Waste Management 38 (2015) 149–156

Contents lists available at ScienceDirect

Waste Management

journal homepage: www.elsevier.com/locate/wasman

MSW oxy-enriched incineration technology applied in China: Combustion temperature, flue gas loss and economic considerations

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ARTICLE INFO

Article history:
Received 10 November 2014
Accepted 24 December 2014
Available online 10 February 2015

Keywords:
Economical
Grate furnace
MSW
Oxy-enriched incineration
Technical

ABSTRACT

To investigate the application prospect of MSW oxy-enriched incineration technology in China, the technical and economical analyses of a municipal solid waste (MSW) grate furnace with oxy-fuel incineration technology in comparison to co-incineration with coal are performed. The rated capacity of the grate furnace is 350 tonnes MSW per day. When raw MSW is burned, the amount of pure oxygen injected should be about 14.5 wt.% under 25% O_2 oxy-fuel combustion conditions with the mode of oxygen supply determined by the actual situation. According to the isothermal combustion temperature (T_a), the combustion effect of 25% O_2 oxy-enriched incineration ($\alpha = 1.43$) is identical with that of MSW co-incineration with 20% mass ratio of coal ($\alpha = 1.91$). However, the former is better than the latter in terms of plant cost, flue gas loss, and environmental impact. Despite the lower costs of MSW co-incineration with mass ratio of 5% and 10% coal ($\alpha = 1.91$), 25% O_2 oxy-enriched incineration ($\alpha = 1.43$) is far more advantageous in combustion and pollutant control. Conventional combustion flue gas loss (q_2) for co-incineration with 0% coal, 20% coal, 10% coal, 5% coal are around 17%, 13%, 14% and 15%, respectively, while that under the condition of 25% O_2 oxy-enriched combustion is approximately 12% ($\alpha = 1.43$). Clearly, q_2 of oxy-enriched incineration is less than other methods under the same combustion conditions. High moisture content presents challenges for MSW incineration, therefore it is necessary to dry MSW prior to incineration, and making oxy-enriched incineration technology achieves higher combustion temperature and lower flue gas loss. In conclusion, based on technical and economical analysis, MSW oxy-enriched incineration retains obvious advantages and demonstrates great future prospects for MSW incineration in China.

1. Introduction

Social development and the improvement of living standards through urbanization and the expanding Chinese population has lead to an increasing yield of MSW in recent years. The growing accumulation of municipal waste has created serious environmental and social problems. MSW in China reached 180 million tons in 2010 and the amount is projected to reach up to 210 million tons in 2015 (Lei, 2011; Liu et al., 2012).

Incineration is an efficient technology for MSW disposal as it operates to reduce waste while realizing a resource in an environmentally sound manner through MSW incineration power generation (Cheng and Hu, 2010; Lu and Peng, 2010). Challenges encountered in the process relate to MSW characteristics such as high moisture content, high ash content and low heating value. Problems like combustion instability, complex pollutants, and unsuitability for plateau areas (Nie, 2008; Zhang et al., 2010) bring additional challenges.

Oxy-enriched incineration technology presents effective methods for overcoming these difficulties as a result of its high combustion efficiency and low pollutant emission (Masaharu, 2001; Gohlke and Busch, 2001). Martin Corporation (Gohlke and Busch, 2001) developed a process for enriching primary air with oxygen called Synthetic Oxygen-enrichment Combustion (SYNCOM). Industrial scale demonstration plants have been implemented in Coburg (Oberfanken, Germany) and Oita (Kyushu Island, Japan). The main benefits in use of oxygen-enhanced combustion can be summarized as follows: (a) increase of flame temperature and stability, (b) enhancement of combustion efficiency, (c) reduction of flue gas and pollutants (Martin and Helmut, 2000; Lacava et al., 2006; Liuzzo et al., 2007; Verdone et al., 2008). Gohlke and Martin reported that an oxy-enhanced waste-to-energy system would be progressive innovation for waste-to-energy technology (Gohlke and Martin, 2007).

Past studies have mainly focused on coal combustion with only a few research studies based on the promising technology of Oxy-

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http://dx.doi.org/10.1016/j.wasman.2014.12.026
0956-053X/

fuel as applied within the MSW incineration industry. The oxygen enrichment condition presented by thermo gravimetric analysis (TGA) is a useful technique for studying the decomposition reactions of a solid fuel yet, combustion and pyrolysis characteristics of MSW as related to TGA have few research studies. Lai et al. studied the combustion behavior of MSW in a TGA under different N_2/O_2 and CO_2/O_2 atmospheres with temperatures ranging from 100 °C to 1000 °C (Lai et al., 2011). Liu et al. also investigated the MSW oxygen-enriched combustion characteristics in N_2/O_2 atmosphere (Liu et al., 2009). Huang et al. explored the oxygen-enriched gasification process for MSW in South China (Huang et al., 2013). Several research studies have centered on combustion or pyrolysis characteristics and kinetics of typical components in MSW such as plastics, cotton (Liu et al., 2010; Lai et al., 2012; Chen et al., 2013; Meng et al., 2013). Chin et al. performed a pilot plant experiment to evaluate the effect of oxygen enrichment on the co-incineration of MSW and organic sludge from a wastewater treatment facility (Chin et al., 2008). Adequate and effective research for practical application of MSW oxygen-enriched combustion technology in China is to be completed.

The entire life cycle of a MSW oxy-fuel incineration power plant was evaluated using the method of Life Cycle Assessment (LCA) to identify and quantify the fossil energy requirements and environmental impacts (Tang et al., 2013). Yan et al. took a circulating fluidized bed boiler with a handling capacity of 1100 tons per day as the research objective and performed the technical and economical analysis based on power consumption and economic calculation under the oxygen-enriched combustion condition with flue gas near zero emission (Yan, 2013). However, similar technical and economical analyses of MSW grate incineration boilers, the most widely used in the Chinese MSW incineration industry, have not been conducted. Consequently, the analyses of a MSW grate incineration furnace with a rated capacity of 350 tons per day are carried out in this study with effects of oxygen concentration, co-incineration percentage of coal, and moisture content in MSW investigated. Results obtained in this study may be utilized for advancement of MSW oxy-fuel incineration technology in China.

2. Objective

A MSW incineration power plant with a grate furnace rated capacity of 350 tonnes per day and located in Wuhan, China, is investigated in this study. A schematic diagram of the oxy-enriched incineration system used in this study is presented in Fig. 1. As shown in Fig. 1, the oxy-enriched incineration system mainly consists of 5 systems; a combustion system, heat exchange system, flue gas treatment system, oxygen injection system, and flue gas recirculation system. Pure oxygen is supplied by a liquid oxygen tank, as delivered by tankers from an oxygen factory. Liquid oxygen must be vaporized by an air evaporator to be gaseous, injected into hot air heated by high temperature steam. Oxy-enriched air with 30% O_2 is injected into the combustion section of the grate. Recirculated flue gas branched at the exit of the bag filter is transferred to front and rear walls using a recirculation fan and is then injected into the furnace through nozzle rows. Recycled flue gas is used to control flame temperature and make up the volume of missing N_2 to ensure there is adequate gas to carry heat through the boiler due to a reduction of primary air.

Currently, MSW co-incineration with coal operates as a primary method to ensure combustion temperature and efficiency in China's MSW incineration industry, therefore co-incineration with different coal mass ratios (5%, 10% and 20%) are compared with oxy-enriched incineration in different aspects. Huangling (HL) bituminous coal is selected for this study to simulate actual coal co-incineration with MSW and the fuels of oxy-enriched incineration are raw MSW from different regions in Wuhan. The proximate and ultimate analyses of HL bituminous coal and MSW are shown in Table 1. As presented in Table 1, the combustible fraction of the raw MSW was less than 25%, while the contents of moisture and ash nearly reached 48% and 28%, respectively. The lower heating value (LHV) of MSW was about 4.645 MJ/kg, similar to that of the average MSW in central China (Zhang et al., 2010). According to Table 1, the raw MSW in Wuhan possessed typical characteristics of high moisture content, high ash content, and low heating value.

3. Methods

3.1. Oxygen consumption of raw MSW oxy-enriched incineration

Based on the ultimate analysis of the raw MSW in Table 1 and mass balance, the oxygen consumption (kg) of burning 1 kg raw MSW on as received basis can be calculated as:

$$W(O_2)_{ar} = (C_{ar}/12 + H_{ar}/4 + N_{ar}/28 + S_{ar}/32 - O_{ar}/32) \times 0.32\ \text{kg/mol} \quad (1)$$

According to Eq. (1), the approximate oxygen consumption of burning raw MSW is 50 wt.%. Excess air factor is commonly near 1.9 with conventional combustion to guarantee sufficient burning in a MSW incineration power plant. Excess air ratio will be reduced with the injection of pure oxygen. Excess air ratio, for this study, is set at 1.43 (Gohlke and Busch, 2001) due to concentration of O_2 in the air at approximately 25% (Masaharu, 2001; Gohlke and Busch, 2001). The volume ratio of pure oxygen injected in total oxy-enriched air is considered x, and the equation is as follows:

$$[x + 0.21 \cdot (1 - x)]/1 = 0.25 \quad (2)$$

$$x = 0.051$$

If Y represents the ratio of oxygen injected in total oxygen consumption, the equation is shown below:

$$Y = x/[x + 0.21 \cdot (1 - x)] = 0.203 \quad (3)$$

Therefore, the consumption of pure oxygen injected into primary air when raw MSW is burned should be 14.5 wt.%. For the 350 t/d MSW oxygen-enriched incineration power plant, the consumption of pure oxygen is 51 t/d (40,700 m^3/d gaseous oxygen).

3.2. Isothermal combustion temperature

Isothermal combustion temperature (T_a) is an integral parameter during the heat transfer process. The method of calculation was referred to the Principles of Boiler (Chen and Chen, 1981) and Boiler Principle and Calculation (Feng et al., 2003). According to heat balance, T_a can be calculated as follows:

$$T_a = (Q_{ar,net,p} \times 1000 + Q_{air,in})/(c_f \times V_f + c_{ash} \times A_{ar}\%) \quad (4)$$

$$Q_{air,in} = \alpha \times V^0 \times \rho_{air} \times h_{ha} \quad (5)$$

$$V^0 = 0.0889 \cdot (C_{ar} + 0.375 S_{ar}) + 0.265 H_{ar} - 0.0333 O_{ar} \quad (6)$$

$$c_f = c_{O_2} \cdot W_{O_2} + c_{N_2} \cdot W_{N_2} + c_{RO_2} \cdot W_{CO_2} + c_{H_2O} \cdot W_{H_2O} \quad (7)$$

$$W_{O_2,N_2,RO_2,H_2O} = V_{O_2,N_2,RO_2,H_2O}/V_f \quad (8)$$

$$V_f = V_f^0 + (\alpha - 1) \cdot V^0 + 0.0161 \cdot (\alpha - 1) \cdot V^0 \cdot W_{air} \quad (9)$$

where $Q_{ar,net,p}$ (MJ/kg) is the lower heating value, measured and calculated through oxygen bomb calorimeter; $Q_{air,in}$ (kJ/kg) is the heating value of hot air in the furnace; c_f (kJ/(m^3 °C)) and c_{ash} (kJ/(kg °C))

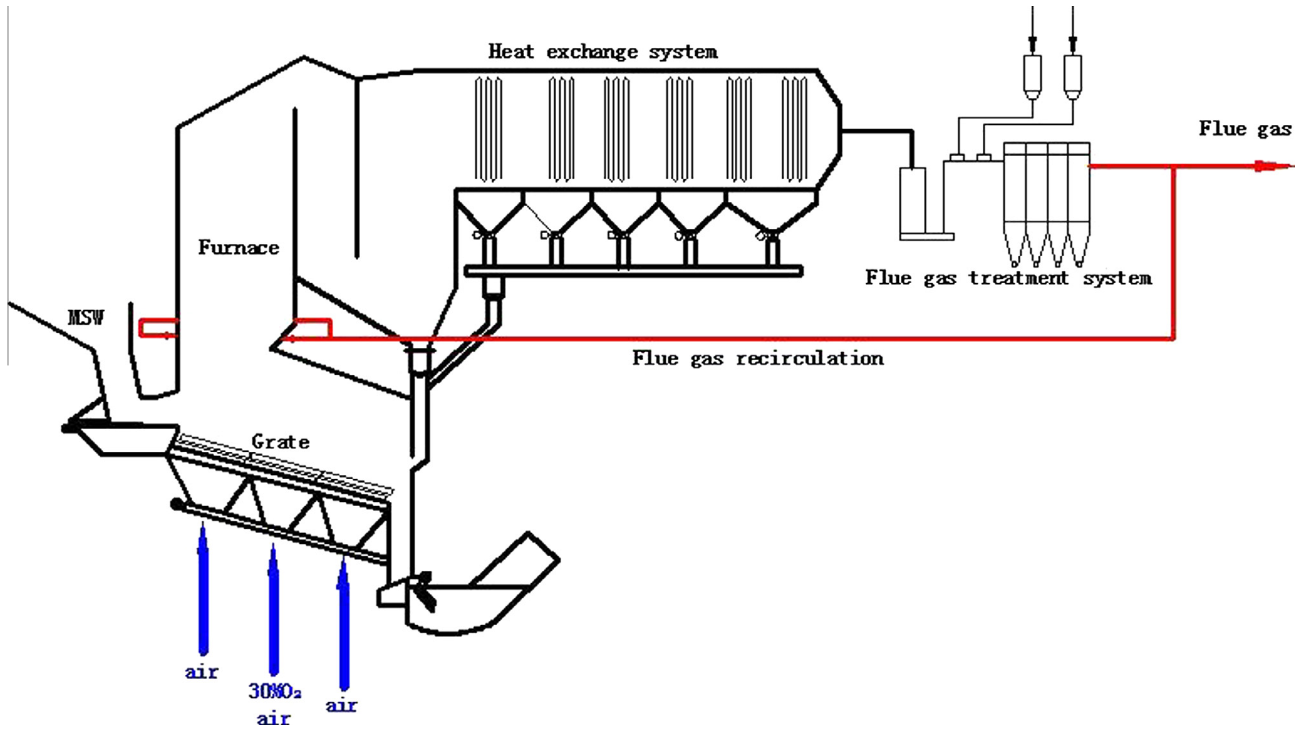

Fig. 1. Oxy-enriched incineration system of a grate furnace.

Table 1
Proximate and ultimate analyses of HL bituminous coal and MSW (as received basis).

Sample	Proximate analysis (wt.%)				Ultimate analysis (wt.%)					$Q_{ar,net,p}$
	M_{ar}	V_{ar}	A_{ar}	FC_{ar}	C_{ar}	H_{ar}	N_{ar}	S_{ar}	O_{ar}	MJ/kg
HL coal	7.27	19.94	26.48	46.31	53.06	2.88	0.81	0.71	8.79	20.89
MSW	47.76	20.13	27.85	4.26	14.06	1.99	0.36	0.37	7.95	4.645

are the specific heat capacities of flue gas and ash, respectively; V_f is volume of flue gas (m^3) and A_{ar} comes from proximate analysis in Table 1; α is the excess air coefficient and V^0 (Nm^3/kg) is the theoretical volume of feed air required for 1 kg as-received fuel burning; ρ_{air} (kg/Nm^3) is the density of feed air and h_{ha} (kJ/kg) is the enthalpy of feed air, because the primary air temperature in MSW power plant is about 150 °C and the value of ρ_{air} and h_{ha} can be found through density-temperature and enthalpy-temperature tables, respectively. C_{ar}, S_{ar}, H_{ar}, and O_{ar} are presented in Table 1. c_f (kJ/(m^3 °C)) is the average specific heat of flue gas including RO_2, N_2, O_2 and H_2O in the case of 1500 °C which is a flame temperature (Williams, 1985). W_{air} (%) is the ratio of conventional air in the total oxy-enriched air; V_{O_2,N_2,RO_2,H_2O} (Nm^3/kg) is the actual volume of RO_2, N_2, O_2 and H_2O in flue gas. Specific heating values of O_2, N_2, RO_2, H_2O and ash are shown in Table 2, under condition of 1500 °C .

Table 2
The specific heating values of O_2, N_2, RO_2, H_2O and ash.

Components	Value (at 1500 °C) kJ/(m^3 °C)	Value (at 170 °C) kJ/(m^3 °C)
O_2	1.5294	1.3352
N_2	1.4440	1.2996
RO_2	2.3354	2.7873
H_2O	1.8527	1.5223
Ash	1.0000	

3.3. Flue gas loss

Oxy-enriched combustion technology can reduce exhaust flue gas volume and flue gas loss which is a chief loss throughout the MSW incineration process. Flue gas temperature in the stack is commonly 170 °C in Chinese MSW incineration power plants. Flue gas loss (q_2) was calculated according to Principles of Boiler (Chen and Chen, 1981).

$$q_2 = h_{f,out}/(Q_{air,in} + 1000 \cdot Q_{ar,net,p}) \times \% \tag{10}$$

$$h_{f,out} = T_{f,out} \cdot c_{f,out} \tag{11}$$

$$c_{f,out} = c_{O_2,out} \cdot W_{O_2} + c_{N_2,out} \cdot W_{N_2} + c_{RO_2,out} \cdot W_{CO_2} + c_{H_2O,out} \cdot W_{H_2O} \tag{12}$$

where $h_{f,out}$ (kJ/kg) and $c_{f,out}$ (kJ/(m^3 °C)) respectively are the enthalpy and the average specific heat of flue gas at the exit of the economizer including RO_2, N_2, O_2 and H_2O. The specific heat values of O_2, N_2, RO_2 and H_2O at 170 °C are displayed in Table 2.

3.4. Economic evaluation

Economic evaluation and comparison between oxy-enriched incineration and co-incineration with coal in MSW power plants take into account the following: (1) government subsidy for

MSW management; (2) costs associated with oxy-enriched air or coal consumption; (3) without consideration of initial investment and operation costs. Considering these factors, plant costs can be calculated as:

$$\Delta C_P = c_O \cdot m_{O,c} + c_C \cdot m_{C,c} - s \cdot m_{W,u} \tag{13}$$

where ΔC_P (USD/d) is the increment of plant cost per day; c_O and c_C (USD/t) are the cost of liquid oxygen and coal per ton; s (USD/tMSW) is the government subsidy for MSW management per ton, respectively; $m_{O,c}$ and $m_{C,c}$ (t/d) are the mass of liquid oxygen and coal consumption per day; $m_{W,u}$ (t/d) is the mass of untreated waste caused by co-incineration with coal. Table 3 provides the associated costs through market investigation and fuel consumption together with actual MSW treatment capacities by calculation.

4. Results and discussions

4.1. Isothermal combustion temperature (T_a)

Based on Table 1, the isothermal combustion temperature (T_a) of MSW incineration with different coal proportions and different oxygen concentrations is calculated. The curves that T_a varied with excess air ratio (α) under the different combustion conditions are displayed in Fig. 2. Fig. 2 illustrates that T_a is obviously influenced by α. Under the conventional combustion condition (21% O_2), T_a of MSW incineration is about 1120 °C where α is 1.2, while that drops to 865 °C when α increases to 2.0. Meaning that combustion temperature goes down with the increase of excess air ratio during the MSW conventional incineration process. When MSW is burned with coal in the coal proportion ranging from 0% to 20% (mass ratio), T_a will increase nearly 50 °C with the increase of 5% coal proportion where α is 2.0. Additionally, the increase of T_a will rise up with the reduction of α, for example T_a will increase by almost 80 °C with the increase of 5% coal proportion when α is 1.2. When MSW is burned under the condition of enriched oxygen (21% to 29% volume ratio), T_a will rise up to approximately 20 °C with increase of 1% oxygen concentration in the case of the same α.

According to the Technical Code for Projects of Municipal Waste Incineration CJJ90-2009 (Construction, 2009), to control pollutant emission, combustion temperature should exceed 850 °C, residence time should be greater than 2 s, and oxygen concentration in furnace outlet gas should be about 6–10%. Fig. 2 indicates that T_a of MSW combustion is just about 860 °C under conventional combustion when α is 2.0. Proving that combustion of raw MSW struggles to achieve the demanded combustion temperature when α is more than 1.9 along with heat exchange and heat loss during the actual MSW incineration process. However, the reduction of α can guarantee neither sufficient combustion nor the oxygen concentration in furnace outlet gas. Hence, MSW is usually co-incinerated with coal in the MSW power plant to ensure sufficient combustion temperature.

According to the Technical Code referred to above, the maximum coal proportion of MSW co-incineration with coal is 20%. Fig. 2 indicates that T_a can reach up to 1100 °C when MSW is co-incinerated with 20% HL coal in the case that α is 1.9, meanwhile, oxygen concentration in furnace outlet gas can reach approximately 7.5%. When MSW combustion is applied with oxy-enriched combustion technology, T_a can reach up to 1100 °C only through injection of 25% O_2 in the case that α is 1.5 or less. The combustion effect and pollutant emission levels of MSW oxy-enriched incineration are improved over MSW co-incineration with 20% coal (Gohlke and Busch, 2001). Furthermore, oxygen concentration in combustion section can reach up to 30%, promoting combustion efficiency and restraining the formation of dioxins and other gas pollutants.

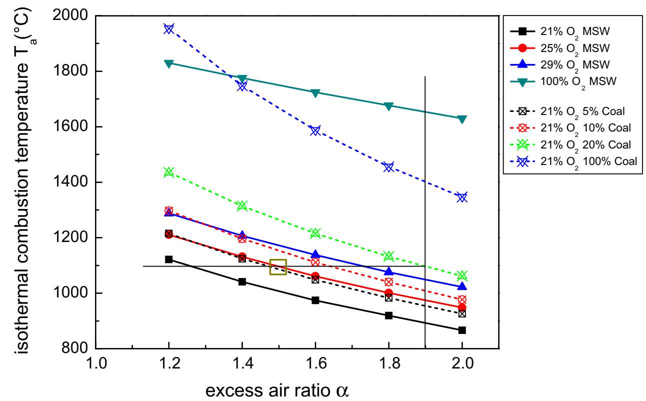

Fig. 2. Isothermal combustion temperature T_a of MSW incinerations with different coal proportions or oxygen concentrations.

The Standard for Assessment on Municipal Solid Waste Incineration Plant, CJJ/T 137-2010 (Construction, 2010), the latest policy, reveals that mass ratio of fossil fuels mixed with MSW during the incineration process will be reduced to only 5% from 20% in the near future. Obviously, T_a of MSW oxy-enriched incineration with 25% O_2 is higher compared to MSW co-incineration with 5% coal in the same α. The policy verifies that oxy-enriched incineration is advantageous over MSW co-incineration coal.

4.2. Flue gas loss (q_2)

As expressed in Fig. 3, flue gas loss of different combustion methods varies with varying excess air ratios α. Obviously, there is an increase in q_2 with an increase in excess air in the same condition. Flue gas loss of MSW conventional combustion is around 13% when α is as low as 1.2 and when α increases to 2.0, q_2 will reach up to more than 17%. The variation tendency is caused by an increase in flue gas rate with a rise in excess air. Under the condition of MSW oxy-enriched incineration, q_2 will rise with the reduction of oxygen concentration in the same α; co-incineration with coal presents the same tendency with the reduction of coal ratio. The difference is that variation between q_2 and α under the oxy-enriched incineration is more evident than under the co-incineration with coal. As indicated in Fig. 3, q_2 under the condition of

Table 3
Fuel consumption, actual MSW treatment capacities and associated costs.

Mass ratio %	Calorie ratio %	Capacity of MSW treatment t/d	Coal consumption t/t(MSW)	Cost of coal consumption USD/d
0	0.00	350	0.000	0
5	19.14	283	0.053	1441.5
10	33.32	233	0.111	2509.5
20	52.93	165	0.250	3986.1
Associated costs		O_2 (liquid, 100%) 80.6 USD/t (in large scale: more than 20 tons/d)	Coal 97.0 USD/t	Subsidy 9.7 USD/tMSW

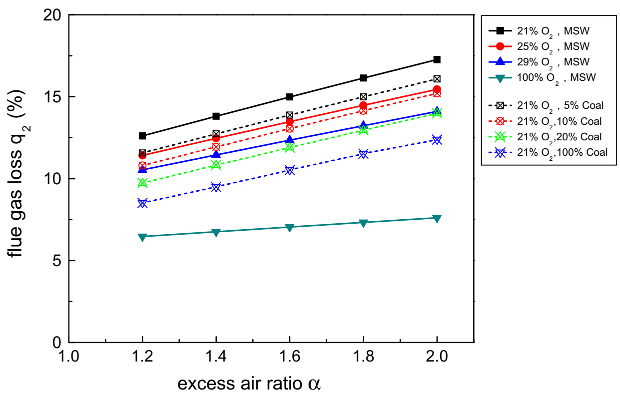

Fig. 3. Variation of flue gas loss under different combustion method in different excess air ratio.

25% O_2 oxy-enriched combustion with 1.43 of excess ratio is approximately 12%. In the same case that α is 1.91, q_2 in the conditions of conventional combustion, co-incineration with 20% coal, co-incineration with 10% coal, co-incineration with 5% coal are around 17%, 13%, 14% and 15%, respectively. Flue gas loss of oxy-enriched incineration is then comparatively lower than the other methods to achieve the same combustion effect.

4.3. Influence of moisture percentage and the related treatment

High moisture content presents challenges for MSW incineration and must be considered, especially in China's rainy season and in areas rich in water resources. The influence of moisture percentage in MSW on lower heating value (LHV_{ar}), T_a and q_2 during oxy-enriched incineration and co-incineration processes must be analyzed.

Figs. 4–6 present the influence of moisture content (M_{ar}) in MSW on LHV_{ar} of fuel, isothermal combustion temperature (T_a) and flue gas loss (q_2) under varying combustion conditions. As is indicated in figures, M_{ar} in MSW has a significant impact on LHV_{ar} of fuel, for instance, LHV_{ar} of pure MSW is less than 4.5 MJ/kg when M_{ar} in MSW is as much as 50%, while that is approximately 8.5 MJ/kg when M_{ar} decreases to 20%, almost twice as much as the former. T_a and q_2 under different M_{ar} of MSW vary widely. If M_{ar} levels are 20% and 50%, T_a levels are about 1150 °C and 850 °C under conventional combustion ($\alpha = 1.91$), respectively. Likewise, q_2 levels are around 12.7% and 17.4%, respectively. In addition, the differences of T_a and q_2 produced by M_{ar} in MSW are more obvious especially in the condition of oxy-enriched combustion.

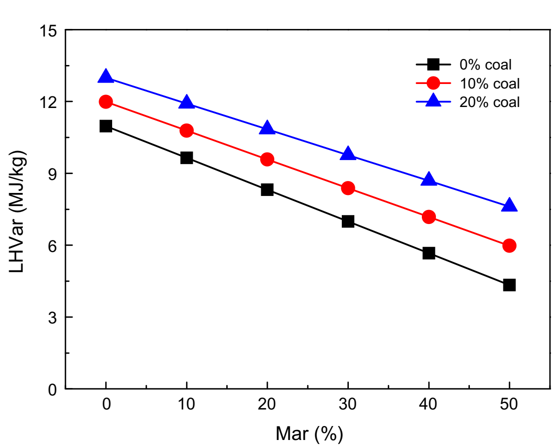

Fig. 4. Influence of moisture content in MSW on lower heating value of fuel.

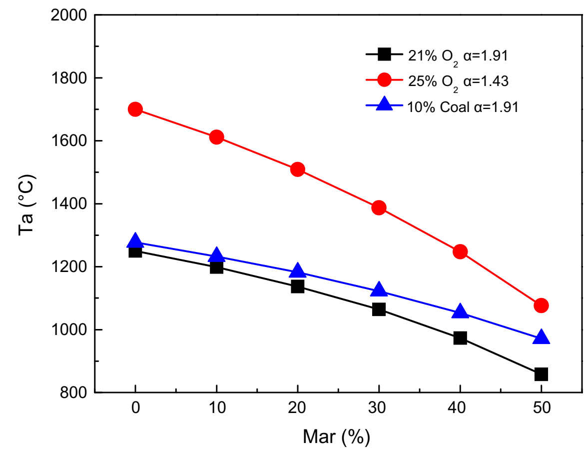

Fig. 5. Influence of moisture content in MSW on isothermal combustion temperature.

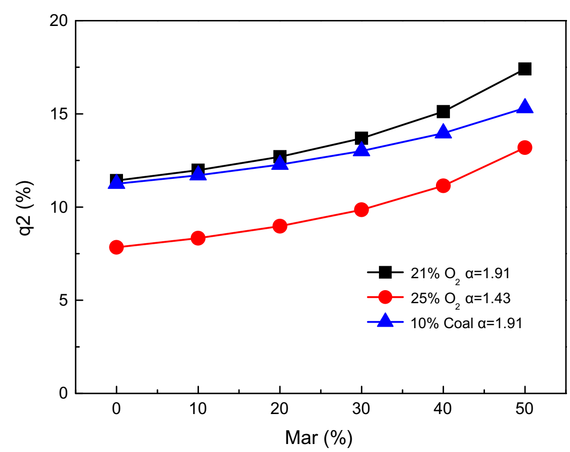

Fig. 6. Influence of moisture content in MSW on flue gas loss.

Reducing moisture content in MSW, as specified, improves the lower heating value of mixed fuels, enhances boiler efficiency and controls pollutant emissions. MSW power plants must participate in MSW dehydration prior to MSW incineration to gain these advantages (A and Zhang, 2004; Yan et al., 2005; Li and Hu, 2007; Li et al., 2008, 2012; Velis et al., 2009; Zhang et al., 2009; Shao et al., 2010).

Three common methods to dehydrate MSW before entering into boiler include; sorting, biodrying, and heating (A and Zhang, 2004; Jia et al., 2004; Li and Hu, 2007; Li et al., 2008, 2012; Zhuang et al., 2008; Tai et al., 2011). Source separation has been considered an effective method of MSW management (López et al., 2010). However, an effective source-separated collection system has not been established in China because of defects in legislation, coordination mechanisms and public awareness (Tai et al., 2011). Li et al. advised two effective methods, bio-waste source separation and biodrying, based on the properties of MSW in China (Li et al., 2008). Jia et al. compared the drying efficiency of several different dehydration schemes. Exhaust gas utilized as a drying medium can increase heat recovery efficiency as moisture content of MSW distinctively decreased, however the flue gas purification system is challenged with complexity as the drying medium still need to manage. Heated air from the air pre-heater adopted as drying medium, slightly improved the calculated heat recovery efficiency while the area of the heat exchange equipment will be increased because the drying medium must be heated by flue gas (Jia et al., 2004). MSW dehydration occurs most efficiently, then, through mechanical drying. Leachate from the process can be disposed by sewage treatment system, retaining efficiency while being cost effective (A and Zhang, 2004).

4.4. Oxygen supply

Oxygen is supplied by three main technologies: cryogenic distillation (CD), pressure swing adsorption (PSA) and membrane separation (MS) (Häring and Ahner, 2008). Table 4 presents a comparison of the three methods. (Bhide and Stern, 1991; Chou et al., 1994; Cornelissen and Hirs, 1998; Budner et al., 1999; Belaissaoui et al., 2014) Cryogenic distillation and pressure swing adsorption (PSA) are currently the greatest utilized.

Membrane separation (MS) does not possess the ability to economically attain high purity O_2 in a large scale production compared to the other two techniques, thus is not suitable for MSW oxygen-enriched incineration on a large scale. Cryogenic distillation (CD) and pressure swing adsorption (PSA) do, however, retain efficient methods for oxygen supply. Liquid oxygen produced by cryogenic distillation is available for purchase from oxygen factories due to high equipment investment or the MSW power plant is able to be equipped with several PSA oxygen generators according to the requirements (2000 m^3/h PSA oxygen generator in this research). Cost calculations of these two schemes for 350 t/d MSW oxygen-enriched incineration power plant are displayed in Tables 5 and 6 with the comparison of the two modes listed in Table 7.

Tables 5 and 6 data indicates the cost of oxygen produced by the PSA oxygen generator per day (2894 USD/d) is obviously lower than the liquid oxygen supply (4158 USD/d). However, utilizing the liquid oxygen supply system has significant advantages in the aspects of initial investment, construction cycle and floor area. PSA oxygen generation systems, though lower in production cost, will greatly increase operation burden of the MSW incineration power plant. MSW incineration power plants with sufficient conditions and located long distances from oxygen producing factories are more suited for PSA oxygen generator use, while plants absent necessary conditions or with locations near oxygen producing factories are best suited for purchase of liquid oxygen.

4.5. Economic analyses

According to Eq. (13) and Table 3, the economic indices of MSW co-incineration with different mass ratio of coal are presented in Fig. 7. According to Fig. 7, MSW co-incineration with coal effects plant costs by increasing them from two aspects: cost of coal consumption and reduction of government subsidy. Because coal removes capacity for MSW treatment as it replaces a portion of the waste stream, thereby decreasing treatment efficiency and driving costs up, additionally allowance of MSW treatment will decrease correspondingly.

Through the analyses of T_a and q_2 above, the combustion effect of 25% O_2 oxy-enriched incineration is identical with that of MSW co-incineration with 20% mass ratio of coal. However, ΔC_P of the MSW co-incineration with 20% coal (5778.3 USD/d) is significantly

Table 5
Cost of 2000 m^3/h PSA oxygen generator.

	Items	Value
A	Energy consumption	0.45 kW h/m^3O_2
B	Energy consumption of auxiliary system	0.045 kW h/m^3O_2
C	Electricity price	0.103 USD/kWh
D	Oxygen consumption	40,700 m^3/t
E	Equipment investment	2,600,000 USD
F	Depreciation years	10
G	Residuals rate	10%
H	Amount of depreciation = (1−G) E/365F	641 USD/d
I	Maintenance cost = 0.025E/365	178 USD/d
J	Cost per day = EC(A + B)+H + I	2894 USD/d

Table 6
Cost of liquid oxygen supply.

	Items	Value
A	Liquid oxygen cost	80.6 USD/t
B	Oxygen consumption	51 tons/d
C	Equipment investment	150,000 USD
D	Depreciation years	10
E	Residuals rate	10%
F	Amount of depreciation = (1−E) C/365D	37 USD/d
H	Maintenance cost = 0.025C/365	10.3 USD/d
I	Cost per day = AB + F + H	4158 USD/d

Table 7
Comparison of two oxygen supply modes.

	PSA oxygen generator	Purchase liquid oxygen
Initial investment (USD)	2,600,000	150,000
Construction cycle (Month)	6–9	3
Floor area (m^2)	1500–2000	50–100
Oxygen cost (USD/d)	2075	4113
Facilities	Complex	Simple
Dependence	Electricity	None
Management	Difficult	Easy

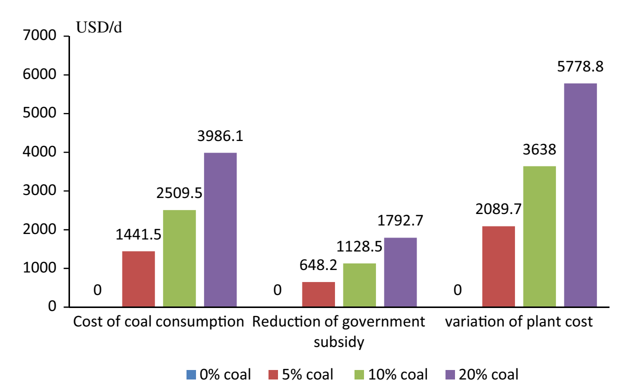

Fig. 7. Economic comparison of MSW incinerator in adoption of co-incineration with different mass ratio of coal (USD/d).

Table 4
The comparison of three processes.

Technology	CD	PSA	MS
Process scale	100–300 tons/d	20–100 tons/d	10–25 tons/d
Oxygen purity	>99%	Around 95%	25–40%
System	Complicated process, difficult operation	Simple process, convenient operation	Simple process, easy operation
Requirement	High pressure, low temperature	Atmospheric pressure, normal temperature	Atmospheric pressure, normal temperature
Security	High-risk	Low-risk	Low-risk

higher than that of the 25% O_2 oxy-enriched incineration (4158 USD/d). Increasing energy consumption and depletion of traditional fossil fuels will drive the price of coal upward. Comparatively, liquid oxygen production costs will decrease with enhanced development of oxygen manufacturing, storage and transportation. Thus, 25% O_2 oxy-fuel incineration costs are advantaged over MSW co-incineration with 20% mass ratio coal.

Currently, Chinese MSW power plant feedstock is mixed with 10% coal during operation. As previously discussed, the cost of 25% O_2 oxy-fuel incineration (4158 USD/d) is slightly higher than that of co-incineration with 10% coal (3638 USD/d). Combustion effects and pollutant emission controls of 25% O_2 oxy-fuel incineration, however, provide advantages to help offset costs. Additionally, according to the Standard for Assessment on Municipal Solid Waste Incineration Plant, CJJ/T 137-2010 (Construction, 2010), in the future, daily processing capacity of a MSW power plant should be above 80% of the rated capacity. Co-incineration with 10% coal is unable to meet the requirement as the actual combustion proportion of MSW is less than 70% in this method. Growth in demand for 25% O_2 oxy-fuel incineration as an energy source in China is quite possible.

Coal mass ratio at just 5% (as required), retains costs (2090 USD/d) far below that of 25% O_2 oxy-enriched incineration (4158 USD/d). Inferiority of the 5% coal co-incineration, however, as opposed 25% O_2 oxy-enriched incineration, arises in combustion temperature, flue gas loss and pollutant emissions. Coal co-incineration at 5% ratio cannot meet future needs for improved MSW combustion conditions as can oxy-enriched incineration with 25% O_2.

For different model of oxygen supply, the price of liquid oxygen (in large scale: more than 20 tonnes/d) is steady at 80.6 USD/ton because cryogenic distillation has been very mature and the oxygen market is stable. And the mainly cost of PSA is power consumption. In general, oxygen costs will be stable in a extended period and even decrease with enhanced development of oxygen manufacturing, storage and transportation. Currently, the profits of Chinese MSW power plant depend on on-grid price and government subsidy. These can ensure the plant using oxy-enriched (25%) incineration to improve combustion. Additionally, the government subsidy may increase with the adoption of new technology. However, conventional incineration can hardly meet the demand of latest environmental standard so that the plant may be shut down. For co-incineration with coal, mass ratio of coal mixed with MSW during the incineration process will be reduced to only 5%. Otherwise, the on-grid price will decrease (nearly 30%) as coal-fired power plant. Therefore, MSW oxy-enriched incineration can achieve better benefits in both economic and environmental aspects. With an increase in the collected residue scale, the oxygen consumption, on-grid electricity and government subsidy will increase in proportion. In this case, PSA (2894 USD/d) is the best model of oxygen supply due to economical efficiency and energy consumption. Oxy-enriched incineration can reduce the scale of the flue gas cleaning system, reducing equipment investment and operating costs. Meanwhile, by reducing flue gas rate, boiler efficiency improves, decreasing flue gas loss. Abilities to meet capacity requirements, improve environmental conditions, and produce cost savings combine to create a superior MSW incineration method with the oxy-enriched version.

5. Conclusions

Technical, economical and environmental analyses of a MSW grate incineration furnace from different aspects were performed in this study. It was discovered that:

Application of 25% O_2 oxy-enriched incineration in MSW grate boiler with a rated capacity of 350 t/d demands the injection of 20.3 vol.% pure gaseous oxygen in total oxygen consumption, and the most suitable excess air ratio (α) should range from 1.4 to 1.5. Accordingly, the consumption of liquid oxygen injected is around 14.5 wt.% when raw MSW is burned with an approximate cost of about 11.6 USD/ton MSW.

According to the isothermal combustion temperature (T_a), the combustion effect of 25% O_2 oxy-enriched incineration ($\alpha = 1.43$) is similar to that of MSW co-incineration with 20% mass ratio of coal ($\alpha = 1.91$). However, the former is superior to the latter in terms of plant cost, flue gas loss and environmental impacts. Despite plant costs of MSW co-incineration with mass ratio of 5% and 10% coal ($\alpha = 1.91$) being less than 25% O_2 oxy-enriched incineration ($\alpha = 1.43$), the 25% O_2 oxy-enriched incineration retains advantages in combustion effect and pollutant emission controls.

In terms of flue gas loss (q_2), q_2 under the condition of 25% O_2 oxy-enriched combustion with 1.43 of excess ratio is approximately 12%. In the same case ($\alpha = 1.91$), q_2 in conventional combustion, co-incineration with 20% coal, 10% coal, 5% coal are around 17%, 13%, 14% and 15%, respectively. Clearly, the q_2 of oxy-enriched incineration is less than other methods in the same combustion effect. The scale of the flue gas cleaning system can be reduced due to the reduction of flue gas rate in oxy-enriched incineration. Accordingly, both equipment investment and operation costs will experience a drop.

High moisture content imposes difficulty for MSW incineration, creating a need for MSW drying prior to MSW incineration. Mechanical drying is the superior dehydration method.

Technical, economical and environmental advantages of MSW oxy-enriched incineration are significant, rendering a great potential for future expansion to meet the needs of China and its expanding municipal solid waste stream.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (No. 51276075), and State Key Laboratory of Coal Combustion in Huazhong University of Science & Technology (No. 201303095), and the Research Foundation of Huazhong University of Science & Technology (No. 2014TS118).

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