APEM journal

Advances in Production Engineering & Management
Volume 16 | Number 3 | September 2021 | pp 348–358
https://doi.org/10.14743/apem2021.3.405

ISSN 1854-6250
Journal home: apem-journal.org
Original scientific paper

Simulation-based optimization of coupled material–energy flow at ironmaking-steelmaking interface using One-Ladle Technique

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ABSTRACT

The ironmaking-steelmaking interface of the steel manufacturing process involves the hot metal ladle circulation and the energy dissipation which are coupled processes with an interrelated but independent relation. Therefore, the synergistic operation of the material flow and the energy flow at the interface is momentous to the effective production of the ironmaking-steelmaking section. However, there is a lack of solutions to realize the synergy. Here, we presented a coupling simulation model for the material flow and energy flow of the ironmaking-steelmaking interface, based on the mathematical description of their operation behaviors, the operation and technical model of the production equipment and the temperature-decreasing model of the ladle. Further, the coupling simulation model was applied to a concrete ironmaking-steelmaking interface using the One-Ladle Technique. The coupling simulation model proved its performance in providing comprehensive decision-making supports and optimized production management strategies by achieving a solution that results in a decline of 10 °C in the average temperature drop of the hot metal and a reduction in the cost per tonne of steel by CNY 1.02.

ARTICLE INFO

Keywords:
Metallurgy;
Ironmaking process;
Steelmaking process;
Ironmaking-steelmaking interface;
Coupled material-energy flow;
Discrete event simulation;
Optimization;
One-ladle technique

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Article history:
Received 8 August 2021
Revised 17 September 2021
Accepted 19 September 2021

1. Introduction

1.1 Problem background and description

The important ironmaking-steelmaking interface serves as the interconnection between the ironmaking plant and the steelmaking plant in the long-route steel manufacturing process. This section involves three processes, i.e. blast furnace (BF) for ironmaking, Kambara Reactor (KR) for hot metal pretreatment and basic oxygen furnace (BOF) for steelmaking. The transportation of the hot metal is the main logistics process in this section. The "One-Ladle Technique" of the ironmaking-steelmaking interface is a new technology for metallurgical process and transportation optimization emerged in the past decade [1]. The specific process is shown in Fig. 1: The empty ladles are pushed, usually, by a locomotive to the BF to charge the hot metal, after which the empty ladles become full ones. The full ladles are then transported to the buffer zone before the KR process. A crane lifts a ladle and transports it to the KR station for processing. Next, the ladle is again lifted by a crane to the BOF, into which the hot metal is poured. The full ladle becomes empty and then is directly put into the buffer zone by the same crane. Finally, the ladle is again transported by a locomotive to the BF and another circulation begins.

The ladle circulating rate affects the temperature drop of the hot metal and the ladle itself. In the circulation process, the material flow and the energy flow show an interweaved and interactive relationship. The multi-flow coupling phenomenon is the inherent characteristics that cannot be neglected when analyzing and optimizing the ironmaking-steelmaking interface [2]. The "One-Ladle Technique" puts forward higher requirements for ladle circulation, energy conversion, and time coordination in the production process. If too many ladles are running in the circulation, the charging waiting time increases, thereby increasing the temperature drop of the hot metal. However, the tapping temperature after the BOF process is constant, therefore the lower temperature of the hot metal poured into the BOF, the more heating agent is necessary to increase the temperature and longer processing time are required, which leads to a longer waiting time for the subsequent full ladle to be handled and a larger temperature drop. In summary, too many ladles will increase the waiting time, temperature drop, process processing time and auxiliary material cost. In turn, the lack of ladles will cause logistics interruption which affects the production. Therefore, the number of online ladles requires scientific decision-making.

The optimization analysis on the flow-coupling should focus on the optimization of logistics parameter configuration with the goal of reasonable cycle time, low production temperature drop, and low production cost. Therefore, aiming at the optimization of the ironmaking-steelmaking interface using the One-Ladle Technique, this paper develops a simulation model to conduct the analyses based on a real steelworks.

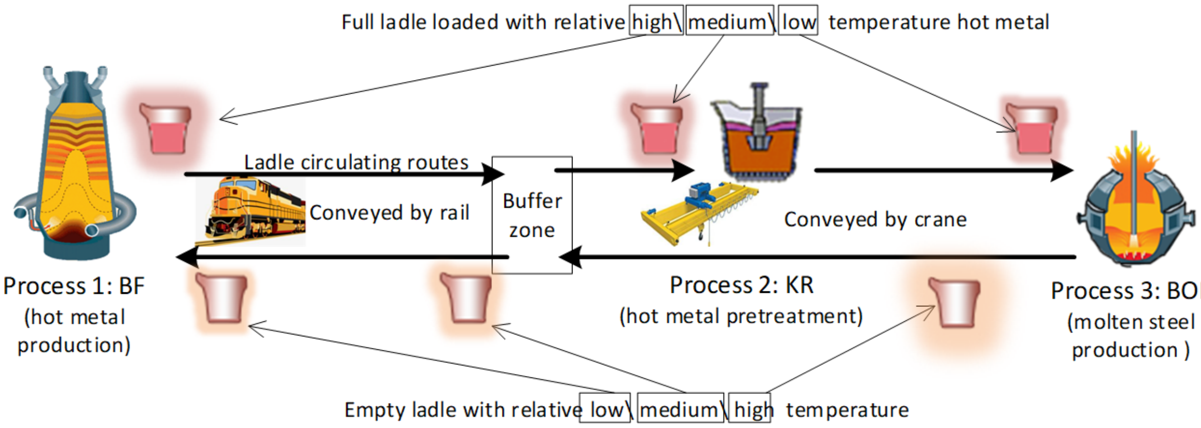

Fig. 1 Schematic of process flows at ironmaking-steelmaking interface

1.2 Previous work

Remarkable progress has been made in recent years in studying the ironmaking-steelmaking interface in terms of layout planning [3-8], connection mode of the interface [9-10], transportation scheduling [11-16], ladle circulating control [1, 2, 17-20], and hot metal temperature drop [21-23]. As regards layout planning, Fan *et al.* [3] analyzed and summarized the characteristics of three modes of transportation: railway, crane + transfer car and special roads at the ironmaking-steelmaking interface, and the relations with One-Ladle Technique and the general layout planning. Wiyaratn *et al.* [6] employed the SLP method in researching and evaluating the connection relationship between processes and compared the optimal schemes of the system under different layout plans. Concerning respect to the connections at the interface, Qiu *et al.* [7] analyzed the technological characteristics of the ironmaking-steelmaking interface in six typical process routes from the aspects of time, temperature, flow rate, production management, hot metal pretreatment effect, energy consumption, environmental pollution, etc. by using systematic scientific reduction theory and holism. As far as transportation scheduling is concerned, Tang *et al.*

[11, 12] studied the issues concerning the scheduling of arriving and departing torpedo ladle locomotives, and established a mixed integer programming model for scheduling of the hot metal transportation locomotives. And for ladle circulating control, Zhao *et al.* [1] adopted the multi-agent system to simulate the production logistics system of steel producers, and pointed out that the logistics efficiency should be improved by shortening refining cycle, increasing transportation speed, upgrading desulfurization equipment, etc. Xiao *et al.* [17] made analyses on possible optimization of production management schemes involving ladle preparation mode, number of online ladles at the ironmaking-steelmaking interface with One-Ladle Technique by material flow simulation. As for hot metal temperature drop, Du *et al.* [21] analyzed the heat dissipation mechanism of hot metal during hot metal receiving, transportation and pretreatment, etc. at the ironmaking-steelmaking interface from a heat transfer viewpoint, and established a mathematical model of hot metal temperature drop at the interface between hot metal ladle and charging ladle. Chen *et al.* [24] studied the fuel gas operation management practices for reheating furnace. Chen *et al.* [25] studied the effect of the production fluctuation on the process energy intensity in iron and steel industry, which revealed the relation of process energy intensity to the production operating rate and qualification rate.

In summary, the current research on the optimization of operation at the ironmaking-steelmaking interface focuses on optimization of the ladle circulation in the material flow or the temperature drop control in the energy flow but ignores the intrinsic rule of coupling control and synergy of material flows and energy flow during the operations at the interface. Operations at the ironmaking-steelmaking interface bear information on five dimensions: plan, time, equipment, operation, and temperature and composition of hot metal. As a single math or model method usually cannot take all the information of different dimensions into comprehensive consideration, it's necessary to perform dimensionality reduction to simplify the information [26], making it difficult to analyze the influence of various factors on production when the material flow is coupled with energy flow, thus offering limited guidance for optimization of the production.

Based on the Tecnomatix Plant Simulation development platform, this paper builds a coupled simulation model. The model considered the operation behaviors of the material flow and energy flow, the operation and technical model of the production equipment and the temperature-decreasing model of the ladle that reflects the energy flow. Different organizing strategies were employed, the performances were evaluated by the production indicators, i.e. ladle cycle time, the temperature of hot metal charged into BOF, operating cost.

2. Simulation model description

2.1 Model description

Driven by the time flow, the material flow and the energy flow in the manufacturing process converge in a certain production process where the processing is handled under the interaction of the two flows. The synergetic coupling of the two flows are reflected through the product output and the energy consumption. Therefore, the simulation model Mod, which consists of Plan P, Time τ, Equipment N and E, Operation f and Material Temperature Component M as shown in Eq. 1, realize the simulated expression to the real manufacturing processes by abstracting their physical characteristics and running rules, as shown in Eq. 2.

$$Mod = f(N, M, E, P^{\tau}) \tag{1}$$

$$S^{\tau} = \begin{cases} f_N(Grid, ME, TE) \\ f_M(Ent, Con) \\ f_E(T_{tra}, AE_{pro}, AE_{Equ}) \\ f_{P^{\tau}}(Equ, Cra, SC) \end{cases} \tag{2}$$

In Eq. 2, S^{τ} refers to the system status at time τ. $f_N(Grid, ME, TE)$ is the modeling rule whereby the ME (main equipment), TE (transportation equipment) and the directed $Grid$ constitute a model operation network. $f_M(Ent, Con)$ describes the operation rules on how the positions and properties change of the material entities Ent (hot metal) and the containers Con (ladle). $f_E(T_{tra}, AE_{pro}, AE_{Equ})$ expresses the energy flow rules. According to the roles of the energy played in the production, the rules contain the energy changing rule T_{tra} characterized in temperatures during transportation between processes, auxiliary energy adding rules AE_{pro} characterized by the addition of auxiliary materials during the processing, and energy consuming rules AE_{Equ} characterized by the consumption of materials when equipment is running. $f_{P^{\tau}}(Equ, Cra, SC)$ is the production (operation) rules at time τ of the equipment or transportation devices (crane Cra and span car SC) under a production schedule.

Through its four simulation modules on logistics, equipment, control and information, as shown in Fig. 2, the simulation model above can simulate the interaction and conversion process of the material and energy during the ladle circulation in a way much closer to the reality:

1) When modelling, the equipment module is first selected to build the simulated production environment. The equipment parameters set include the operating procedures, durations, types and amounts of energy consumed;
2) When running, the logistics rules in the operation control module and the control models in the material-energy control module can be called to push the simulation running as planned and calculate the changes in transportation temperature, material and energy medium consumption occurred during the ladle circulation. Various process data is recorded by the information module, which realizes the quantitative analysis of the simulation system.

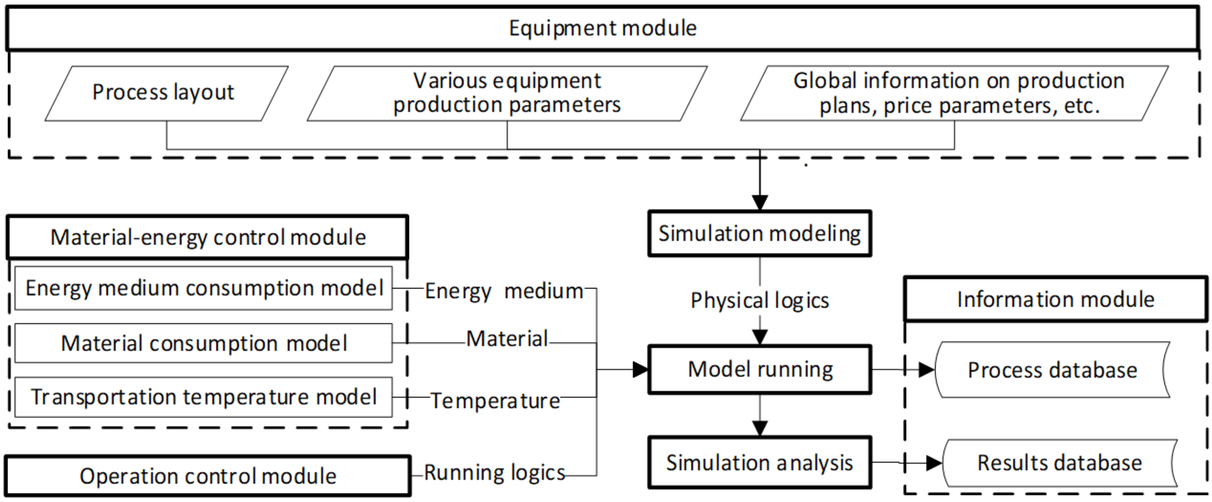

Fig. 2 Modules in simulation model

2.2 Functions of two key modules

The control modules in the simulation model contain the operation control module and the material-energy control module, as shown in Table 1, which serve as the running brain of the model, directing the orderly changing of the materials and energy in the logistical network. The operation control module controls the orderly transportation and processing of the material units between or in the process(es); while the material-energy control module is responsible for calculating the energy media needed to achieve the target temperature.

Table 1 Technical parameter design for two key modules

Type	Model		Description	Function
Operation control module	Production plan model		P_{TPush}	Decide the production plans, target composition and temperatures for each process according to the casting plan
	Crane operation and scheduling model		C_{Sche}	Order the cranes to complete the transportation tasks
	Span car operation and scheduling model		V_{Sche}	Order the span car com transporting task across bays
	Process equipment operation model		E_{Sche}	Executing production task according to equipment operating procedures
Material- energy control module	Material consumption model	Production specification model	M_{Rule}	Set the consumption per ton of steel in a certain process
		Linear consumption model	M_{Line}	Material consumption has a linear relationship with the components to be processed
		Non-linear relational model	M_{NonL}	Material consumption has a linear non-relationship with the components to be processed
		Temperature compensation model	M_{TCom}	Adopt physical heating method to reach target temperature
	Energy medium consumption model	Electric energy consumption model	Q_{Power}	Electric energy consumption for equipment operation
		Water consumption model	Q_{Water}	Consumption of water of various types for equipment operation
		Gas consumption model	Q_{Air}	Consumption of gases for equipment operation
	Temperature change model	Temperature drop model for hot metal charged into different ladles	T_{Charg}	Temperature drop caused by change of the hot metal containers
		Temperature drop model for hot metal transportation	T_{Trans}	Temperature changes of hot metal under different working conditions
		Temperature change model for the lining of an empty ladle	T_{Ladle}	Temperature changes of empty ladle under different working conditions

2.3 Logic flow of simulation operation

The actual production can be deemed as the combination of a series of chronological events, including the transport events and processing events of the unit material. Therefore, the coupling simulation model employs the trigger-based discrete simulation mechanism in which the temperature and material composition information carried by the hot metal is set as the conditions to activate various sub-models of the control modules under different events. The activating conditions are shown below:

```
Start Simulation
   Call $P_{TPush}$ for production plan
Do
      Scan task queue
      Select task characteristics
      Case transportation task
            If Crane transportation then
                Call $C_{Sche}$ and $T_{Charg}$ and $T_{Trans}$ and $T_{Ladle}$
            End
            If Span car transportation then
                Call $V_{Sche}$ and $T_{Charg}$ and $T_{Trans}$ and $T_{Ladle}$
            End
      Case process processing task
         Call $E_{Sche}$
         Call $M_{Rule}$ and $M_{Line}$ and $M_{NonL}$ and $M_{TCom}$
         If using power, then
               Call $Q_{Power}$
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```
          End
          If using water, then
              Call $Q_{Water}$
          End
          if using gaseous media, then
              Call $Q_{Air}$
          End
     End inspect
   Loop until Simulation End
```

In the simulation operation, the temperature of hot metal is used as the condition to decide the priority of related transportation tasks. When reaching the process equipment, the temperature and composition of hot metal is firstly corrected according to the transportation situation and then treated as the inputting condition for the processing tasks. The corresponding material-energy model is enabled to calculate the materials and energy added to bring the temperature and property of the hot metal to reach the target. After that, the new information on hot metal temperature and composition is achieved and a loop starts until the end of the final process. More details are shown in Fig. 3.

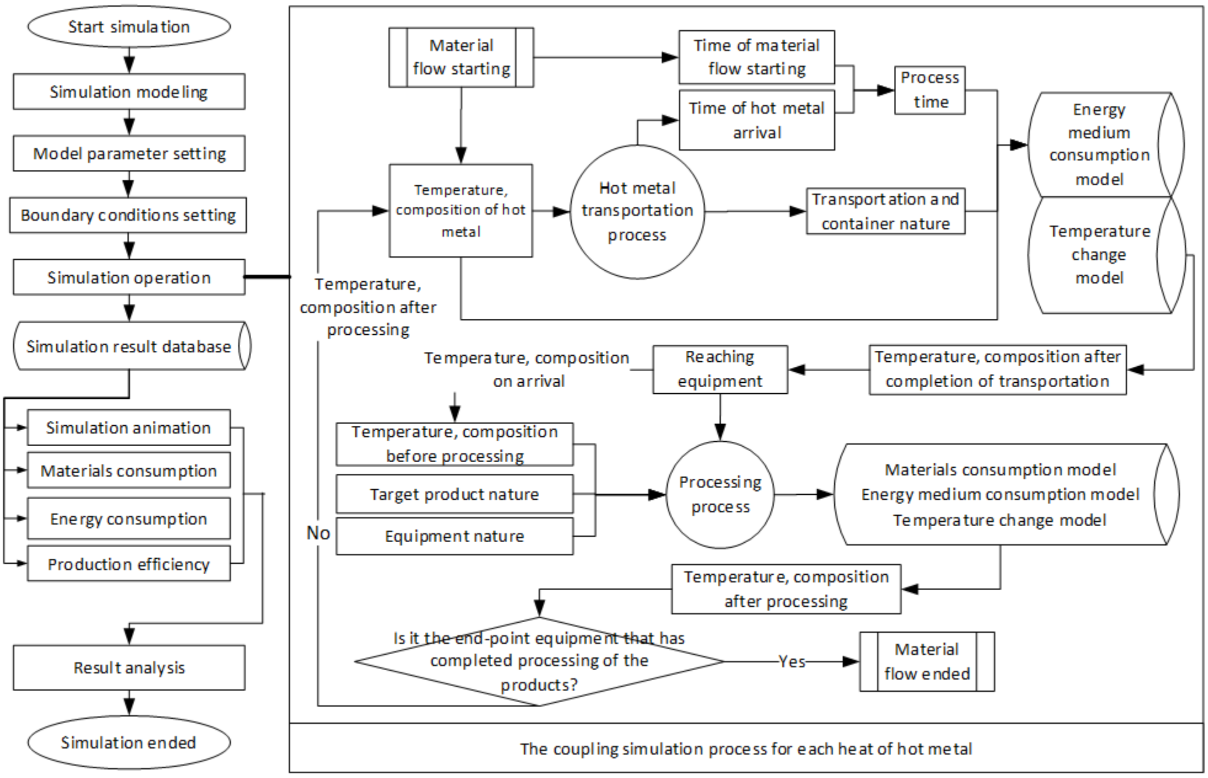


Fig. 3 Model operation flow

3. Results and discussion: Case studies

3.1 Simulation cases

The advantages the One-Ladle Technique offers vary greatly with the enterprises where it was employed. Aiming at offering optimal recommendations to improve the ironmaking-steelmaking interface logistics of Steelworks, A using One-Ladle Technique, a simulation model is built to obtain the operation solutions under different production strategies. Fig. 4 shows the model built on the operating relationships between specific equipment, material flow and energy flow of Steelworks A. The interface is composed of 2 BF, 4 KR, 3 BOF and other auxiliary devices. The ladle is transported by the span car between BF and buffer zone, and by crane between buffer zone, KR and BOF. The moving path of the full ladle is marked by the directed red lines while the path of the empty ladle by the directed green lines.

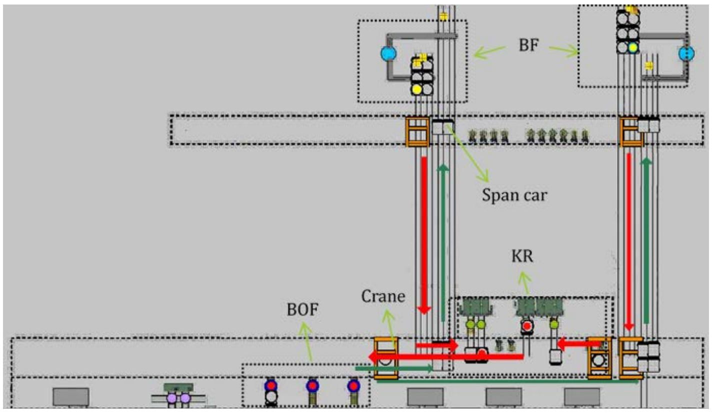


Fig. 4 Model simulation operation

In Fig. 4, each circle represents an empty ladle, and each red filled circle, and yellow filled circle stands for a ladle fully charged and a ladle half charged. When a filled circle is in the center of the equipment, it means a ladle is under processing at that station. By setting different process parameters in the model, the simulation operation provides indicative parameters describing the operating characteristics of the system quantitatively, allowing for analyses on how to ensure optimization of the production with the One-Ladle Technique.

According to the historical performance record of the two BFs in Steelworks A, 4 to 5 ladles on average are prepared to charge hot metal from the two under normal conditions, and 6 ladles are used at the peak period. Each BF has two tapping outputs through which the hot metal is tapped, the ladles prepared and tapping lines of each BF are set as shown below in Table 2.

In real operation, the tapping durations of the two BFs is different. Therefore, two tapping conditions are considered for #1 BF and #2 BF: One is that both BFs tap at the same time, and the other is that one taps 1 hour earlier than the other. These two tapping conditions, when combined with the ladle preparation patterns as mentioned above in Table 2, lead to 6 different working conditions, as shown below in Table 3.

In order to analyze the impact of different logistics parameters on production, the simulation is modeled according to the 1:1 layout of the ironmaking-steelmaking interface of Steelworks A. The simulation span is 24 h, during which 92 heats of hot metal are transported into the BOF. The hot metal output rate of the BFs is set to be 400 t each time, the hot metal tapping rate is 5 t/min, the initial temperature of the hot metal is 1500 °C. The BOF processing time is 38 min/ while the KR processing time 36 min. The speed of the span car carrying a full ladle is 20 m/min, and 30 m/min when carrying an empty ladle. The running speed of the crane is 60 m/min and the hoisting/dropping time 2.5 min. The temperature drop in the transportation process is 1 °C/min.

Table 2 Number of ladles prepared for each tapping line

		Ladle prep. pattern 1	Ladle prep. pattern 2	Ladle prep. pattern 3
Number of tappings per day		12	12	13
Total number of ladles made available per BF		6	5	4
Taphole A	Number of tapping lines	2	2	2
	Number of pallets per line	3	3	3
	Number of ladles for #1 tapping line	3	3	2
	Number of ladles for #2 tapping line	3	2	2
Taphole B	Number of tapping lines	2	2	2
	Number of pallets per line	3	3	3
	Number of ladles for #3 tapping line	0	0	0
	Number of ladles for #4 tapping line	0	0	0

Table 3 Establishment of simulation cases

Case No.	Ladle preparation pattern	Tapping condition
Case I	Pattern 1	Two BFs tapping at the same time
Case II	Pattern 1	One BF tapping 1 hour earlier than the other
Case III	Pattern 2	Two BFs tapping at the same time
Case IV	Pattern 2	One BF tapping 1 hour earlier than the other
Case V	Pattern 3	Two BFs tapping at the same time
Case VI	Pattern 3	One BF tapping 1 hour earlier than the other

3.2 Analyses of the simulation model results

Analyses of the simulation model results are included in the comprehensive evaluations of the material flow and the energy flow. Therefore, the ladle cycle period ρ_{ladle} is used to evaluate the material circulation efficiency (see Eq. 3). It shows that when the proportion of heats is higher while the cycle time for those heats is shorter, the material flow operation efficiency is higher. And, the average temperature of the hot metal charged into BOF t_{charge} is adopted to analyze the energy losses of the system (see Eq. 4). It suggests that the higher the average temperature of hot metal charged into BOF, the lower the temperature drop of the system. The operating costs C comprehensively reflects the situation of various material energy consumed by the system under the action of the material flow coupled with the energy flow, which is useful to evaluate the production outcomes (see Eq. 5).

$$\rho_{ladle} = \frac{Num(T_{min} \leq T_{ladle} < T_{max})}{n} \times 100~\% \tag{3}$$

$$t_{charge} = \sum_{i=1}^{n} t_i / n \tag{4}$$

$$C = \sum_{j=1}^{m} (P_j \times W_j) / S_{weight} \tag{5}$$

In these equations, $Num(T_{min} \leq T_{ladle} < T_{max})$ represents the number of heats within the ladle cycle time, between T_{min} and T_{max}; n means the total number of heats; t_i is the temperature of the hot metal in a heat when it can be charged into the BOF; P_j refers to the unit price of the Material j consumed; W_j stands for the weight of the Material j consumed; m is the total types of materials consumed, and S_{weight} is the amount of the molten steel produced.

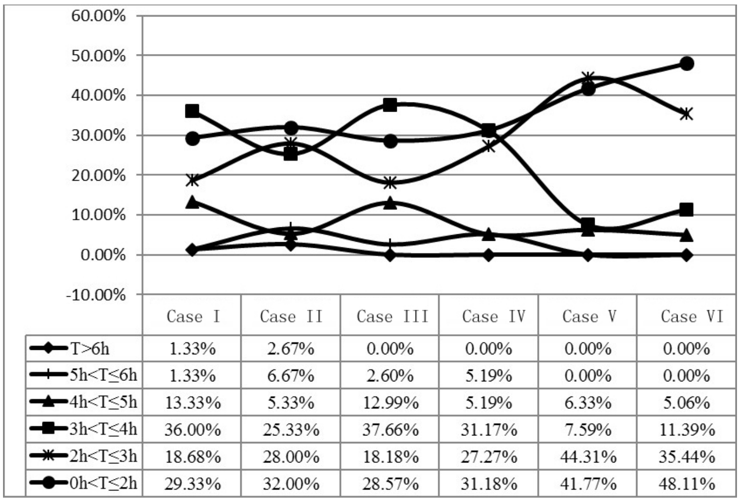
3.3 Analyses of simulation results

The simulation test was carried out according to the aforementioned input conditions. From the perspective of material flow operation efficiency, production condition is a significant impact factor. As shown in Fig. 5, there is a significant difference in the distribution of the ρ_{ladle} of each case. Both Cases I and Ⅱ have a production situation where the ladle cycle period is greater than 6 hours. This means that some ladles are in a condition waiting for the hot metal tapping; the logistics operation efficiency of Case VI is the highest, and the ratio of the number of furnaces in the range of 0 to 2 hours for the turnover time of the iron ladle is 48.11 %, which is the lowest (case 1) 18.78 % higher. It can be seen that the tank allocation system 3 and the interval tapping of the two BFs are beneficial to improve the operating efficiency of the material flow.

Temperatures of the hot metal charged into the BOF are used as an indicator to measure the energy flow conversion. Under the same initial temperature conditions, the higher the temperature of the hot metal transported into BOF, the smaller the temperature drop of the system. Fig. 6 presents the effect of different material flow operation efficiencies on the energy flow. The average temperature of the hot metal charged into the BOF in Case VI with the highest material flow operation efficiency is 10.3 °C higher than that in Case I. This indicates that the higher the material flow operating efficiency, the smaller the temperature drop of the system.

Different transportation time of the hot metal causes temperature fluctuation when it arrives at the BOF, thus influencing the consumption of production materials. In the simulation, the material consumption model is used to calculate the consumption of material and energy for each process realization of equal changes in the nature of hot metal material flows at different temperatures, and the production effects are comprehensively reflected in the operating costs. Fig. 7 shows the comparison of operating costs between different cases by using Case I as the benchmark. The costs per tonne of steel in Case VI are CNY 1.02 yuan lower than in Case I, which is an annual CNY 10.2 million yuan saving considering a steel plant with a 10 million tonnes capacity of the steel production.

The built simulation model is, as shown above, able to reproduce the processes in which the material flow and the energy flow interact at the ironmaking-steelmaking interface. It also can quantitatively reflect the impact of different production strategies on operation in terms of indicators such as ladle cycle time, temperature of hot metal charged into BOF, and operating costs, thus eliminating the restrictions of evaluating production only from the perspective of material flow efficiency or temperature control in energy flow. The analyses of the simulation results also indicate that application of the optimization strategies, e.g., increasing the tapping frequency, reduces the total number of ladles prepared for each BF. Moreover, an 1 hour tapping interval of two BFs enables Steelworks A to increase the average temperature of the hot metal charged into BOF by 10.28 °C, and reduce the cost per tonne of steel by CNY 1.02.



	Case I	Case II	Case III	Case IV	Case V	Case VI
◆ T>6h	1.33%	2.67%	0.00%	0.00%	0.00%	0.00%
+ 5h<T≤6h	1.33%	6.67%	2.60%	5.19%	0.00%	0.00%
▲ 4h<T≤5h	13.33%	5.33%	12.99%	5.19%	6.33%	5.06%
■ 3h<T≤4h	36.00%	25.33%	37.66%	31.17%	7.59%	11.39%
✳ 2h<T≤3h	18.68%	28.00%	18.18%	27.27%	44.31%	35.44%
● 0h<T≤2h	29.33%	32.00%	28.57%	31.18%	41.77%	48.11%

Fig. 5 Distribution of the ρ_{ladle} of each case

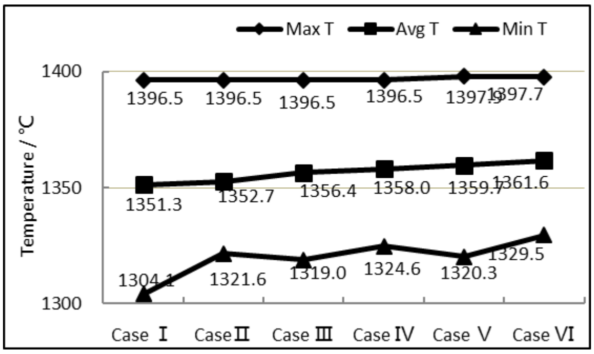


Fig. 6 Comparison of temperatures of hot metal charged into BOF

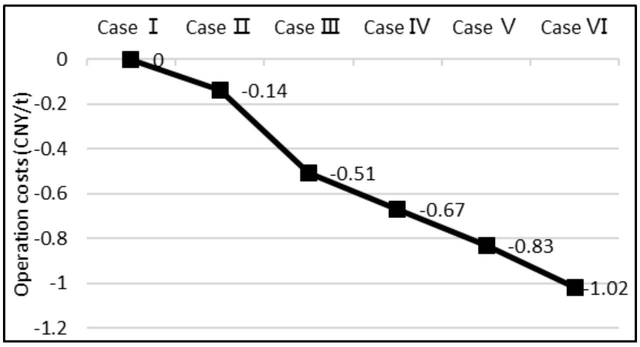


Fig. 7 Comparison of operating costs (in CNY per tonnes of steel)
Note: The operating cost in Case I is used as the benchmark reference

4. Conclusion

The coupling simulation model built in the study considered the operation behaviors of the material flow and energy flow of the ironmaking-steelmaking interface, the operation and technical model of the production equipment and the temperature drop model of the ladle. The energy-flow-driven moving process of the material simulated by the model reflects the interrelated but independent relation between material flow and energy flow.

The simulation results suggest that the simulation model can provide comprehensive decision-making supports for actual operation control and optimization of production management strategies. The optimized production management strategies result in an increase of 10 °C in the average temperature of the hot metal charged into BOF and a reduction in the cost per tonne of steel by CNY 1.02.

The methodology for building the coupling simulation model can be extended to the entire steel manufacturing process and become an optimizer to steel producers by providing decision-making supports in achieving efficiency improvements and cost reductions.

Acknowledgment

This work was financially supported by the National Natural Science Foundation of China (Grant No. 51734004) and partly by the National Key Research and Development Program of China (Grant No. 2020YFB1712803 and No. 2017 YFB0304005).

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