A Compound Cycle for Power Generation by Utilizing Residual Heat of Flue Gas in Electric Steelmaking Process

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Abstract

Electric furnace short process steelmaking is one of the most important steelmaking methods in the world today, and the waste heat recovery potential of electric furnace flue gas is huge. The research on the recovery of electric furnace flue gas waste heat is of great significance. In order to make better use of this part of the heat, in this paper, a compound cycle of nitrogen Brayton cycle as a first-order cycle and toluene transcritical Rankine cycle as a second-order cycle is proposed to recover waste heat from furnace flue gas in steelmaking process for power generation. A mathematical model was established with the net output power as the objective function and the initial expansion pressure, the final expansion pressure, the initial expansion temperature and the initial pressure of the second cycle as the independent variables. The effect of multivariate on the net output power of the waste heat power generation cycle is studied, and then, the optimal parameters of the compound cycle are determined. The results show that under the general electric furnace steelmaking process, the power generation efficiency of this new cycle can be increased by 21.02% compared with the conventional cycle.

Keywords

Electric Furnace Steelmaking, Flue Gas Waste Heat, Compound Cycle, Heat Transfer Pinch, Net Output Power

1. Introduction

Electric furnace steelmaking is one of the most important steelmaking processes today. Since most of the raw materials for electric furnace steelmaking are scrap

steel, it plays a good role in saving energy and protecting the environment and purifying the metallurgical environment. Electric furnace steelmaking also has the advantages of less capital investment and low operating costs. Therefore, the development of compact electric furnace short processes has become a strategic focus of many countries.

In recent years, there have been many related studies on electric furnace steelmaking. At present, the method of defining the optimal electric operating parameters of the electric arc furnace (EAF) uses foam slag practice technology, which is not only expensive, but is only used in AC EAF with good stability. Reference [1] proposes a new control system that can be applied to both AC EAF and DC EAF systems, and is cheaper and more stable. And through multiple verification tests, it proves that the technology shortens the working time and improves the power factor in practical applications; coherent jets are widely used in electric arc furnace (EAF) steelmaking processes to enhance chemical energy input, speed up the smelting rhythm, and promote uniformity of bath temperature and composition. A coherent jet of mixed injection of CO_2 and O_2 (COMI) is proposed in Reference [2], which shows great application potential in reducing dust generation in electric arc furnace steelmaking. At the same time, based on the conceptual model of eddy current dissipation, a computational fluid dynamics model of coherent jets with COMI was established using the overall and detailed chemical kinetic mechanism (GRI-Mech 3.0), and the concept was verified. The results show that the chemical action of CO_2 has indeed played a positive role; Reference [3] has studied element migration during hydrothermal treatment of zinc-containing electric arc furnace dust (zinc-containing EAFD). At the same time, it was found that most of the Fe, total Cr and silicon (Si) in the leaching residue existed in the form of Fe_2O_3, Cr_2O_3 and SiO_2 respectively, and could be recycled; In Reference [4], dust slag/lime from an electric arc furnace (EAF) was used to treat acidic wastewater in the industry. The test proves that EFA dust slag and lime can effectively remove Co, Cr, iron, nickel and zinc in wastewater, and the removal rate reaches more than 99.6%. This technical route not only recycles the dust and slag of the electric arc furnace, but also has simple operation and only requires mechanical mixing. It replaces the chemicals used in wastewater treatment, has good economy, and is environmentally friendly; In Reference [5], the effects of EAF steel slag on the fracture and temperature sensitivity of warm-mixed asphalt (WMA) were tested. The results show that the presence of EAF slag in modified asphalt mixtures has reduced the resistance of asphalt to fracture at low temperatures. Temperature sensitivity has a positive synergy.

It can be seen that the research on electric furnaces mainly focuses on improving the working efficiency of electric furnaces and the recycling of slag. The research on the recycling of electric furnace flue gas is relatively small. In fact, the recovery potential of electric furnace flue gas is huge. The unit energy consumption is about 12.4 GJ/ton of steel [6]. Among them, about 13% - 20% [7] of

energy exists in the form of flue gas waste heat during electric furnace steelmaking., For example, a major steel producer, China's electric furnace steel output in 2018 was 105 million tons [8], and energy consumption was about 1.3×10^9 GJ, where the flue gas waste heat energy was not less than 1.69×10^8 GJ, how to use this part of waste heat reasonably, should be taken seriously.

There are many studies on the recovery and utilization of flue gas waste heat throughout some industrial fields for reference. Reference [9] put forward a novel idea, proposes and analyzes a novel integrated system for high-pressure hydrogen production from steel furnace waste heat. This study combines an industrial waste heat source with a thermochemical Cu-Cl cycle and a hydrogen compression system; Reference [10] proposed a compound cycle using CO_2 and air as the heat exchange working medium, organic Rankine cycle as the bottom cycle, this new cycle has excellent thermodynamic performance in the temperature range of 500°C - 700°C; Reference [11] studied the use of mixed working fluids in an ORC system operating in combined heat and power (CHP) mode. The results show that when optimizing the overall performance of the ORC-CHP system provided by industrial waste heat sources, the temperature and load Patterns are a key factor affecting organic selection. Yang M [12] *et al.* proposed an economic parameter of the net power output index to obtain the maximum net power as the output index, using zero ODP and lower GWP working fluid to optimize the geothermal ORC system. The results show that under the optimization of economic performance, the performance of R600 is the best, followed by R600a, R1233zd, R1234yf, R1234ze and R290. In addition, the use of R600, R600a and R1233zd systems requires lower working pressure and lower equipment purchase costs.

Aiming at the heat recovery of electric furnace flue gas, building on research by seniors, this paper proposes a compound cycle composed of nitrogen Brayton cycle and transcritical toluene Rankine cycle.

2. Design of Compound Cycle

2.1. Design of Compound Cycle

At present, the power generation of flue gas waste heat boilers for steel-making electric furnaces often uses the water Rankine cycle [13] for heat exchange. Rankine cycle has a heat transfer pinch during the heat exchange process between the working medium and the flue gas, leading to a low waste heat recovery efficiency [14]. Both Gas Brayton cycle and transcritical Rankine cycle, the heat exchange between the working medium and the heat source is a temperature change process, which has a good matching degree with the heat source, can avoid pinch problems. Steelmaking electric furnace flue gas emissions are intermittent [15], the heat storage process [16] [17] is set up to solve the flue gas temperature fluctuation problem [18] [19], after the average heat storage temperature, the parameters of the waste heat have changed, and the power generation cycle needs to be re-designed [20] [21].

In the electric furnace steelmaking process, the waste heat recovery device is set in the flue gas dedusting system. After the flue gas is dedusted, the temperature is reduced from 1600˚C to about 800˚C, and has a few characteristics: high initial temperature, large temperature drop, almost constant specific heat capacity, continuous smooth enthalpy drop curve. For the heat recovery of flue gas in this temperature range, N_2 is a good choice: not only suitable for high temperature flue gas of electric furnace, but also lower requirements for operating pressure of the system. Due to the limitation of exhaust pressure, the heat release temperature of the Brayton cycle is high, so the transcritical organic Rankine cycle is used as the second stage to recover this part of the waste heat. Therefore, this paper proposes a compound cycle using the nitrogen Brayton cycle as the first-stage cycle and the transcritical organic Rankine cycle as the second-stage cycle.

Configuration of compound cycle: the compression process of the Brayton cycle uses a multi-stage compression-intercooling scheme. Referece [22] found that this method can better improve the system efficiency, which is beneficial to reducing the exhaust temperature and improving the utilization of waste heat; there is no thermal device set in the Brayton cycle, referring to the research [23] on the Brayton cycle, shows that the influence of the heat recovery contrast work is faint. But a heat recovery device is provided in the transcritical organic Rankine cycle [24] to improve the thermal efficiency of the cycle.

2.2. Selection of Organic Working Medium

In the compound cycle, the heat source for second-order cycle is nitrogen, which is at the outlet of the Brayton cycle expander, with a temperature exceeding 400˚C. Reference [25] believed that toluene, benzene and cyclohexane are suitable for medium temperature organic Rankine Cycles; both aromatic hydrocarbons and silicone-based working mediums are suitable for high-temperature organic Rankine cycles, in which the performance of aromatic hydrocarbon organics is better than that of silicones and other hydrocarbon-based working mediums [26]; Critical temperature is an important parameter for screening organic working mediums. Reference [27] proposed that the working medium is generally more suitable when its critical temperature is 40˚C - 60˚C lower than the initial temperature of the heat source; Reference [28] carried out a comparative study of Alkanes working mediums, with benzene, toluene, and water, the results show that n-dodecane and toluene are the best working fluids at 500˚C heat source. Combining above points, in this paper toluene is selected as the working medium of the organic Rankine cycle. Heat exchange working fluid for transcritical organic cycle (Table 1).

2.3. Compound Cycle Workflow

The process flow of the compound cycle of flue gas waste heat power generation proposed in this paper is shown in Figure 1.
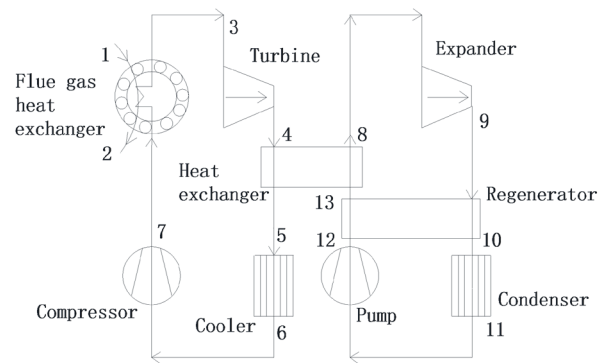
Figure 1. Flow chart of the compound cycle system.

Table 1. Critical parameters of organic working fluids.

	Decane	Toluene	Benzene	Cyclohexane	Cyclopentane
Critical temperature (t/°C)	330.40	318.60	288.94	280.94	238.60
Critical pressure (P/MPa)	2.150	4.126	4.898	4.075	4.520

A flue gas heat exchanger with heat storage function is set between 1-2. Through the heat storage heat exchanger, the intermittent and fluctuating electric furnace flue gas is converted into a heat source with continuous and stable flow, besides its temperature drop curve is smooth and continuous [29]. It is helpful to alleviate the problem of heat transfer pinch of the thermal system and promote the smooth operation of the recovery system.

1-2 is the exothermic process of flue gas in the flue gas heat exchanger; 3-4 is the adiabatic expansion process of nitrogen in the turbine, 4-5 is the exothermic process of nitrogen in the intermediate heat exchanger, 5-6 is the constant pressure exothermic process of nitrogen in the cooler, 6-7 is the adiabatic compression process of nitrogen in the compressor, 7-3 is the constant pressure heating process of nitrogen in the flue gas heat exchanger; 8-9 is the process of adiabatic expansion of toluene in the expander, 9-10 is the exothermic process of toluene in the regenerator, 10-11 is the constant-pressure exothermic process of toluene in the condenser, 11-12 is the adiabatic compression process of toluene in working fluid pump, 12-13 is the heat absorption process of toluene in the regenerator, and 13-8 is the constant pressure heat absorption process of toluene in the intermediate heat exchanger.

The pressure-enthalpy diagram describing the thermodynamic process of this workflow is shown in **Figure 2**.

Figure 2 shows the pressure and enthalpy change curves of the two working mediums in the compound cycle, and the respective gas-liquid saturation lines are given for reference. Among them, curve 3-7 is the pressure enthalpy change curve of nitrogen in the first cycle, curve 8-13 is the pressure enthalpy change curve of toluene in the second cycle. With reference to **Figure 2**, the properties of the nitrogen Brayton cycle and the toluene transcritical organic Rankine cycle can be understood more intuitively.
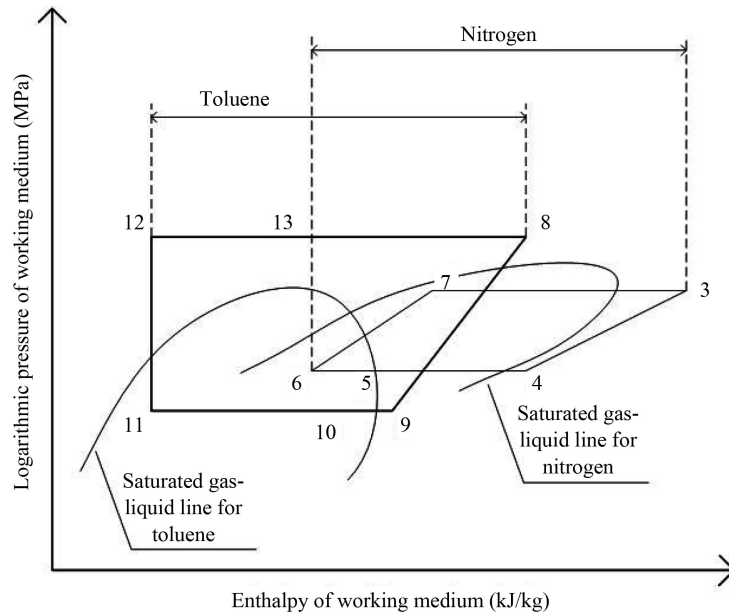
Figure 2. h-lgP diagram of the compound cycle system.

3. Mathematical Model of Compound Circulation System and Optimization Goals

3.1. Mathematical Model

This article explores the superiority of the compound cycle by adopting a method of establishing a mathematical model for calculation and verification. Several assumptions need to be made when calculating: It is assumed that both the flue gas and the heat exchange working medium are steady state and steady flow; Ignore the influence of the working medium's gravity potential energy; Ignore the macro kinetic energy changes of the working medium except for the expansion; Ignore the friction loss of the working medium except for the expansion and compression; Ignore the heat loss of the shell of each component in the cycle.

Exothermic heat of flue gas:

$$Q_1 = m_y \int_{t_1}^{t_2} c_{py} dt \tag{1}$$

Mass flow of nitrogen in the first-cycle:

$$m_1 = Q_1 / (h_3 - h_7) \tag{2}$$

Turbine power of the first-cycle:

$$W_{e1} = m_1 (h_3 - h_4) \tag{3}$$

Compressor power of the first-cycle:

$$W_{c1} = m_1 (h_7 - h_6) \tag{4}$$

Net output work of the first-cycle:

$$W_{net1} = W_{e1} - W_{c1} \tag{5}$$

Heat exchanger capacity of the second-cycle:

$$Q_2 = m_1 \left(h_4 - h_5 \right) \tag{6}$$

Mass flow of toluene in the second-cycle:

$$m_2 = Q_2 / \left(h_8 - h_{13} \right) \tag{7}$$

Expander power of the second-cycle:

$$W_{e2} = m_2 \left(h_8 - h_9 \right) \tag{8}$$

Pump power of the second-cycle:

$$W_{c2} = m_2 \left(h_{12} - h_{11} \right) \tag{9}$$

Net output work of the second-cycle:

$$W_{net2} = W_{e2} - W_{c2} \tag{10}$$

Net output work of the compound cycle:

$$W_{net} = W_{net1} + W_{net2} \tag{11}$$

- m_y = Mass flow of flue gas (kg/s);
- C_{py} = Constant pressure specific heat capacity of flue gas (kJ/kg·K);
- $h_1 - h_2$ = The enthalpy of flue gas at the inlet and outlet of the flue gas heat exchanger (kJ/kg);
- $h_3 - h_7$ = The enthalpy of the state point of nitrogen in the first-cycle (kJ/kg);
- $h_8 - h_{13}$ = The enthalpy of the state point of toluene in the second-cycle (kJ/kg).

3.2. Optimization Goals and Methods

Optimize the main parameters of the compound cycle, including the state points 3 and 4 of the first cycle, and the state point 8 of the second cycle. With the maximum net output work as the goal, explore the influence of the main variables of the compound cycle on the net output work.

4. Electric Furnace Flue Gas and Equipment Parameters

4.1. Physical Parameters of Flue Gas

4.1.1. Specific Heat of Constant Pressure of Flue Gas

The physical parameters of the heat source are the basis of the calculation.

The electric furnace waste heat recovery device is located in the middle of the flue gas dust removal system, the inlet is connected to the combustion sedimentation chamber, and the outlet is connected to the dust removal equipment. The composition of the flue gas passing through the combustion sedimentation chamber changes, and its composition is shown in Table 2 [30].

Table 2. Composition of electric furnace flue gas.

Flue gas composition	CO	CO_2	N_2	O_2	SO_2	H_2O
Volume fraction (%)	0.00	7.90	76.00	15.93	0.00	0.00

Under cyclic conditions, each component in Table 2 can be treated as an ideal gas. The constant pressure specific heat capacity regression Equation (13) of the flue gas can be obtained by Equation (12).

$$C_p = \sum_{i=1}^{n} C_{pi} x_i \tag{12}$$

$$C_{py} = 0.997209591 + 1.1641 \times 10^{-4} t \tag{13}$$

- C_p = Constant pressure specific heat capacity of mixed gas (kJ/kg·K);
- C_{py} = Constant pressure specific heat capacity of flue gas (kJ/kg·K);
- C_{pi} = Constant pressure specific heat capacity of each component (kJ/kg·K);
- x_i = The volume fraction of each component.

4.1.2. Calculation of Flue Gas Dew Point

The acid dew point of the flue gas will affect the setting of parameters at the flue gas heat exchanger, in this paper, the acid dew point of the electric furnace flue gas is calculated according to Equation (14) [31], and the acid dew point of the flue gas is calculated to be 84.15˚C.

$$T_{sid} = 10.8809 + 27.6 \lg p_{H_2O} + 10.83 \lg p_{SO_3} + 1.06 \left(\lg_{SO_3} + 2.9943 \right)^{2.19} \tag{14}$$

- P_{H2O} = Partial pressure of water vapor in flue gas (Pa);
- P_{SO3} = Partial pressure of SO_3 gas in flue gas, there is no SO_3 in electric furnace flue gas (Pa).

4.2. Parameter Setting of Compound Circulation System

For some equipment parameters are set here. According to the influence of the narrow point temperature difference on the waste heat boiler [32] and reference to the general waste heat power generation engineering situation [33] [34], the heat exchange temperature difference of the heat exchanger in the compound cycle is set to be 15˚C, and the condenser temperature difference is set to be 15˚C. Set the condensing temperature is 35˚C, both the isentropic efficiency of the turbine and expander are 0.9, and the isentropic efficiency of the compressor is 0.8. The physical parameters of the flue gas-related gas and the compound cycle heat exchanger working mediums are obtained from the Refprop 9.1 [35] physical property database.

5. Optimization Results and Analysis

5.1. Effect of Compound Cycle Parameters on Net Output Power

In order to analyze the influence of the main variables of the composite system on the net output work, it is assumed that the temperature of the electric furnace flue gas at the inlet of the circulation system is 800˚C and the mass flow rate is 1 kg/s after the heat storage's equal temperature treatment.

Figure 3 is under the working condition of P_3 = 1.3 MPa, the relationship between P_3, P_4, and net output power/ΔW_{net}. As can be seen from Figure 3, ΔW_{net} varies with P_3 increases, and within a certain range of P_3 and P_4, the larger P_4, the

higher the rate of change of ΔW_{net} with the increase of P_3. The pressure ranges of P_3 and P_4 are determined by the overall lower working pressure of the Brayton system and the appropriate pressure ratio of the expander.

Figure 4 is the correspondence curve between P_4 and W_{net} under the condition of P_3 = 1.3 MPa. As can be seen from Figure 4, W_{net} and P_4 are negative. Relatedly, the larger P_4 and smaller W_{net}.

The influence of the working fluid state on the W_{net} of the compound cycle system at the inlet of the secondary circulation expander was studied. The pressure of P_8 was not set too high, because the excessively high working pressure had an impact on system safety and work efficiency. The requirements for the quality pump pressure ratio are more demanding.

Figure 5 is the influence curve of T_8 and P_8 on ΔW_{net}. It was found that when T_8 is the same, the change trend of ΔW_{net} between the pressure gradients of P_8 is roughly the same and the value of W_{net} is small. The curve of P_8 = 6 MPa shows different trends. Because the value of ΔW_{net} is small too, this should be a normal phenomenon caused by the physical properties of the working medium itself.

Figure 6 is the corresponding curve of T_8 and net output work W_{net} under the condition of P_8 = 8 MPa. It was found that W_{net} is positively correlated with T_8, and the larger T_8 is, the larger W_{net} The larger the increase is steady.
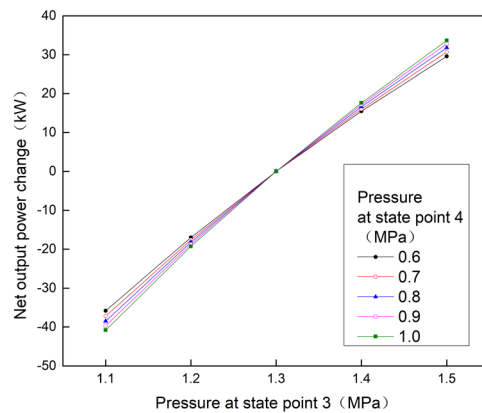
Figure 3. Curve of the influence of P_3 and P_4 on ΔW_{net}.
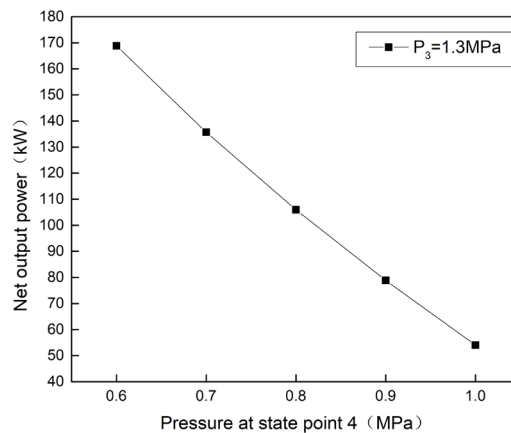
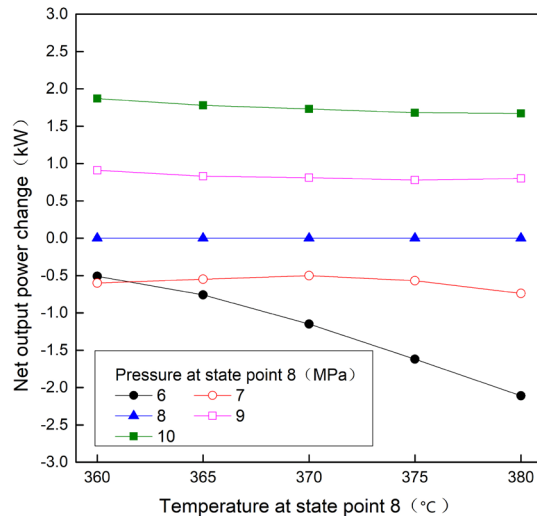**Figure 4.** Curve of P_4 effect on W_{net} under P_3 = 1.3 MPa.

Figure 5. Curve of the influence of T_8 and P_8 on ΔW_{net}.
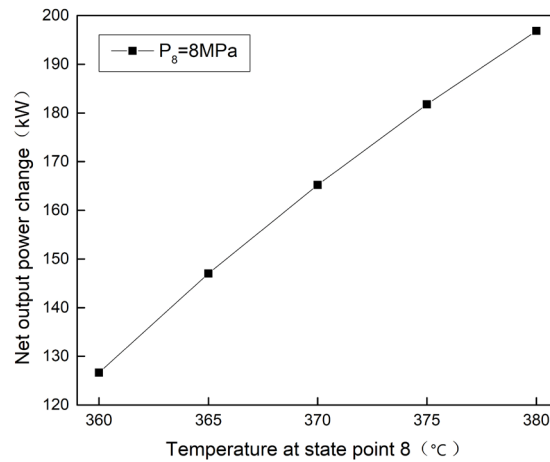

Figure 6. Curve of T_8 effect on W_{net} under $P_8 = 8$ MPa.

5.2. Compound Cycle Optimization Parameters

With Equations (1)-(11) as the calculation criterion and the maximum net output work as the goal, the main variables of the composite system were optimized and calculated. The optimization results are shown in **Table 3**. The physical property parameters of the heat exchange working fluid are obtained from the Refprop 9.1 physical property database obtain.

5.3. Comparison of Compound Cycle and Water Rankine Cycle

In order to evaluate this compound cycle, the main indexes of the traditional water Rankine cycle and the compound cycle system as two types of waste heat recovery of the steelmaking electric furnace flue gas recovery were compared. The waste heat recovery efficiency is shown in Equation (15), and the results are shown in **Table 4**.

$$\eta = W_{net}/Q_y \times 100\% \tag{15}$$

Table 3. Optimization parameters of the compound cycle.

P_3 (MPa)	P_4 (MPa)	P_8 (MPa)	T_8 (°C)
1.5	0.6	10	380

Table 4. Comparison of result of recovery of waste heat form.

|	Net output power (kW)	Increase rate (%)	Waste heat recover efficiency (%)	Increase rate (%)
Compound cycle	198.54	22.52	27.00	21.02
Water Rankine cycle	162.05	-	22.31	-

- W_{net} = Net output power of the circulation system (kW);
- Q_y = Exothermic heat of flue gas (kJ).

It can be known from **Table 4** that the net output power and waste heat recovery efficiency of the composite cycle proposed in this paper are 22.52% and 21.02% higher than those of the traditional Water Rankine cycle (calculated in ref [36]).

6. Effect of Cycle Parameters on Exhaust Temperature

Exhaust temperature is a non-negligible index parameter in waste heat recovery. Excessive exhaust temperature will cause inconvenience to the subsequent exhaust process, not only increase costs, but also cause adverse effects on the environment. The influence of the operating conditions of the compound cycle system on the exhaust temperature is shown in **Figure 7**.

It can be seen from **Figure 7** that the t_2 increases with the increase of P_3 and the decrease of P_4. Combining **Figure 3**, t_2 and W_{net} is positively correlated, so when determining the compound cycle operating conditions in actual engineering, it is necessary to consider the comprehensive consideration of the effect of the exhaust temperature.
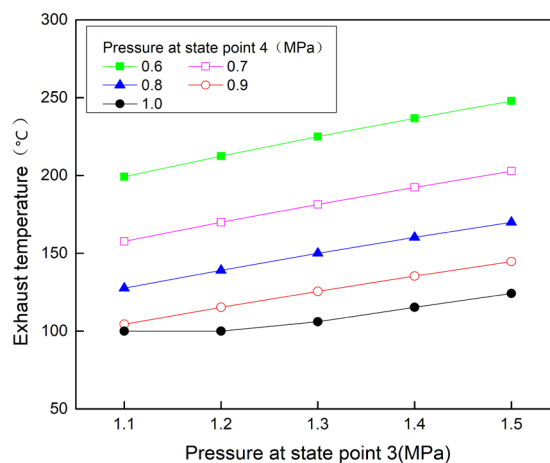
Figure 7. Curve of the influence of P_3 and P_4 on exhaust temperature/t_2.

7. Conclusions

Aiming at the characteristics of flue gas waste heat from steelmaking electric furnaces, this paper proposed a compound cycle consisting of a nitrogen Brayton cycle and a transcritical toluene Rankine cycle for waste heat power generation.

Under the optimal working conditions of the compound cycle, the net output power and waste heat recovery efficiency are respectively 22.52% and 21.02% higher than the traditional Water Rankine cycle, which reflects the superiority of the compound cycle.

The net output power W_{net} of the compound cycle increases with the increase of P_3, P_8, t_8, and decreases with the increase of P_4. Among them, P_8 has a smaller impact.

The increase of P_3 and the decrease of P_4, while bringing higher W_{net}, also lead to an increase in the temperature of the electric furnace flue gas.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Vicente, A., Picon, A., Arteche, J.A., Linares, M., Velasco, A. and Sainz, J.A. (2020) Magnetic Field-Based Arc Stability Sensor for Electric Arc Furnaces. *Measurement*, **151**, 107-134. https://doi.org/10.1016/j.measurement.2019.107134

[2] Wei, G.S., Zhu, R., Wu, X.T., Yang, L.Z., Dong, K., Cheng, T. and Tang, T.P. (2018) Study on the Fluid Flow Characteristics of Coherent Jets with CO_2 and O_2 Mixed Injection in Electric Arc Furnace Steelmaking Processes. *Metallurgical and Materials Transactions B*, **49**, 1405-1420. https://doi.org/10.1007/s11663-018-1209-8

[3] Wang, H.-G., Gao, J.-M., Liu, W.W., Zhang, M. and Guo, M. (2016) Recovery of Metal-Doped Zinc Ferrite from Zinc-Containing Electric Arc Furnace Dust: Process Development and Examination of Elemental Migration. *Hydrometallurgy*, **166**, 1-8. https://doi.org/10.1016/j.hydromet.2016.08.004

[4] Forsido, T., McCrindle, R., Maree, J. and Mpenyana-Monyatsi, L. (2019) Neutralisation of Acid Effluent Steel Manufacturing Industry and Removal of Metals Using an Integrated Electric Arc Furnace Dust Slag/Line Process. *SN Applied Sciences*, **1**, 1-6. https://doi.org/10.1007/s42452-019-1649-z

[5] Motevalizadeh, S.M., Sedghi, R. and Rooholamini, H. (2020) Fracture Properties of Asphalt Mixtures Containing Electric Arc Furnace Slag at Low and Intermediate Temperatures. *Construction and Building Materials*, **240**, Article ID: 117965. https://doi.org/10.1016/j.conbuildmat.2019.117965

[6] He, L.B. (2013) Waste Heat Power Generation Technology of Steelmaking EAF. *Industrial Furnace*, **35**, 16-17.

[7] Zeng, T. (2016) Research and Application of Waste Heat Power Generation Technology in Steel Making Furnace. *World Nonferrous Metals*, No. 9, 192-193.

[8] Xinluo Information (2018) Annual Report on China EAF Steel Industry Chain 2018. http://www.iccsteel.com/dlyg/show-htm-itemid-31742.html

[9] Ishaq, H., Dincer, I. and Naterer, G.F. (2018) Industrial Heat Recovery from a Steel Furnace for the Cogeneration of Electricity and Hydrogen with the Copper-Chlorine Cycle. *Energy Conversion and Management*, **171**, 384-397. https://doi.org/10.1016/j.enconman.2018.05.039

[10] Wang, H.-X., Li, G. and Ren, L.Y. (2017) Study on Optimization of Compound Cycle Based on Heat Recovery of Medium and High Temperature Flue Gas. *Chemical Engineering*, **10**, 15-19.

[11] Oyewunmi, O.A., Kirmse, C.J.W., Pantaleo, A.M., *et al.* (2017) Performance of Working-Fluid Mixtures in ORC-CHP Systems for Different Heat-Demand Segments and Heat-Recovery Temperature Levels. *Energy Conversion and Management*, **148**, 1508-1524. https://www.orcid.org/0000-0002-5202-8457 https://doi.org/10.1016/j.enconman.2017.05.078

[12] Yang, M. and Yeh, R. (2016) Economic Performances Optimization of an Organic Rankine Cycle System with Lower Global Warming Potential Working Fluids in Geothermal Application. *Renewable Energy*, **85**, 1201-1213. https://doi.org/10.1016/j.renene.2015.07.067

[13] Cao, X.C. (2008) Development and Application of Waste Heat Recovery. In: *Papers Collection of the Fourth Annual Youth Academic Conference of China Metal Society*, Iron & Steel Editorial Department, Beijing, 418-423.

[14] Yu, L.J., Zhu, Y.D. and Wu, Y.D. (2015) Low and Medium Temperature Waste Heat Power Generation Technology. Shanghai Jiao Tong University Press, Shanghai, 47-49.

[15] Zhang, L.L., Niu, G.B. and Yang, J. (2018) Application Status and Renovation of Flue Gas Waste Heat Recovery of Electric Furnaces. *Metallurgical Power*, **220**, 49-51 + 68.

[16] He, X.Z., Zhou, Z.D. and Zhang, P. (2012) Application and Analysis of Regenerative Equalizing Technology in Flue Gas Treatment and Waste Heat Utilization of Electric Furnace. *China Steel*, **12**, 32-33.

[17] Lin, Y.X., Alva, G. and Fang, G.Y. (2018) Review on Thermal Performances and Applications of Thermal Energy Storage Systems with Inorganic Phase Change Materials. *Energy*, **165**, 685-708. https://doi.org/10.1016/j.energy.2018.09.128

[18] Yang, J., Wang, M.J. and Zhang, H. (2011) Technology of Waste Heat Recovery from EVF High Temperature Exhaust Gas. *Steelmaking*, **27**, 62-65.

[19] Dong, M.L. and Zhou, T. (2015) Total Waste Heat Recovery Device for Off-Gas of EAF. *Steelmaking*, **31**, 73-77.

[20] Wang, Z.W., Shi, W.T., Ren, X.N., *et al.* (2015) The Optimal Design of Waste Heat Power Generation System of Electric Furnace's Flue Gas. *Energy Conservation Technology*, **33**, 457-459.

[21] Tu, A.M., Zhang, Q.Z., Cheng, H., *et al.* (2013) Application of Waste Heat Power Generation Technology for Energy Conservation in Ferroalloy Electric Furnace. *China Steel*, **3**, 38-41.

[22] Ma, Y.G., Liu, M. and Yan, J.J. (2017) Thermodynamic Study of Main Compression Intercooling Effects on Supercritical CO_2 Recompression Brayton Cycle. *Energy*, **140**, 746-756. https://doi.org/10.1016/j.energy.2017.08.027

[23] Zhang, Z.L., Chen, L.G., Ge, Y.L., *et al.* (2012) Energy Analysis and Optimization of Combined Regenerative Brayton and Two Parallel Inverse Brayton Cycles with Regeneration after Inverse Cycles. *Journal of Thermal Science and Technology*, **11**, 369-376.

[24] Bo, H.Y., Zhu, J.L. and Li, T.L. (2015) Parametric Optimization and Working Fluid Selection for Transcritical ORC System. *Acta Energiae Solaris Sinica*, **36**, 2625-2631.

[25] Chen, Q.C., Xu, J.L. and Miao, Z. (2013) Working Fluid Selection for Medium Temperature Organic Rankine Cycle. *Proceedings of the CSEE*, **33**, 29-35.

[26] Lai, N.A., Wendland, M. and Fischer, J. (2011) Working Fluids for High-Temperature Organic Rankine Cycle. *Energy*, **36**, 199-211. https://doi.org/10.1016/j.energy.2010.10.051

[27] Li, Y.C. (2017) Recovery from Medium- to High-Temperature Flue Gas and Experimental Study on Thermal Stability of Organic Working Fluids. School of Materials Science and Engineering, Tianjin University, Tianjin.

[28] Siddiqi, M.A. and Atakan, B. (2012) Alkanes as Fluids in Rankine Cycles in Comparison to Water, Benzene and Toluene. *Energy*, **45**, 256-263. https://doi.org/10.1016/j.energy.2012.06.005

[29] Wang, Z.Y., Liu, Z.L. and Ma, C.F. (2005) Experimental Study on Heat Transfer Characteristics of the Charging/Discharging of a Heat Pipe Heat Exchanger with Latent Heat Storage. *Journal of Engineering Thermophysics*, **26**, 989-991.

[30] Zhou, H. (2011) The Development of Calculation Software to Thermal Calculation of Waste Heat Boiler for Electric Furnace. Northeastern University, Shenyang.

[31] Okkes, A.G. and Badger, B.V. (1987) Get Acid Dew Point of Flue of Gas. *Hudrocarbon Processing*, **7**, 53-55.

[32] Liang, W., Liu, Y.J. and Dai, Z. (2010) Influence of Pinch Temperature Difference at HRSG. *Power System Engineering*, **26**, 74-74.

[33] Ahmed, A., Esmaeil, K.K., Irfan, M.A. and Al-Mufadi, F.A. (2018) Design Methodology of Heat Recovery Steam Generator in Electric Utility for Waste Heat Recovery. *International Journal of Low-Carbon Technologies*, **13**, 369-379. https://doi.org/10.1093/ijlct/cty045

[34] Peng, S., Zhou, X., Li, Q.M., Zhong, D., Huang, Z. and Wang, B.M. (2018) Thermodynamic Performances Analysis of the Energy Recovery from Air Cooling Steam Turbine Exhaust by ORC. *Journal of Thermal Science and Technology*, **17**, 219-224.

[35] Lemmon, E.W., Huber, M.L. and Mclinden, M.O. (2010) NIST Standard Reference Database 23: Reference Fluid Thermodynamic and Transport Properties—REFPROP, Version 9.1, Standard Reference Data Program. National Institute of Standards and Technology. NIST NSRDS.

[36] Bi, H.W. (2013) Comprehensive Recovery and Utilization of Furnace Gas in Steel-Making Electric Furnace. Outstanding Figures, 10.