a large amount of pulverized coal was used, which ultimately increases the overall carbon emission of the process. Compared with the total CO₂ emissions in the FIGP-coal, CO₂ emissions from FIGP-H₂ are reduced by 45.3 %, FIGP-CH4 reduced by 7 %, and FIGP-biomass increased by 179.1 % due to higher fuel amount. For unit energy consumption, CO₂ emissions are 71.55 Nm³/MW, 107.56 Nm³/MW, 138.49 Nm³/MW, and 148.63 Nm³/MW for FIGP-H₂, FIGP-CH₄, FIGP-coal, and FIGP-biomass. Although biomass theoretically has higher hydrogen to carbon ratio than coal, this advantage is offset by a low LHV disadvantage, leading to a higher CO₂ emission.

Regarding gas composition, the exhaust gas CO_2 proportion is the highest in FIGP-coal and the lowest in FIGP-H₂. However, due to the large amount of N₂ introduced into the CCP, the CO₂ proportion is less than 30 %, which will bring trouble to the subsequent de-CO₂ process. There is significant potential for using high-quality gas to prepare other chemical products for carbon sequestration rather than burning it to generate electricity. It should be noted that the equivalent carbon dioxide emission was not considered in this paper. If the equivalent CO₂ of electric power is considered, the equivalent CO₂ emission in China is 0.1603 kg/MJ, while that in the United States is 0.1071 kg/MJ. Even if the maximum FIPG biogas is used, the CO₂ emission in each process is about 13.75–20.60 kg, which is very small compared with the overall carbon emission.

4. Conclusions

To promote the development of the flash ironmaking process, a complete flash ironmaking cycle power generation process (FIPG) is firstly constructed in this paper. The material, energy, and exergy flow are investigated to determine the potential, and different fuels are



Fig. 14. The Sankey chart of exergy flow in FIGP-H2.



Fig. 15. The Sankey chart of exergy flow in FIGP-CH₄.



Fig. 16. The Sankey chart of exergy flow in FIGP-coal.

compared. The process simulation was established based on the Gibbs free energy minizine principle, which can be divided into the flash ironmaking coupling (FIC), settler heating (SH), and combined cycle power (CCP) processes. The sensitivity analysis was used to determine the optimum conditions, and the optimized material flow was obtained. The mass flow, energy flow, exergy flow, and CO_2 emissions were calculated and compared simultaneously. The main conclusions include the followings:

1. In FIC, the optimized conditions determined using the crossings points of temperature (1350 °C) and reduction degree (0.7) contours are (H₂: $R_F = 0.16$, $R_O = 2.11$), (CH₄: $R_F = 0.43$, $R_O = 1.58$) and

(Coal: $R_F = 0.59$, $R_O = 0.88$). Due to the low heating value of biomass, its optimized amount remains far higher than others even with reduced requirements (reduction degree = 0.6) (Biomass: $R_F = 4.3$, $R_O = 0.39$). In SH, except for the biomass condition, which requires a high level of extra fuel, the other three cases have only a slight difference. A suitable replenished oxygen/coal ratio ($R_{OR} = 0.74$) ensures a high carburization rate and temperature with fewer fuel amounts.

2. From the perspective of energy conversion, fuels account for the absolute majority of heat expenditure, while the electricity produced by CCP accounts for most of the energy benefit. Meanwhile, chemical energy from iron is the third largest expenditure item, with a share



Fig. 17. The Sankey chart of exergy flow in FIGP-biomass.



Fig. 18. The comparison of CO₂ emissions during different processes.

ranging from 10.91 % to 21.71 %. Exergy analysis provided a detailed flow chart showing the highest efficiency (48.6 %) in FIPG-H₂ and the lowest (43.0 %) in FIPG-biomass. Compared with IGCC, FIPG obtained a higher efficiency in FIPG-coal because of the storage energy effect in the hot metal. In terms of the economy, the value of by-products can account for about 30 % of the overall economic benefits. Adding iron ore can enhance energy utilization and economic benefits with the same fuel consumption.

- 3. The most critical CO₂ generation stage is the CCP process. The CO₂ emissions per energy consumption unit are 71.55 Nm³/MW, 107.56 Nm³/MW, 138.49 Nm³/MW, and 148.63 Nm³/MW for FIPG-H₂, FIPG-CH₄, FIPG-coal, and FIPG-biomass.
- 4. In a comprehensive comparison, the FIPG-H₂ has the highest energy efficiency and exergy efficiency and the lowest CO₂ emissions. However, hydrogen is a semi-industrial product, and its preparation process has not been included in the calculations. A cheap and low-energy hydrogen preparation process would be the key to realizing hydrogen metallurgy. FIPG-CH₄ and FIPG-coal are close in energy or exergy efficiency, but the latter has much higher carbon emissions.

The biomass is unfavorable for the FIC because it is challenging to meet the temperature and reduction degree requirements. However, since biomass is a renewable energy source from vast sources, gasification and purification followed by FIC are more reasonable than direct gasification in the FIC reactor.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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