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Fluctuating Waste Heat Characteristics in Steel Plants: Recovery Optimization Study

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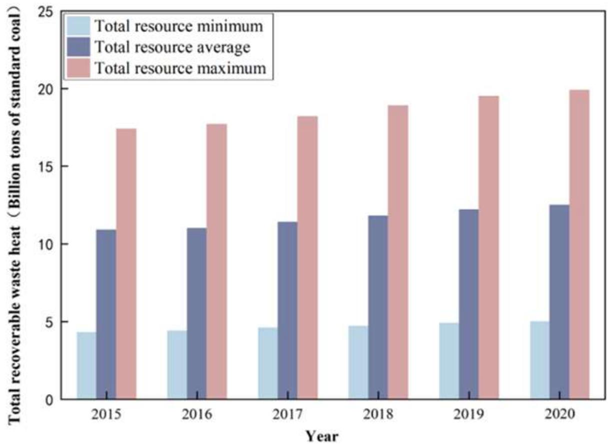
1. Introduction

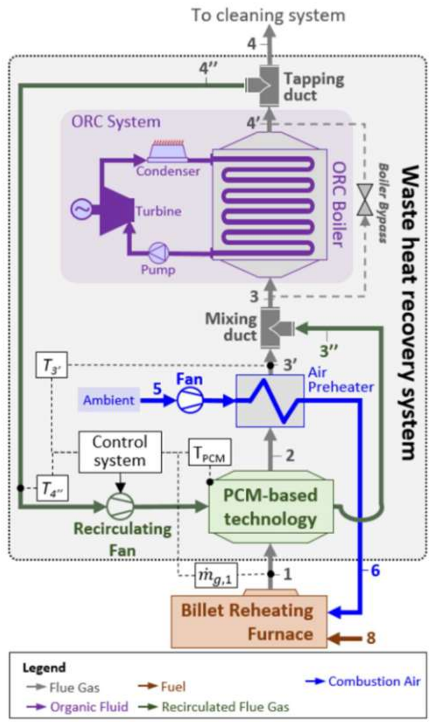
- **Low-carbon energy necessary**
  - High-carbon energy: global warming, environmental pollution
  - Steel plant waste heat gain attend
  - Low waste heat recovery: 30%~50%
- **Fluctuation of waste heat**
  - Hinder a constant supply of thermal energy for consumers, raises the difficulty of utilizing waste heat [3]
  - Influence the stable operation of waste heat utilization systems, reduced efficiency of waste heat utilization
- **Research**
  - High-temperature phase change materials on ORC[4]
  - Heat storage measures on ORC
  - Lack study in waste heat heating



Total recoverable waste heat resource in China[1]

The recovery of waste heat of China's steel industry[2]

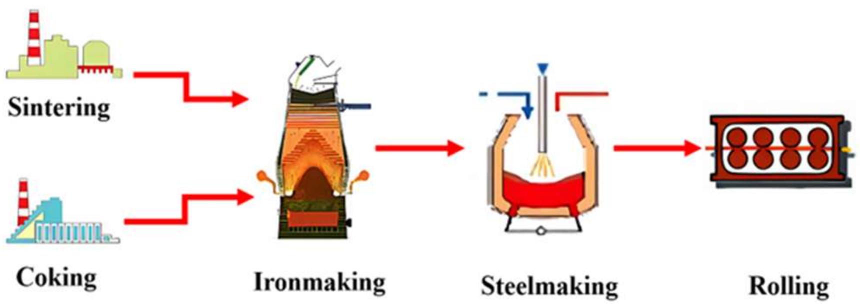
The quality of waste heat	Rate of recovery(%)
Low grade	1.59
Medium grade	30.2
High grade	44.4

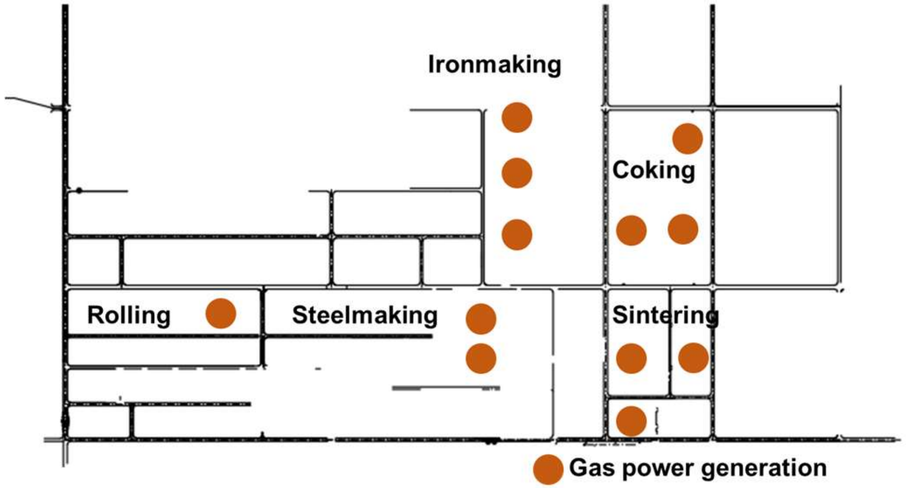


Integration of the PCM-based technology in the current waste heat recovery system[3]

[1] B. Liu, M. Jia, Y. Liu, Estimation of industrial waste heat recovery potential in China: Based on energy consumption, Applied Thermal Engineering(2024).
[2]G. Ma, J. Cai, W. Zeng, H. Dong, Analytical Research on Waste Heat Recovery and Utilization of China's Iron & Steel Industry, Energy Procedia(2012).
[3] P.J. Binderbauer, Regarding the generation of time resolved industrial waste heat profiles, Applied Thermal Engineering (2023).
[4] F. Dal Magro, M. Jimenez-Arreola, A. Romagnoli, Improving energy recovery efficiency by retrofitting a PCM-based technology to an ORC system operating under thermal power fluctuations, Applied Energy(2017) .

2. Method Introduction to steel plant





- **Location:** Tangshan, China
- **Production:** 13.7 million t/year

Process	Sources of waste heat
Coking	Flue gas Cooling water from primary cooler Exhaust steam from power generators
Sintering	Flue gas Exhaust air from ring cooler Exhaust steam from power generator
Ironmaking	Flue gas from hot blast furnace Slag flushing water from blast furnace Slag flushing steam from blast furnace Cooling water from blast furnace wall
Steelmaking	Converter gas cooling water Oxygen lance cooling water
Rolling	Flue gas from heating furnace
Gas power generation	Flue gas

2. Method Waste heat test

Location

- Slag flushing water, blast furnace wall cooling water(Ironmaking)
- Oxygen lance cooling water, converter gas cooling water (Steelmaking)
- Primary cooler cooling water(Coking)

Other waste heat

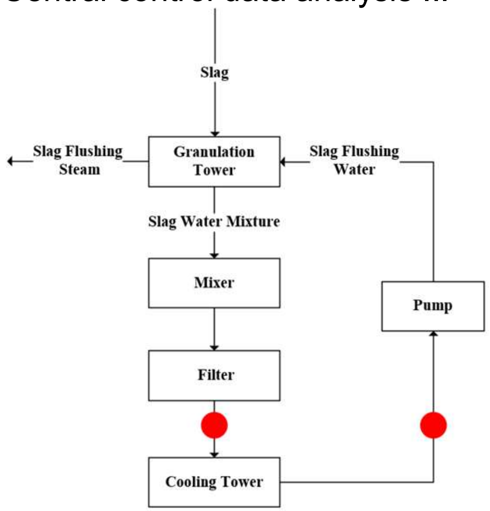
- Central control data analysis ...

Equipment

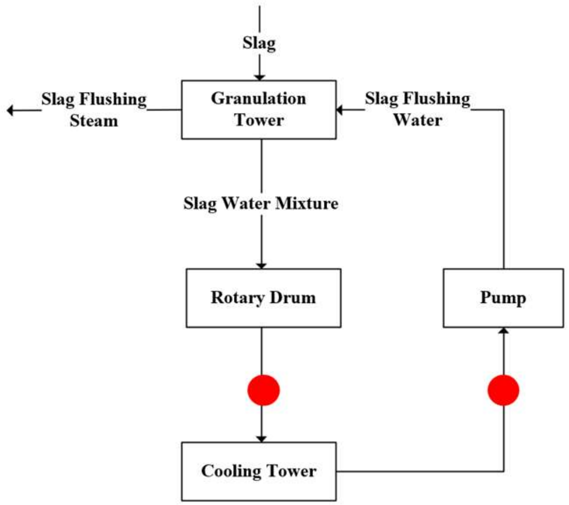
- WZY-1 thermometer(45)
- TDS-100H ultrasonic flowmeter

Frequency

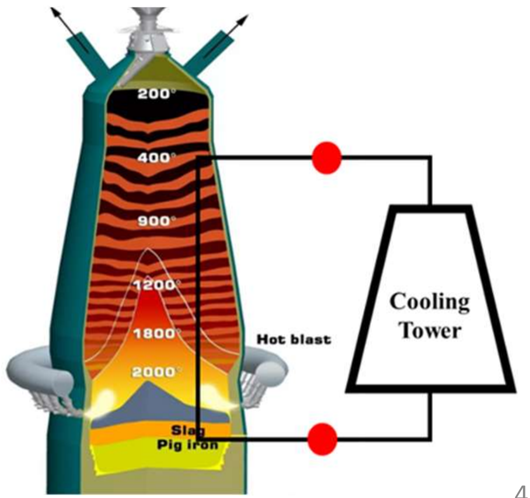
- Once *every 5 min* or *every 30 s*



Blast furnace 1# & 2# slag flushing



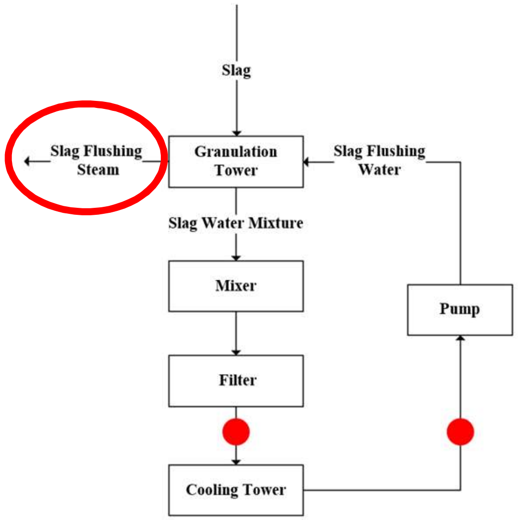
Blast furnace 3# & slag flushing

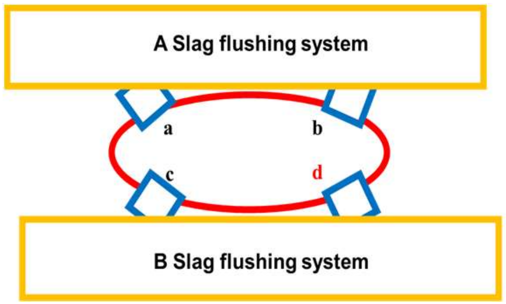


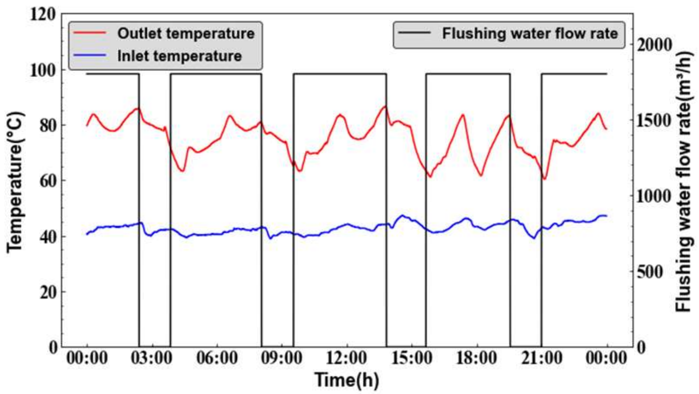
Blast furnace wall cooling water

3. Result Waste heat analysis with fluctuation characteristics(Ironmaking)

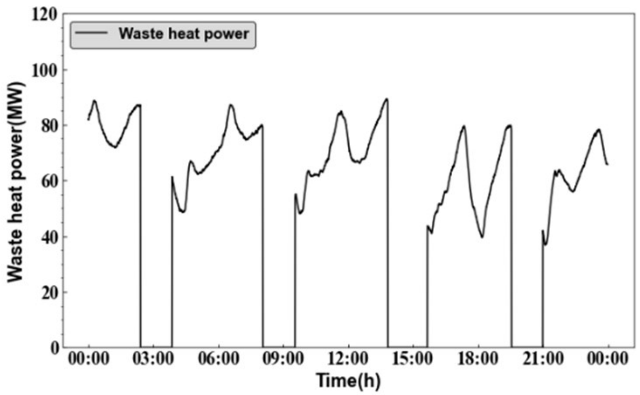
$$CV = \frac{\sigma}{\mu} \times 100\%^{[3]}$$







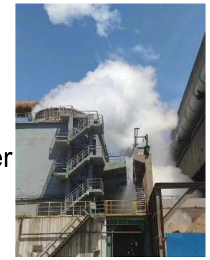
2#A slag flushing temperature & flow rate



2#A slag flushing power

Slag flushing steam

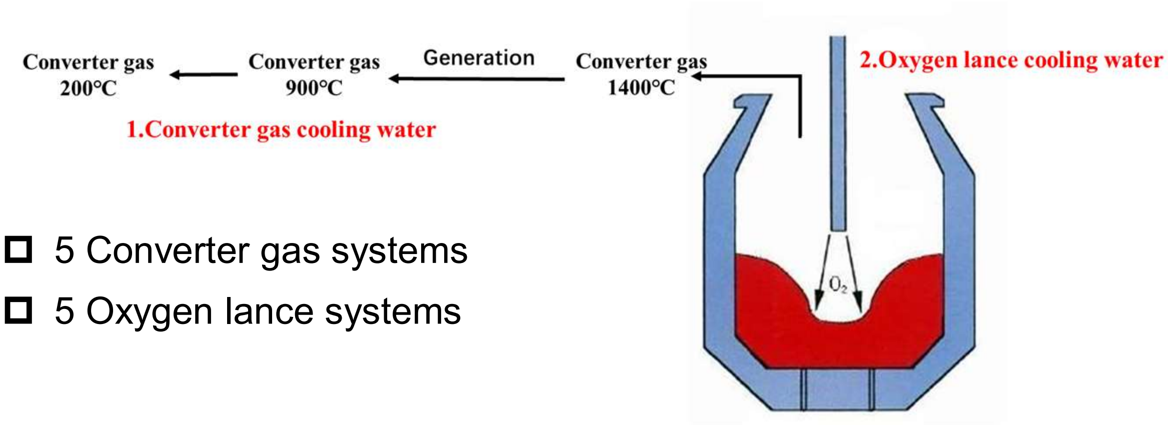
- Fluctuation: as same as water
- Power: 42%[1] of slag flushing water



Source	Power(MW)[2]	CV
1#A Slag flushing water	15.12	**71.2%**
1#B Slag flushing water	14.45	**122.5%**
2#A Slag flushing water	50.13	**62.7%**
2#B Slag flushing water	17.56	**120.2%**
3#A Slag flushing water	28.41	**61.6%**
3#B Slag flushing water	15.61	**115.3%**
Slag flushing steam	59.34	——
Total	**200.62**	

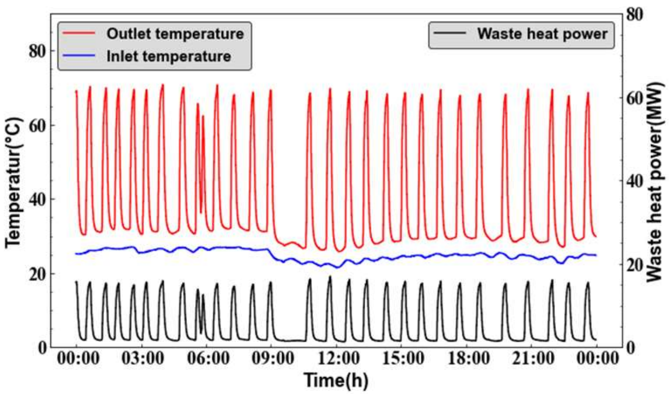
[1] Based on water replenishment data
[2] Average value
[3] The ratio of standard deviation and mean

3. Result Waste heat analysis with fluctuation characteristics(Steelmaking)

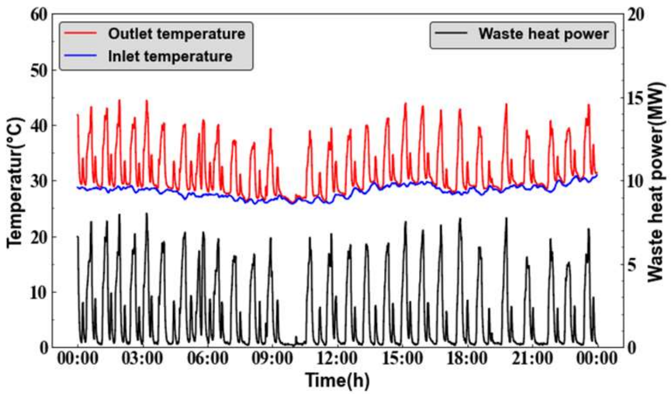


- 5 Converter gas systems
- 5 Oxygen lance systems

Source	Power(MW)[1]	CV
Converter gas	32.13	**97.5%**
Oxygen lance	12.43	**110.6%**
Total	**44.57**	



1# Converter gas cooling water

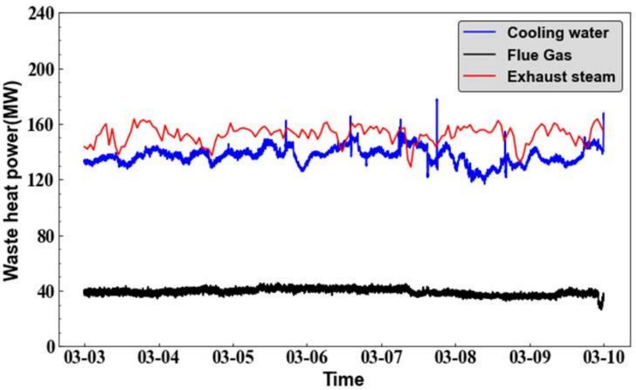


1# Oxygen lance cooling water

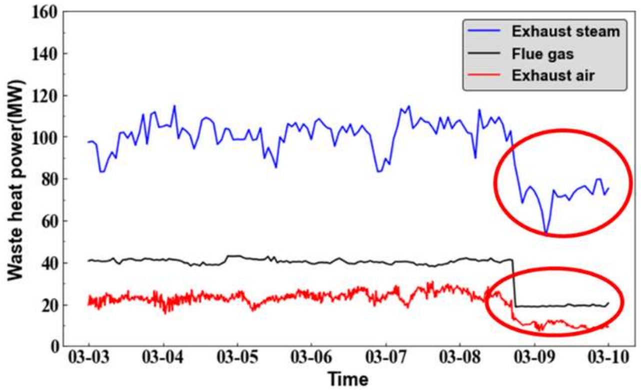
- **Fluctuating waste heat**
  - P_{Total}=245.18MW
  - All CV>50%

[1] Average value

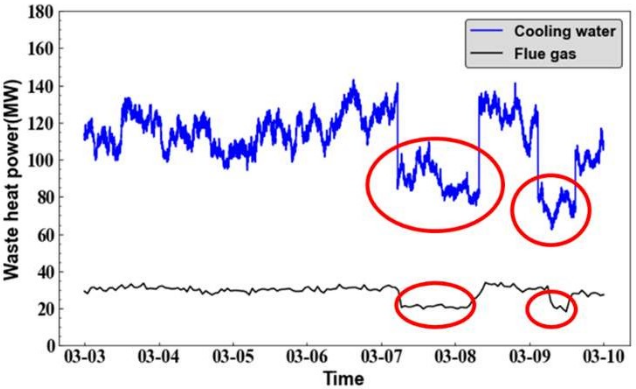
3. Result Waste heat analysis without fluctuation characteristics



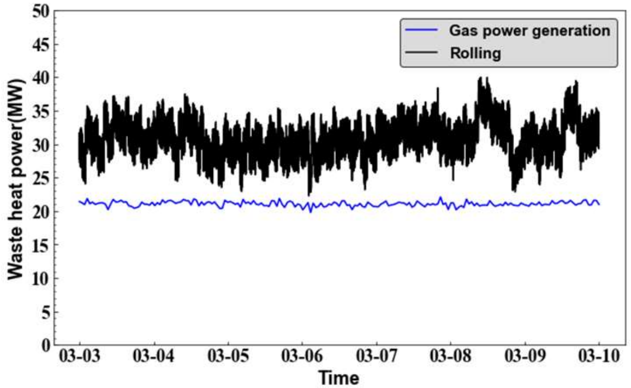
Coking waste heat without fluctuation



Sintering waste heat without fluctuation



Ironmaking waste heat without fluctuation



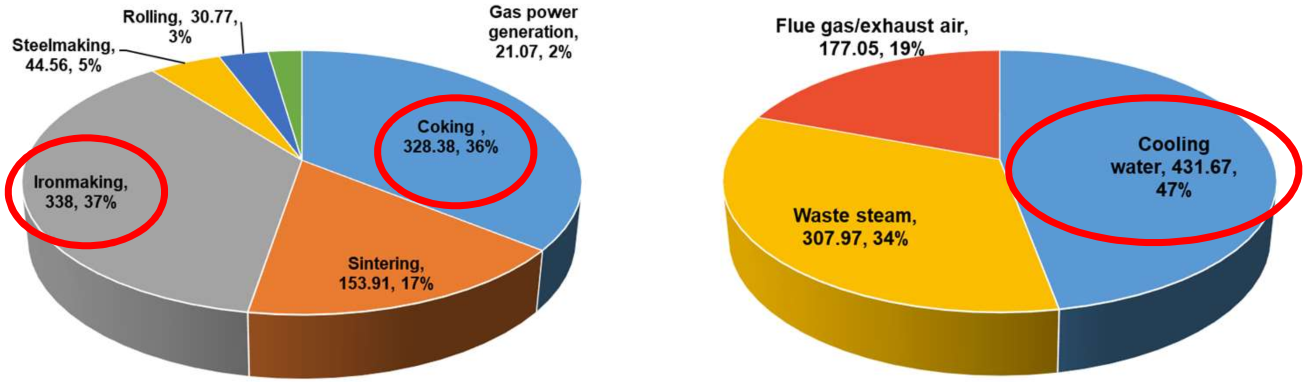
Rolling & Gas power generation waste heat without fluctuation

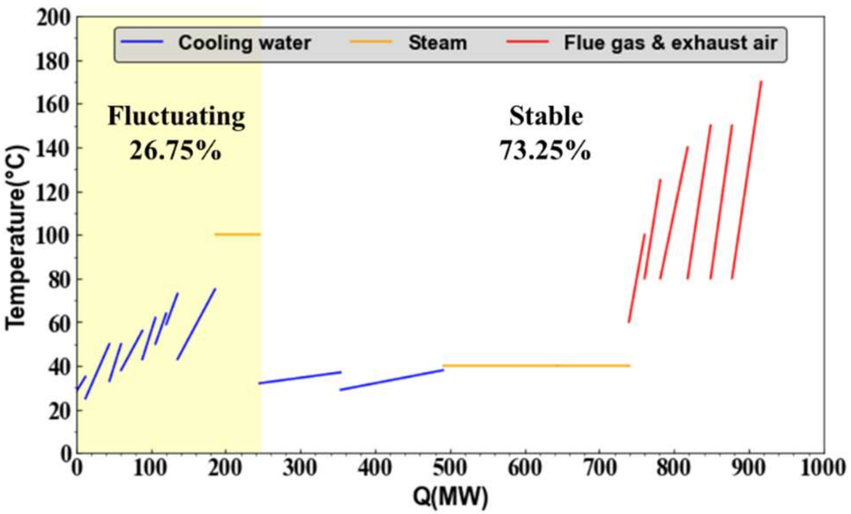
Process	Type	Power (MW)	CV
Coking	Cooling water	137.03	**4.6%**
	Flue gas	39.03	**6.0%**
	Exhaust steam	152.32	**4.0%**
Sintering	Exhaust steam	96.31	**13.4%**
	Flue gas	36.59	**22.5%**
	Exhaust air	21.01	**26.9%**
Ironmaking	Cooling water (Blast furnace wall)	108.80	**15.1%**
	Flue gas	28.58	**13.3%**
Rolling	Flue gas	30.77	**8.5%**
Gas power generation	Flue gas	21.07	**1.5%**
Total		**671.51**	

3. Result Cluster analysis of waste heat resources

Waste heat power

- P_{Total}=916.69MW
- Most Process: Ironmaking, Coking
- Most Medium: Cooling water





Fluctuating waste heat

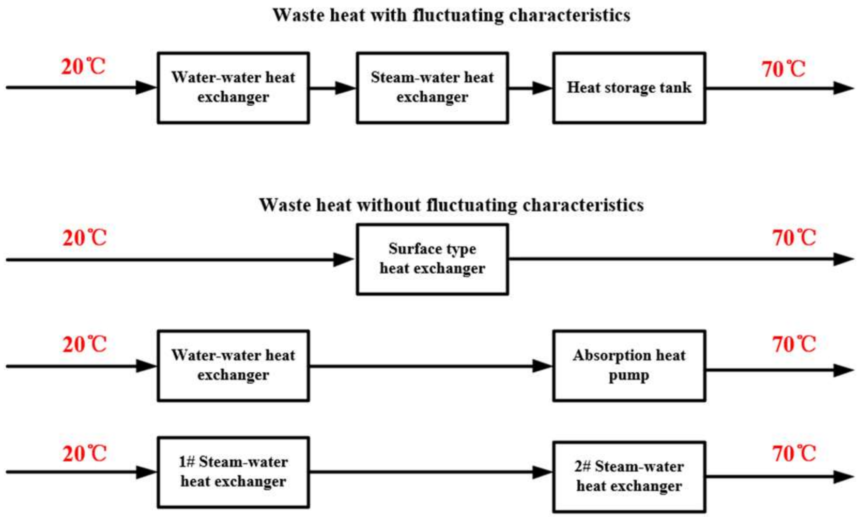
Process	Source	Medium	Power(MW)[1]
Steelmaking	Converter gas	Cooling water	32.13
	Oxygen lance	Cooling water	12.43
Ironmaking	Slag flushing water	Cooling water	141.28
	Slag flushing steam	Steam	59.34
Total			**245.18**

[1] Average value

3. Result Design method of waste heat utilization scheme

Design considerations

- Consumer: the base load for long-distance heating
- Parallel-dominant, complemented by series-parallel
  - Prevent interference between waste heat sources
  - Facilitate the implementation of the project in phases during the specific construction
- Utilization methods
  - Fluctuation: adjust circulating water flow rate & heat storage
  - Stable: adjust and redesign programs to accommodate fluctuations



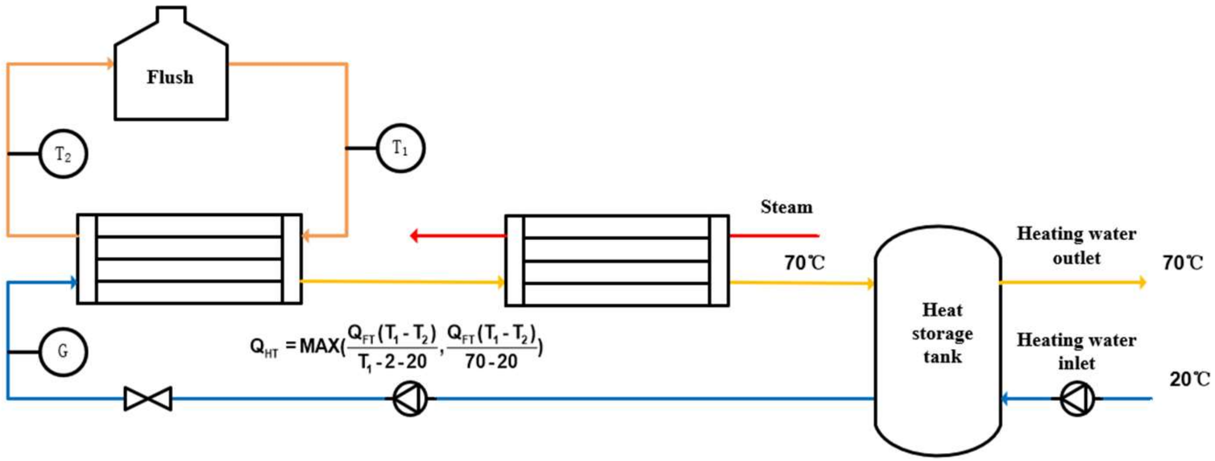
Basic parameter

Type	Supply temperature	Return temperature	△T of HE	△T of AHP	△T of flue gas-water HE	UA of water-water HE	UA of steam-water HE	UA of flue gas-water HE
Parameter	70°C	20°C	2K	3K	10k	4000W/m²/K	4500W/m²/K	70W/m²/K

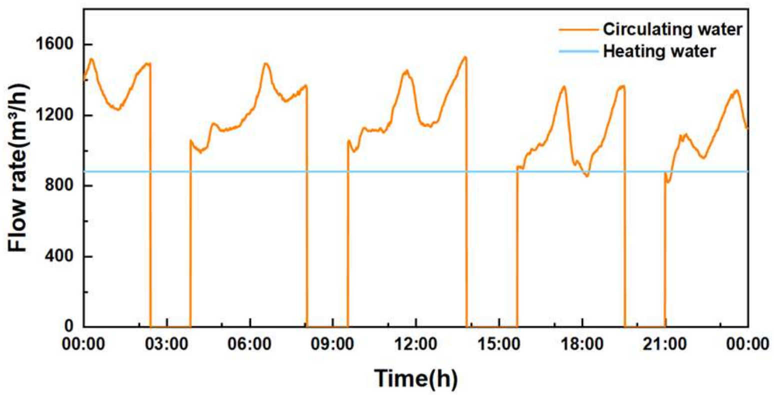
3. Result   Waste heat utilization with fluctuation

☐ 2#A slag flushing system

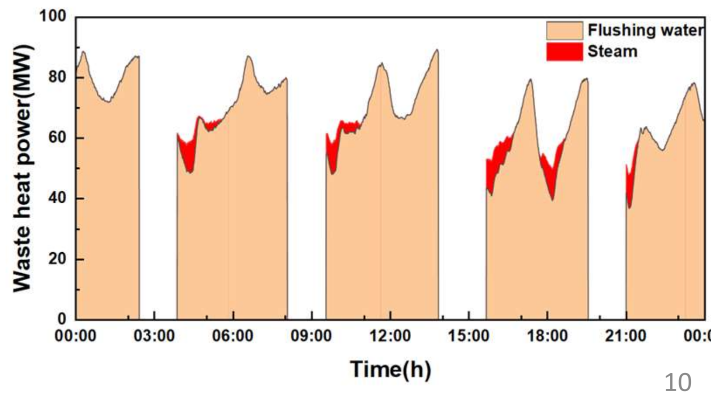
- Temperature——steam supplement
- Power——circulating water flow rate & heat storage tank
- Volume——integrating the difference between the circulating water flow and the heating water flow



$$Q_{HT} = MAX\left(\frac{Q_{FT}(T_1 - T_2)}{T_1 - 2 - 20}, \frac{Q_{FT}(T_1 - T_2)}{70 - 20}\right)$$



Changes in water flow rate



The heating power from slag flushing water and steam

3. Result Waste heat utilization without fluctuation

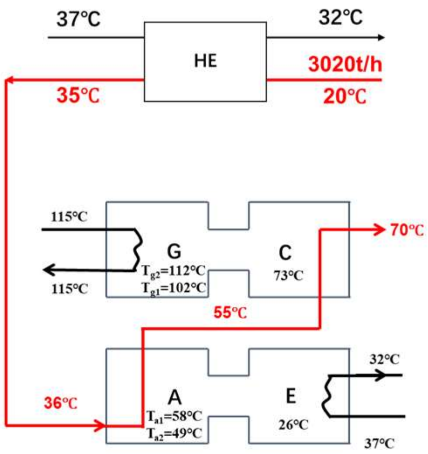
☐ Other waste heat without fluctuation

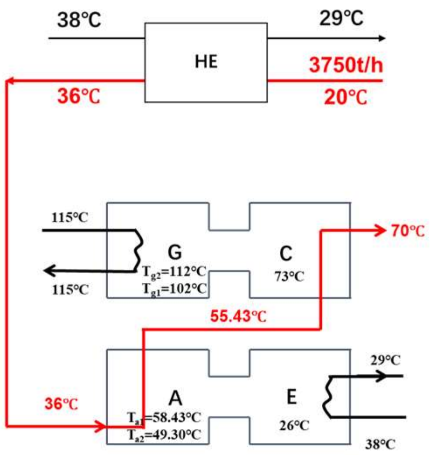
- Cooling water——HE & AHP
- Flue gas——Surface type HE
- Steam——HE

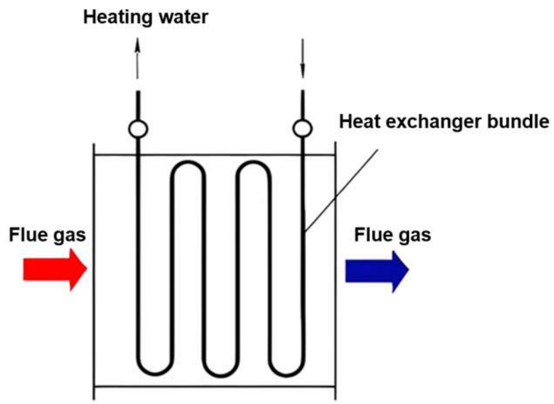
  (modify power generators to meeting other steam requirements)

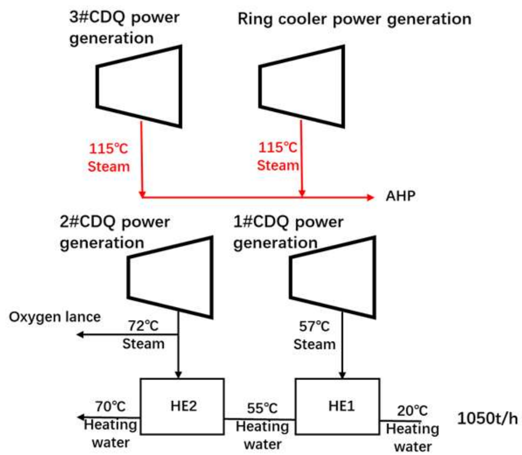
☐ Result of program(fluctuation and stable)

- Heating water 15,603 t/h
- 9,436,694 GJ / heating season
- 18 million m^2
- 1.29 USD/GJ







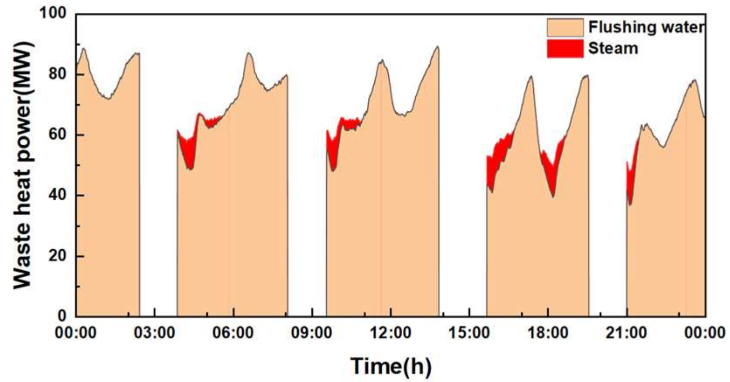


4. Discussion

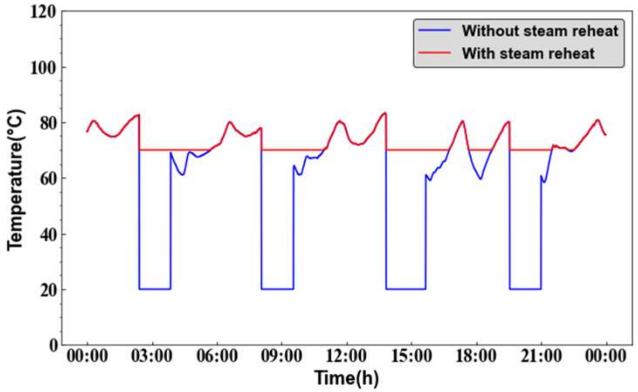
☐ 2#A slag flushing system

- Not adjust water flow rate, no heat storage
- Utilize 20% more waste heat, steam demand is only 10%

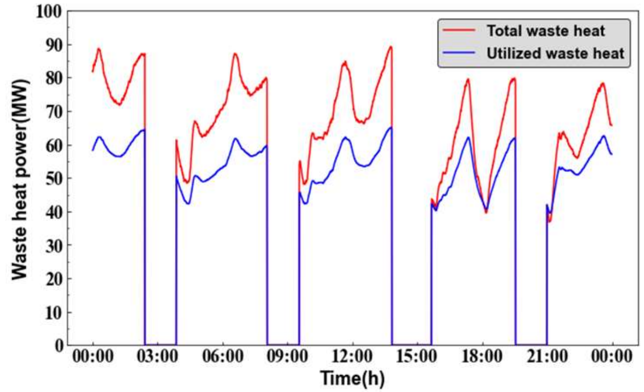
Type	Waste heat utilization power(GJ)	Steam supplementary heating power(GJ)
Consider fluctuation	**4331**	**112**
Ignore fluctuation	**3441**	**1260**



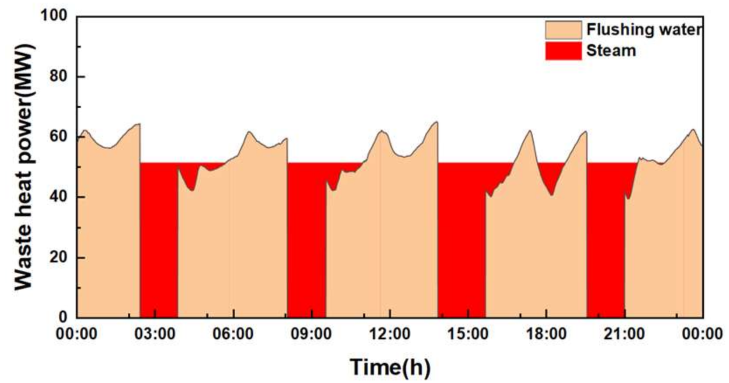
The heating power of flushing water and steam (Consider fluctuation)



The variation in the outlet temperature of the heating water



The utilization of waste heat



The heating power of flushing water and steam (Ignore fluctuation)

5. Conclusion

☐ Innovation points

- Fluctuation test and analysis
- Parallel-dominant, complemented by series-parallel
- Design program

Type	Strategy	Result
Fluctuation(26.75%)	Adjust water flow rate Heat storage tank	Increase the utilization rate of the waste heat by **20%** Reduce steam demand by **90%**
Stable(73.25%)	HE、AHP、 Surface type HE …	Adjust and design the utilization scheme to accommodate other fluctuation Improve the overall efficiency of waste heat utilization in the whole plant
Total		Recover more than 9 million GJ waste heat per heating season, Investment cost of **1.29 USD/GJ**

☐ Future research

- Focus on practical implementation
- Waste heat fluctuations in other industries are lack

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Appendice Measurement point layout

Ironmaking Process Measurement Point layout table

Measurement point location	Equipment number
Inlet of the slag flushing water	1*2*3
Outlet of the slag flushing water	1*2*3
Inlet of the blast furnace wall cooling water	1*3
Outlet of the blast furnace wall cooling water	1*3
Total	18

Steelmaking Process Measurement Point layout table

Measurement point location	Equipment number
Inlet of the oxygen lance cooling water	1
Outlet of the oxygen lance cooling water	2+3
Inlet of the converter gas cooling water	1
Outlet of the converter gas cooling water	1
Total	8

Coking Process Measurement Point layout table

	Measurement point location	Equipment number
First stage	Outlet of each primary cooler	4
	Total inlet and outlet of the stage	1*2
Second stage	Outlet of each primary cooler	4
	Total inlet and outlet of the stage	1*2
Third stage	Outlet of each primary cooler	5
	Total inlet and outlet of the stage	1*2
Total		19

Appendice Waste heat test result table(stable)

Waste heat type	Waste heat source	Outlet temperature/°C	Inlet temperature/°C	Heat power/MW
Cooling water	Blast furnace wall	37	32	108.80
	Primary cooler	38	29	137.03
Steam	Dry quenching coke	40	40	152.32
	Ring cooler	40	40	96.31
Flue gas & Exhaust air	Ring cooler	100	60	21.01
	Gas power generation	125	80	21.07
	Sintering	140	80	36.59
	Heating furnace	150	80	30.77
	Hot blast furnace	150	80	28.58
	Coking	170	80	39.03
Total				671.51

Appendice Waste heat test result table(fluctuation)

Waste heat type	Waste heat source	Outlet temperature/°C	Inlet temperature/°C	Heat power/MW
Cooling water	Oxygen lance	35	28	12.43
	Converter gas	50	25	32.13
	1# A Slag flushing	73	59	15.12
	1# B Slag flushing	64	50	14.45
	2# A Slag flushing	75	43	50.13
	2# B Slag flushing	62	43	17.56
	3# A Slag flushing	56	38	28.41
	3# B Slag flushing	50	33	15.61
Steam	Slag flushing steam	100	100	59.34
Total				245.18

Appendice Economic

Basic parameters

Item description	Parameter
Surface type heat exchanger	55.96 USD/m²
Steam-to-water HE	279.78 USD/m²
Water-to-water HE	139.89 USD/m²
AHP	69.94 USD /kW cooling capacity
Water storage tank	27.98 USD /m³
Steam storage tank	279.78 USD /m³
Electricity cost	83.93 USD/MWh
Heating days per year	120 days
Equipment operating life	10 years
Equipment installation cost	10% of initial investment

Initial investment cost

Item description	Initial investment (1000 USD)	Equivalent cost (USD/GJ)
Water-to-water plate HE	2872	0.0308
Steam-to-water plate HE	741	0.0084
Surface type heat exchanger	2308	0.0238
Heat water storage tank	211	0.0028
AHP	19030	0.2014
Steam storage tank	1399	0.0154
Heating water distribution system	14863	0.1581
Steam distribution system	8114	0.0853
Water pump initial investment	283	0.0028
Construction cost	4982	0.0529
Total	**54803**	**0.5817**

Appendice Economic

Operating cost

Item description	Decrease generation power output(MW)	Electricity cost (1000 USD /Heating season)	Electricity Cost (USD/GJ)
1# CDQ power generator	1.53	370	0.0392
2# CDQ power generator	3.35	810	0.0853
3# CDQ power generator	8.45	2043	0.2168
Ring cooler power generator	13.07	3159	0.3343
Pump	1.44	348	0.0364
Total	**27.84**	**6730**	**0.7120**