Feasibility analysis on the coupling power system of municipal solid waste incinerator and coal-fired unit

Shanshan Miao¹, Dehua Wang, Yaning Yin, Shengli Han, Ting Wang, Chong Li, Ying Huang, Xin Guo, Weilai Wang, Qiang Yu and Yingwei Zhu

State Key Laboratory of Efficient and Clean Coal-Fired Utility Boilers (Harbin Boiler Company Limited), Harbin 150046, Heilongjiang Province, China

¹Email: miaoshanmiaoshan@163.com

Abstract. In this paper, the coupling capacity matching is related to chlorine content in MSW incinerator, denitrification and desulfurization efficiency of coal-fired boiler. Based on an 850 t/d municipal solid waste (MSW) incinerator and a 1000MW ultra-supercritical coal-fired unit, the effect of the dual-chain coupling of steam and flue gas on the coal-fired unit is studied, including corrosion of heating surface in furnace, dioxin emissions, pollutants emission, and fly ash comprehensive utilization. Through the influence research to the coal-fired boiler, it can be seen that influence on the heating surface is small at high temperature. The flue gas environment of coal-fired boiler can also inhibit the synthesis of dioxin and the flue gas of waste incinerator meet to the ultra-low emission standard of pollutants of coal-fired units and the heavy metals content of fly ash of coal-fired boiler is not hazardous waste. After the coupling, the generation efficiency of MSW incinerator can rise up from 20% to 31.6% and the MSW incinerators operate investment reduced by 40% with significant economic benefits. The coupling mode can be generalized of waste incinerator and coal-fired boiler that obtain feasibility for engineering application.

1. Introduction
In 2018, Municipal Solid Waste (MSW) incinerator cleanup scalar has accumulated 228 million tons in Chinese cities [1], and the waste generation would continue to grow by 8-10% per year. Three main MDW treatment approach were 1andfill, compost and incineration. Incineration is the most efficient treatment method since it has the maximum reduction capacity, remarkable reduction, complete treatment and little pollution as well as electricity generation, which is the most important waste treatment method in China at present and even in the future [2-3].

However, the existing waste incinerators burned in the main form of grate furnaces. Inadequate mixing of garbage and air results in insufficient combustion of garbage carbon content, which produces high carbon dioxide (CO) content of fly ash in flue gas. In the MSW incinerator, the power consumption rate of many auxiliary is as high as 20%. In order to avoid low temperature corrosion, high exhaust temperature is designed. Waste furnace exhaust temperature up to 180~210°C. Low steam parameters cause the unit generation efficiency to be only 18~25%. Besides, the heating surface can cause high temperature corrosion to accelerate when the heating surface wall temperature >480°C [3], so upper limit the superheater outlet temperature is 450°C. In order to purify the residual dioxin and other dioxin pollutants / carcinogens in the tail flue gas, need to install flue gas purification system, the dioxins remaining in the tail flue gas purification system need to inject activated carbon for
adsorption and removal [3-4]. But activated carbon is expensive and cannot be reused. However, the activated carbon cost is high, and the adsorbed activated carbon will produce new solid waste. The unit investment money of per ton waste is high about 500000.

2. Recommendation coupling reason
The coupling of MSW incinerator and coal-fired unit is a new kind of waste disposal method. At present, there is no technical precedent for the coupling mode. Coal-fired units have higher steam parameters and generate electricity with a higher efficiency of up to 45%. The auxiliary power consumption rate of large coal-fired units is generally only 5%, and the auxiliary power consumption rate decreases greatly after coupling, and the actual power supply capacity is greatly improved.

After the steam coupling, MSW incinerators are more efficient at generating electricity. The heat transfers on the heating surface of large-scale coal-fired units take advantage of recovering, which utilize the waste heat of the flue gas to improve the efficiency of heat utilization. It reduces the heat pollution and the coal consumption.

After Flue gas coupling, the environment of the coal-fired unit can decrease the chlorine concentration then reduce the corrosion of the heating surface and inhibit the dioxin generation. The waste heat of flue gas can be recovered to the greatest extent. Flue gas treatment process waste power plant not only need desulphurization and denitrification, but also remove dioxins, heavy metals and so on to discharge into the atmosphere, coupled with the flue gas purification system of coal-fired units, waste incineration flue gas up to the coal-fired unit pollutant ultra-low emission standards (NOx, SO2, dust, etc.). The flue gas coupling can reduce the cost of waste incinerator facilities and operation and maintenance costs include flue gas purification system, chimney, turbine, electric generator, etc.

However, so far, there is no technical precedent for coupling generation of garbage and large coal-fired boilers at home or abroad. The coupling system lacks feasibility, economy and technical aspects of in-depth understanding. Therefore, this paper takes 850 t/d waste incinerator and 1000 MW ultra-supercritical coal-fired unit as an example to study the influence and economy of coal-fired boiler after coupling.

3. Coupling method
Coupling of 850t/d MSW incinerator with 1000MW USC coal-fired unit as an example, a dual-chain coupling system is established. The main steam of 390°C generated by MSW incinerator is coupled with the thermal system of the coal-fired boiler on the steam coupling. The produced flue gas by the MSW incinerator is coupled with the coal-fired boiler on the flue gas coupling. The process parameters of MSW incinerator and USC coal-fired unit are shown in Table 1.

| Item                | MSW incinerator | USC coal-fired unit |
|---------------------|----------------|--------------------|
| Capacity / 1000MW   | /              | 1000MW             |
| Main steam flow     | 73t/h          | 3100t/h            |
| Main steam Outlet   | 6.5MPa         | 28.3MPa            |
| Main steam pressure | 390°C          | 605°C              |
| Fuel consume        | 850t/d         | 426.5t/h           |

3.1. The steam side coupling of MSW incinerator with USC coal-fired unit
According to the turbine balance diagram, Steam parameters of pressure 6.4MPa and temperature 390°C at 110%MCR of MSW incinerator were reducing temperature and pressure instead of second-stage extraction of pressure 6.5MPa and temperature 372°C at BMCR for 1000MW USC coal-fired unit. Figure 1 shows a schematic diagram of the steam side coupling of MSW incinerator with USC coal-fired unit. Thermal calculation results of steam side coupling are shown in Table 2.
Based on the analysis and evaluation of the thermal cycle system of coal-fired unit in service, the outlet steam parameters of the waste heat boiler worked out, the main plant of the coal-fired power unit is sent to the coal-fired power unit by the transmission pipeline to replace part of the steam-driven secondary pumping into the regenerative system for steam coupling. Making use of the advantages of efficient thermal system of coal-fired units, the medium temperature and sub-high pressure steam parameter of waste incineration boiler draws into the thermal cycle system of large-scale coal-fired units. The heat consumption of power generation could further depress, and the cycle efficiency of power generation could improve. The steam coupling evaluated by thermodynamic calculation that the rated load of the MSW incinerator is 16.6MW within the range of load suitable for coupling generation.

3.2. The flue gas coupling of MSW incinerator with USC coal-fired unit

The 400 ℃ flue gas from the MSW incinerator passed through the multi-pipe dust collector, and the hot flue gas is introduced into the coal-fired boiler by the high temperature fan, which can be used as the external heat source of the boiler recycling flue gas [5]. Through the furnace high temperature combustion zone, convection heating surface, SCR, air preheater, dust catcher, desulfurization equipment, the flue gas after purification is discharged along the chimney. More than 85% of fly ash particles in the flue gas of a refuse incinerator were caught by multi-tube dust collector, and acid-induced acidic fly ash was also caught chloride, fluoride and sulfide. Figure 2 shows a schematic diagram of the flue gas side coupling system of MSW incinerator with USC coal-fired unit.

The 400 ℃ flue gas from MSW incinerator is regarded as recirculating flue gas of coal-fired boiler. The technology has been widely used in steam temperature control of reheat steam temperature adjustability of secondary reheat boiler [5]. HBC’s thermal calculation procedure works out at thermal calculation results of flue gas side coupling between the MSW incinerator and coal-fired boiler are shown in Table 3.

Under BMCR working conditions, the 400 ℃ gas proportion of the waste incinerator to the coal-fired boiler is 5.7%. The flue gas temperature at the bottom of the screen decreased by 19 ℃ and the
exhaust gas temperature of boiler increased by 9℃. Considering the thermal gain caused by 400℃ hot flue gas, the boiler efficiency can increase by 0.8%. According to the thermal calculation and evaluation, within the load range of the coal-fired power generation unit suitable for coupling generation, power generation capacity of coupling the MSW incinerator with coal-fired unit is 8.2MW at the rated load.

![Figure 2. The flue gas coupling system of MSW incinerator with USC coal-fired unit.](image)

**Table 3. Thermal calculation results of flue gas coupling.**

| Item                                    | Design BMCR | Coupling BMCR |
|-----------------------------------------|-------------|---------------|
| Main Steam outlet temperature(℃)        | 605         | 605           |
| Reheat steam outlet temperature(℃)      | 603         | 603           |
| Separator temperature(℃)                | 434         | 430           |
| Air excessive coefficient                | 1.15        | 1.15          |
| Total Flue gas volume of boiler (t/h)   | 3796        | 3970          |
| Total consumption of boiler(t/h)        | 426.5       | 415.9         |
| Flue gas temperature at the bottom of  screen(℃) | 1382       | 1363          |
| Exhaust gas temperature(℃)              | 124         | 133           |
| Boiler efficiency (%)                    | 94.71       | 95.49         |

The coupling of municipal solid waste incinerator and coal-fired unit power system: High-temperature flue gas and steam from MSW incineration enter the pulverized coal-fired boiler and the regenerative system of coal-fired power unit respectively. The total coupling power generation capacity is 24.8MW, and the conversion of MSW power generation per unit load is 699 kWh/t. The coupling power generation efficiency is 31.6%, which is higher than that of traditional waste incineration power plants are only 20%.

### 3.3 Limiting factor of coupling

On The flue gas coupling, the more coupling flue gas, the greater surface corrosion of coal-fired boiler and the lower boiler life. The higher coupling flue gas is higher smoke temperature at the inlet of the denitrification units and higher temperature range of the catalyst and lower denitrification efficiency. The higher coupling flue gas will cause too high chlorine concentration in the acid removal tower and affect desulfurization efficiency. Meanwhile, the amount of waste water generated will increase and the cost of waste water treatment will increase. Influence of heavy metals carried by fly ash on the poisoning of desulfurization and denitrification catalyst after flue gas side coupling.

### 4. Influence of flue gas on coal-fired boiler after coupling

MSW incineration flue gas mainly consists of four harmless substances nitrogen, oxygen, carbon dioxide and water steam. However, one percent harmful pollutants mainly include particulate matter, heavy metals, acidic pollutants, residual organic matter, and dioxin. So these flue gas pollutants on coal-fired boilers after coupling are analyzed. Original concentration of flue gas pollutants in MSW incinerator (dry flue gas along 11% oxygen under standard state) [3] was referred.
4.1. The effect of HCl in the flue gas of MSW incinerator on the corrosion of high temperature heating surfaces of coal-fired boilers.

High temperature corrosion rate of boiler tube begins from 320℃, the corrosion rate accelerated after 480℃ and reaches maximum between 600℃ and 700℃ [6-8]. Then the serious corrosion area is concentrated on the high temperature heating surface [7].

The concentration range of HCl in waste incinerator flue gas is 500-600mg/Nm³, while the chlorine content in the coal is 0.02%-0.025% in converting coal. The gas content in the raw coal is 0.01%, the chlorine content in the coal range 0.03 to 0.035% in the coal boiler after coupling. In general, no more than 0.25% chlorine in coal will not cause serious corrosion of boilers heating surface. The following corrosion calculations are based on the maximum chlorine content of coal in coupling coal-fired boiler 0.035%. HBC researched and developed the mature calculation method about calculate the corrosion rate of chlorine content to each heating surface of the boiler [9].

\[ r = f(T_m, T_{gas}, Cl, \sigma, \sum K, N) \]  

where \( r \) is corrosion rate (nm/h), \( T_m \) is tube wall temperature(℃), \( T_{gas} \) is flue gas temperature(℃), \( Cl \) is chlorine content in coal(%), \( \sigma \) is tube material, \( \sum K \) is gas composition, \( N \) is pipe position.

Calculate the corrosion rate of the heating surface at high temperature and evaluate the service life of the heating surface.

4.2. Dioxins emission analysis in flue gas of coal-fired boiler after coupling

The formation mechanism of dioxin in MSW incinerator: the fuel itself contains dioxin and is not damaged in combustion and is present in the combustion flue gas [10-11]. Fly ash contains carbon, oxygen, hydrogen, chlorine, etc, which catalyzes the synthesis of intermediate products or dioxin on the fly ash surface between 250℃ and 500℃ [12-13]. Fuel combustion produces dioxin precursors with similar dioxin structure on the incomplete condition, and dioxins are synthesized at low temperature condition [14].

Pollution control standard for municipal solid waste incineration dioxins Emission limits of 0.1ngTEQ/Nm³ the emission concentration of dioxin is 1-10ngTEQ/Nm³ in MSW incinerator [15]. In general, removal of dioxin by activated carbon injection in flue gas purification system. The flue gas environment changed after the coupling that comparison flue gas environment of MSW incinerator to coal-fired boiler is shown in Table 4.

| Units                               | MSW incinerator | Coal-fired boiler |
|-------------------------------------|-----------------|-------------------|
| Combustion temperature(℃)          | 850             | 1100~1500         |
| Residence time (s)                 | ≥2              | ≥3                |
| Operating oxygen(%)                | 6~12            | 2.5~3.0           |
| Chlorine concentration(mg/Nm³)     | 500~600         | 38                |
| carbon in fly ash (%)              | ~5              | ~1                |

The dioxins break down completely above 800℃ [16]. Coal-fired boilers at 1100-1500℃ are hotter than MSW incinerator flue gas, and stay for more than 2s, so they can completely destroy dioxins and dioxins precursors. The operating environment in the furnace of coal-fired boiler is propitious to decomposition of dioxin and to reduce CO emission. The operation oxygen content of coal-fired boiler is 2.5%-3%, and the secondary generation of dioxin in the tail of coal-fired boiler is restrained. The oxygen content of coal-fired boiler is 250-500℃. The carbon content in fly ash of coal-fired boiler is lower than that of MSW incinerator, which can effectively inhibit the secondary synthesis of dioxin. The chlorine content in coal converted from HCl to coal-fired boilers is low. Lower chlorine content can also inhibit the secondary synthesis of dioxin [17]. Coupling scheme fully meets GB18485-2014 standard of dioxins emission limits of 0.1ngTEQ/Nm³.
4.3. Technical analysis of the flue gas ultra-low emission from coal-fired boilers after coupling.

Large coal-fired boiler is equipped with a complete air pollutant purification system. The main equipment includes SCR denitrification installation, electrostatic precipitator, and tail wet desulphurization device.

The SCR denitrification installation of large coal-fired boiler can effectively remove the NOx of the flue gas from MSW incinerator. The dust removal device can wipe off the fly ash dust of the flue gas from MSW incinerator, the tail wet desulphurization device can deeply remove the acid gas components include SO2, HCl from the flue gas, realizing the super net emission of exhaust gas from the MSW incinerator and saving the investment and operation cost of the flue gas purification system.

4.4. The effect of residual fly ash after flue gas purification of municipal solid waste incinerator on the comprehensive utilization of fly ash from coal-fired boiler.

In the incinerator fly ash was detected Ca, Na, K, Mg, Fe, Al, Ti, Ba, P, As, Ni, Mn, Pb, Cd, Cu, Cr, Zn, Hg, Sn, Cl, S and the content distribution of heavy metal elements in the fly ash and slag of incinerator is different because of the different precipitation properties of heavy metal elements and their compounds, the content of heavy metals such as Cd, Cr, Pb, Hg, Sn, Zn, Cu is high in fly ash from incineration [3]. The content of heavy metals in fly ash of municipal solid waste fluctuates widely, and the maximum and minimum values of some species are more than 10 times. Comparison values of heavy metals in cement production is shown in Table 5.

| Heavy metal | HJ662-2013 (mg/kg-cem) | Coupling heavy metal elements (mg/kg) |
|------------|------------------------|--------------------------------------|
| Cr         | 320                    | 65.660−68.682                        |
| Zn         | 37760                  | 58.112−92.481                        |
| Mn         | 3350                   | 174.055                              |
| Ni         | 640                    | 0.189−0.944                          |
| Mo         | 310                    | --                                   |
| As         | 4280                   | 0.311                                |
| Cd         | 40                     | 0.277−0.692                          |
| Pb         | 1590                   | 36.844−52.895                        |
| Cu         | 7920                   | 48.970−60.490                        |
| Hg         | 4                      | 0.196                                |

The coupling of 850t/d MSW incinerator with 1000MW USC coal-fired unit as an example, the fly ash quality of coal-fired is 264 times higher than the fly ash of MSW incinerator. But the content of heavy metals in fly ash of MSW incinerator is very high when the fly ash is uniformly distributed. It will be greatly diluted after the coupling.

The fly ash environment of pulverized coal boiler is alkaline. After coupling, it is not easy to precipitate and has higher the stability. Melt phase transition occurs at 1130°C, heavy metal elements stabilize in molten glass after coupling. The concentration of heavy metal decreases sharply, the soluble salt of heavy metal is not easy to precipitate, and heavy metal is not easy to precipitate.

The heavy metals content of fly ash of coal-fired boiler accord in coupling scheme fully meets the technical specification for environmental protection of cement kiln co-disposal of solid waste HJ662-2013 issued by the ministry of environmental protection. The fly ash from large-scale coal-fired boilers can be used for producing cement and other purposes without the influence of coupling schemes.

5. Economic analysis

2 x850t/d waste incinerators and 2 x1000MW of ultra-supercritical coal-fired units are calculated by the coupling of 5700 hours per year and 8000 hours per year, respectively. The load of the waste
furnace cannot be less than 70% BMCR and run with stable load for a long time, with 8000 hours per year h, and 5700 hours per year in coal-fired power plants. coal-fired coupled waste power generation, can apply to the government to increase the annual use of coal-fired units hours. Economy analysis of MSW incinerator before and after coupling is shown in Table 6.

**Table 6.** Economy analysis of MSW incinerator before and after coupling.

| Item                        | unit | Coupling scheme 1 | Coupling scheme 2 | MSW incinerator |
|-----------------------------|------|-------------------|-------------------|-----------------|
| Daily waste disposal        | t/d  | 2X850             | 2X850             | 2X850           |
| annual waste disposal       | ×10⁴ t/a | 40.4             | 56.7             | 56.7            |
| Static investment           | ×10⁹ RMB | 56110           | 56110            | 85000           |
| Unit cost                   | ×10⁹ RMB /t/d | 33              | 50               |
| Annual utilization hours    | h    | 5700              | 8000             | 8000            |
| Per ton waste on grid power | kWh/t | 595              | 595              | 463             |
| Generation electricity      | %    | 31.6              | 31.6             | 25.6            |
| efficiency                  | %    | 17.9              | 27.7             | 8.63            |
| Project rate of return      | %    | 5.62              | 3.61             | 11.59           |
| Annual utilization hours    | annual | 5.62              | 3.61             | 11.59           |

The unit cost of coal-fired coupled waste power generation is 66% of that of waste incinerator, the power generation efficiency is 1.23 times that of waste incinerator, and the investment recovery period is 48% and 32% of that of waste power plant, which greatly shortens the investment payback period. After coupling, the smoke exhaust temperature is further reduced and the power generation efficiency is improved, which is 1.23 times of the waste incinerator, annual power generation has obvious economic benefit advantage of 37400 MW•h, and the investment economic benefit is remarkable.

6. Conclusions
The coupling is very beneficial. The generation efficiency increased from 25.6% to 31.6%. The exhaust temperature reduced from 200°C to 133°C by using the complete endothermic surface of the large coal-fired unit to exchange heat with the flue gas, and the waste heat of the waste incinerator exhaust smoke is recovered to the greatest extent. Furthermore, using the flue gas purification system of the original coal-fired boiler, both the flue gas after waste incineration and the coal-fired boiler can achieve super-clean emission, reducing the flue gas purification system of the original waste incinerator and saving the investment of 200000/t/d. The waste coupling power generation technology can not only achieve the waste reduction, harmless, resource utilization, but also achieve low cost. Two representatives can also be a single coupling, do not affect each other.

The coupling technology between coal-fired and waste is feasible, energy saving and environmental protection advantages are remarkable. Saving resources has a huge environmental benefit at the same time. The research results are an important direction for the future development of the energy market. Through the above analysis, it is recommended to adopt the coupling mode of waste incinerator and coal-fired boiler.

Acknowledgements
The authors gratefully acknowledge the financial support provided by Science Foundation Program of HeiLongJiang Outstanding Youth (Grant No. JC2017014).

References
[1] 2019 *China statistical yearbook*
[2] Bai L CH 2014 Waste incineration engineering technology *China Architecture Press*
[3] Zhou J H 2014 MSW incineration and power generation technology *China Power Press*
[4] Zhang M W, Feng G X, Huang R, etc 2015 Removal of dioxin in flue gas from a large-scale MSWI by domestic activated carbon injection. *Chinese Journal of Environmental Engineering* 9(11) 5531-5536
[5] Guo X, Zhao G B, Sun Z H 2018 Effect of Recirculated Flue Gas on Steam Parameters of 660MW Double Reheat Boiler Proceedings of the CSEE 38(4) 1101-1110

[6] Li W W 2000 Flue gas including chlorine harmful substance formation and control was studied after wastes combusted [D] Zhejiang University

[7] Pan C Y 2004 A study on high temperature corrosion of HCl in MSW boiler superheater sector Zhejiang university

[8] Hidenori M, Natsuko K 2019 destruction behavior of short-and medium-chain chlorinated paraffin in solid waste at a pilot-scale incinerator Chemosphere

[9] 2010 Coal ash erosion section of fuel and combustion- index Doosan Power Systems

[10] B.R. Stanmore 2004 The formation of dioxins in combustion systems Combustion and Flame 136(398-427)

[11] Gang Z, Kang S M, Huang X X 2018 Influence of PCDD/Fs from a simple waste incinerator on the plant environment IOP conference series: earth and environmental science

[12] Lu S Y, Yan J H, Li X D, etc 2003 Experimental Study on PCDD/FS formation on Waste Incinerator Fly Ash Via De Novo Synthesis-Effects of Oxygen, Carbon and Catalyst Proceedings of the CSEE 23(11) 178-183

[13] Li X D, Yang Z C, Yan J H, etc 2003 Effects of Chlorine on HCl and PCDD / FS Emission in a MSW Incinerator Journal of Engineering Thermophysics 24(6) 1047-1050

[14] Hutzinger O, Blumich M J, vander Berg M, et al Sources and fate of PCDDs and PCDFs: an overview Chemosphere 985(6-7) 581-600

[15] 2014 Pollution control standard for municipal solid waste incineration GB18485

[16] Gordon M 2002 Dioxin characterization formation and minimization during municipal solid waste(MSW) incineration: review Chemical Engineering Journal 86(343-368)

[17] Wilkstrom E, Marklund S 2001 The influence of Level and Chlorine Source on the Formation of Mono-to Octa-Chlorinated Dibenzo-p-Dioxins, Dibenzofuran and Coplanar Polychlorinated Biphenyls During combustion of an artificial municipal waste Chemosphere 43 227-234