Choices of heat exchanger network for incineration plant fuelled with high water content municipal solid waste

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Abstract

Heat balance calculation was used to evaluate the effect of municipal solid waste (MSW) drying on the heat recovery of MSW incineration. Heat recovery efficiency and steam production rate were compared when hot air from air preheater, exhaust flue gas and steam were chosen as media to dry MSW. The calculation results showed that MSW drying always enhances heat recovery by promoting effective steam production. When air preheater was arranged to be heated by flue gas in the heat exchanger network and exhaust flue gas after the air preheater was used as drying medium, heat recovery efficiency and steam production rate gained the highest values, but at the same time flue the gas scrubbing system should be re-designed to match this heat exchanger network choice.

Keywords: municipal solid waste drying, heat exchanger network, heat balance calculation, heat recovery efficiency, steam production rate, water content.

1 Introduction

Presently more and more municipal solid wastes (MSW) incineration plants are setting up in China, grate furnaces are prevalently adopted and heat recovery system are normally based on superheated steam Rankine cycle to generate power. This kind of MSW incineration system depends on a high low heat value of MSW to maintain a stable and efficient operation. But in many cities in China
especially southern cities that have much rainfall, heat values of MSW fluctuate a lot with their normal values in the range of 600~1500 kcal/kg, some newly set-up incineration plants cannot be put into operation without consumption of auxiliary fuel. The water contented in MSW not only reduces heat value, deteriorates ignition and combustion, but also raises the vapor pressure in the flue gas thus elevates the dew point. Finally the water in MSW exits from the system in the form of vapor together with flue gas at above 200°C and contributes a lot to heat loss of Q\textsubscript{2}, the heat entrained by exhaust flue gas. Because of the high dew points, the wall temperature of the rear heat transfer surface should be high enough to prevent corrosion, and air preheaters are normally installed outside of the flue duct with steam as heating source or they are designed to be two stages with the first stage being steam-heated, which causes loss to the overall heat recovery.

Furthermore, the arrangement of flue gas scrubbing system would also affect the heat recovery efficiency by influencing the choice of heat exchanger network of the system. For acidic gas concentration in the flue gas affects dew point considerably, if they can be intercepted at higher temperatures, then dew point of flue gas can be reduced and more heat transfer surface can be installed. Presently the prevailing semi-dry scrubbing system adopted in the incineration plants is to spray Ca(OH)\textsubscript{2} slurry and active carbon into the flue gas, the flue gas should be hot as 240~250°C to evaporate all the water in the slurry thus the heat loss of Q\textsubscript{2} is considerably high, at the same time the produced air pollution control products bear dioxins formed during the flue gas cooling process and need special treatment. In this paper the methods for removing moisture from MSW before incineration and effective heat exchanger networks matched with suitable flue gas scrubbing system are discussed.

2 Choices of MSW dewatering method

There are usually three choices to remove moisture contained in MSW: to let MSW store for some time and the water would come out by natural infiltration, which is the case for MSW in storage pool in front of the furnace; The second and the reliable method is to dry MSW by contacting (directly or indirectly) with hot media such as hot air, steam and hot flue gases. The amount of water being removed can be controlled by controlling time, area and temperature of hot media etc. The third method is to remove water from MSW by mechanical press, but the part absorbed by capillaries or chemically bound is difficult to be removed. If water content of MSW is higher than 50% percent, mechanical press can be performed first and then dried with hot media.

Based on the above discussions, the effects of MSW drying on heat recovery efficiency and on arrangement of heat exchanger networks were analysed here using the working fuel water content (notated as \(W^y\)) of 45% as the basis, which is a common design value for incineration plants. Heat recovery efficiency is calculated by heat balance analysis. According to the type of drying media adopted, the heat exchanger network for heat recovery and the flue gas scrubbing system may have different choices, as shown in table 1.
Table 1: Choices for MSW drying method and heat exchanger network.

<table>
<thead>
<tr>
<th>Choice</th>
<th>MSW drying</th>
<th>Heat exchanger network buildup</th>
<th>Suitable flue gas scrubbing system</th>
<th>Operation features</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>On the grate in the furnace by hot flue gas circulation</td>
<td>Waterwall, convective boiler tubes, super heater, economizer, air preheater heated by steam and a grate dryer</td>
<td>Normally semi-dry scrubbing system is used</td>
<td>Furnace more complicated, vapor pressure in the flue gas unchanged; ignition and combustion improved.</td>
</tr>
<tr>
<td>2</td>
<td>By flue gas exiting from economizer</td>
<td>Waterwall, convective boiler tubes, super heater, economizer, air preheater heated by steam, and flue gas / MSW directly contacting dryer</td>
<td>Dry or wet flue gas scrubbing system for cooled flue gas from MSW dryer</td>
<td>Full utilization of waste heat, ignition and combustion improved. But the flue gas scrubbing system needs to be re-designed for cooled flue gas from MSW dryer.</td>
</tr>
<tr>
<td>3</td>
<td>By flue gas exiting from air preheater</td>
<td>Waterwall, convective boiler tubes, super heater, economizer (or none), air preheater in flue duct, and flue gas / MSW directly contacting dryer</td>
<td>High temperature flue gas scrubber match with scrubbing system as Choice 2</td>
<td>Full utilization of waste heat, ignition and combustion improved. But heat transfer surface for economize was abridged.</td>
</tr>
<tr>
<td>4</td>
<td>By hot air coming from air preheater</td>
<td>Waterwall, convective boiler tubes, super heater, economizer (or none), air preheater in flue duct, and hot air / MSW directly contacting dryer</td>
<td>High temperature flue gas scrubber matched with scrubbing system as Choice 1</td>
<td>Increased air preheater heat transfer surface and decreased economizer surface. Combustion improved. No necessary for the treatment of used air from MSW dryer.</td>
</tr>
<tr>
<td>5</td>
<td>By steam abstracted from turbine</td>
<td>Waterwall, convective boiler tubes, super heater, economizer, air preheater heated by steam, and MSW dryer</td>
<td>The same flue gas scrubbing system as Choice 1</td>
<td>Ignition and combustion improved. The evaporated moisture separated from the combustion system.</td>
</tr>
</tbody>
</table>

As high temperature resistant draft fan and flue gas distribution damper are necessary for Choice 1, it is not easy to be applied and won’t be discussed later. Choice 2, 3, 4 and 5 are more practical and easier to be carried out, thus the following discussions are based on comparison of these four choices.

3 Heat balance calculation for different heat exchanger networks

Heat balance calculation is based on an incinerator with capacity of 300 tonnes per day. Elemental composition of MSW fuelled to this incinerator is listed in table 2. The pressure and the temperature of supersaturated steam produced by waste heat boiler are 4.0MPa and 400℃. The temperature of feed water is 145℃, and the temperatures of ambient air and heated air are 25℃and 150℃ respectively. The temperature of exhaust flue gas is designed to be 240℃ to fit the semi-dry flue gas scrubbing system. It should be mentioned that in the present heat exchanger networks, the air preheater or its first stage is normally a
steam–air heat exchanger outside of flue duct, in order to uniformly define the heat balance system, air preheater is excluded in the system. Correspondingly, the steam deducted of the consumption in air preheater and MSW dryer is defined as “effective steam”, which is the expected heat energy recovery.

For simplicity, only one stage preheater is considered in the calculation, which is practical when low heat value of MSW is high.

Table 2: Elemental composition of MSW for incineration (%).

<table>
<thead>
<tr>
<th>Element</th>
<th>C&lt;sup&gt;y&lt;/sup&gt;</th>
<th>H&lt;sup&gt;y&lt;/sup&gt;</th>
<th>O&lt;sup&gt;y&lt;/sup&gt;</th>
<th>S&lt;sup&gt;y&lt;/sup&gt;</th>
<th>Cl&lt;sup&gt;y&lt;/sup&gt;</th>
<th>N&lt;sup&gt;y&lt;/sup&gt;</th>
<th>A&lt;sup&gt;y&lt;/sup&gt;</th>
<th>W&lt;sup&gt;y&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Content</td>
<td>14.95</td>
<td>2.78</td>
<td>9.15</td>
<td>0.23</td>
<td>0.02</td>
<td>0.65</td>
<td>27.22</td>
<td>45</td>
</tr>
</tbody>
</table>

*: C<sup>y</sup>, H<sup>y</sup>, O<sup>y</sup>, S<sup>y</sup>, Cl<sup>y</sup>, N<sup>y</sup> and A<sup>y</sup> are mass fractions of elements C, H, O, S, Cl, N and ash contained in the working fuel in percent.

3.1 Initial parameters and conditions

For simplicity, the following assumptions are made without causing defection to precision and university of calculation results.

3.1.1 Rate of fly ash to bottom ash

The solid residues resulted from MSW incineration include fly ash and bottom ash. According to the operation experiences, fly ash is around 10% of the total residues and the bottom ash accounts 90% of the total.

3.1.2 Excess air coefficient

According to operating experiences, it is designed that excess air coefficients change with water content and the changing law is shown in fig.1.

3.2 Calculation of main parameters

3.2.1 Heat income of the system

Heat income of the system includes low calorific value of working MSW and heat entrained by combustion air.

3.2.1.1 Low calorific value of working MSW Q<sub>dv</sub><sup>y</sup>

To calculate Q<sub>dv</sub><sup>y</sup>, first high heat value of working MSW Q<sub>gw</sub><sup>y</sup> should be calculated with the help of some experimental formulae, [1]:

\[
Q_{gw}^y = 340C^y + 1430(H^y - \frac{1}{8}O^y) + 105S^y \text{ kJ/kg} \quad (1)
\]

Then Q<sub>dv</sub><sup>y</sup> can be calculated as follows, [2]:

\[
Q_{dv}^y = Q_{gw}^y - 226H^y - 25W^y \text{ kJ/kg} \quad (2)
\]
3.2.1.2 Heat input by combustion air $Q_{r,k}$ can be easily obtained by:

$$Q_{r,k} = \alpha^* \cdot V^0 (ct)_{rk} \text{kJ/kg} \quad (3)$$

where $\alpha^*$ is excess air coefficient at the inlet of furnace, whose data are shown in fig. 1. $V^0_k$ is theoretical volume of air needed for combustion one kilogram of MSW and $(ct)_{rk}$ is specific enthalpy of the hot air. The overfire air and the air leaks into the furnace are assumed to be at ambient temperature of 25°C and their enthalpy is neglected.

3.2.2 Heat output from the balance system

There are six items in this catalogue, they are effective heat $Q_1$, heat loss entrained by exhaust flue gas $Q_2$, chemical incomplete combustion loss $Q_3$, physical incomplete combustion loss $Q_4$, heat lost to the surroundings $Q_5$ and heat loss entrained by ash, slag and cooling water $Q_6$. The ratio of those six items to the heat income are the heat loss rates and notated with the corresponding lowercases $q_1$, $q_2$, $q_3$, $q_4$, $q_5$ and $q_6$ respectively. They can be calculated with the help of formulae, tables and figures given by Shiguang Xi et al [2]. But for the calculation of heat loss $Q_4$, some additional information is needed. Heat loss $Q_4$ includes two parts: carbon contented in fly ash and carbon contented in bottom ash. Those carbon contents, production of bottom ash and fly ash and ash content in MSW are related as:

$$BA^\gamma = G_{hz} \cdot (1 - R_{hz}) + G_{fh} \cdot (1 - R_{fh}) \quad (4)$$

where B is the consumption of MSW per hour in kilogram; $R_{hz}$ and $R_{fh}$ are carbon contents in bottom ash and fly ash respectively; $G_{hz}$ and $G_{fh}$ are mass of bottom ash and fly ash produced per hour respectively, based on the above assumption, $G_{hz}$ and $G_{fh}$ can be related as: $G_{fh} = 0.1 \times (G_{hz} + G_{fh})$. With the help of laboratory measurement, $R_{fh}$ was found to be in the range of 2~3% and was assumed to be 2.5% in the calculation. $R_{hz}$ changes with factors like low heat value of MSW, water content $W^\gamma$ and combustion rate, etc. To investigate how $R_{hz}$ changes with low calorific value of MSW, MSW of the same composition as in table 2 was used in the laboratory and its water content was changed by drying or adding water to find the law between water content in MSW and carbon content in the produced ash. Comparison of experimental data and incineration plant operation records gives the relationship of $R_{hz}$ and the low calorific value as:
\[ R_{hz} = 0.97838 \cdot Q_{y}^{r} \cdot e^{-Q_{y}^{r}} + 1.35935 \cdot e^{-Q_{y}^{r}} + 0.009625 \]  \tag{5}

### 3.2.3 Heat recovery efficiency

Gross heat recovery efficiency \( \eta \) was calculated by counter-balance method as

\[ \eta = (1 - \frac{Q_{2} + Q_{3} + Q_{4} + Q_{5} + Q_{6}}{Q_{dw} + Q_{r,k}}) \times 100\% \]  \tag{6}

When steam is consumed in the air preheater or MSW dryer, net heat recovery efficiency \( \eta_{j} \) is obtained by deducting the heat consumed:

\[ \eta_{j} = \eta - \frac{Q_{q}}{Q_{dw} + Q_{r,k}} \]  \tag{7}

where \( Q_{q} \) is the heat entrained by the steam consumed.

### 3.2.4 Steam production rate

For purpose of economic evaluation, the parameter of steam production rate is introduced and defined as the ratio of effective steam production to water free MSW incinerated and noted as \( \varepsilon \), which presents the amount of effective steam produced by incinerating one kilogram dry MSW and can be regarded as an index for economic benefit from heat recovery. If \( \varepsilon \) was increased, then energy recovery was enhanced.

To simplify the discussion and the calculation, the as-received MSW from municipality is assumed to be the same. Calculation steps for individual heat exchangers weren’t shown here. For different choices of MSW drying method and heat exchanger network, \( \eta_{j} \), \( \varepsilon \), theoretical combustion temperatures and other key parameters are calculated and shown in figs 1–6.

![Figure 1: Excess air coefficient and air consumption changing with water content in MSW.](image1)

![Figure 2: Ratio of flue gas and hot air used in dryer to the total changing with water content.](image2)
4 Results and discussions

4.1 Effect of MSW drying on the system arrangement

Fig. 1 shows the changes of excess air coefficient and air consumption with water content in MSW, it can be seen that the excess air coefficient descends as MSW becomes drier (water content decreased). This is because that the dried MSW is easier to ignite and air used for heating MSW on the grate is decreased and the air supplied to the furnace is only for combustion. And if the as-received MSW from municipality keeps the same, the total air consumed would decrease as water content decreases for Choice 2, 3 and 5, therefore the surface of air preheater can be saved and its size can be smaller in those three networks. But for the case of Choice 4, hot air is used to dry MSW, the total air supplied to air preheater includes two parts: the part for combustion and the part for drying. It increased as water content decreased because the later part increased, as shown in fig. 2, bigger part of the total hot air is needed for drying as the required water content decreased. This would pose overload to air blowers in the incineration plant, and larger air-blowers or additional ones should be installed to meet the demand. Fig.2 also shows that when flue gas was used as drying medium, the drier the MSW, the bigger part of the total flue gas is needed. For Choice 4, the used air can be discharged into MSW storage pool without any treatment, while for Choice 2 and 3 additional induced fan may be needed and the used flue gas should be treated before discharge. It should be noted that as water content decreased from 45% to 25%, all of the flue gas produced in the combustion process is needed for drying, therefore the whole flue gas scrubbing system needs to be changed. For Choice 5 when steam is used as heating medium, the air supply and flue gas treatment system can be remained unchanged, only an indirect heating dryer is needed therefore the system is relatively simpler.

Now let’s take a look of temperature distribution, fig. 3 shows temperature of flue gas exiting from economizer and the corresponding heat loss rate. It can be seen that when hot air is used as heating medium (Choice 4), as water content reduced to 37~38% flue gas temperature at the inlet of air-preheater is up to 404~414°C, which is a normal inlet temperature for economizer, this means the heat transfer surface of economizer is totally or partially replaced by air preheater. For economizer has a larger heat transfer coefficient, the heat transfer surface of the new system should be larger. To decrease water content further will trench on the heat transfer surface of steam superheater, and the type of air preheater may need to be changed. So if hot air is used as drying medium, it is suggested that only a slight decrease of $W_y$ be adopted.

4.2 Effect of air preheater choice on heat recovery efficiency and the system arrangement

From figs. 5–6, it can be seen that the heat exchanger networks with air preheater installed inside the flue duct correspond to higher heat recovery efficiencies and
especially higher steam production rates than the networks with air preheater
heated by steam. Especially for Choice 3, the steam production rates and heat
efficiencies always correspond to highest values. But at the same time, air
preheater installed inside the flue duct with cool air introducing into it is exposed
to low temperature corrosion. According to temperature evaluation for the air
preheater, when cool air is introduced at 25°C the wall temperature at the inlet of
cool air could be as low as 106°C and dew point of untreated flue gas is
generally around 150~180°C according to operation experiences. Therefore high
temperature flue gas scrubber should be equipped for this system.
4.3 The effect of MSW drying on heat recovery and steam production

Fig. 3 shows that for Choice 4 when hot air is used as drying medium the heat loss rate of $q_2$ is increasing as $W^y$ decreasing. For choices 2, 3 and 5 when flue gas and steam is adopted as drying medium, heat loss $q_2$ dropped down with water content $W^y$. Because of the special definition of heat balance system here, $q_2$ is not a decisive factor affecting overall heat recovery. Fig. 4 shows that theoretical combustion temperature (notated as $t_H$) increases as $W^y$ decreasing; and that when the amount of dry MSW incinerated is the same, the true combustion rate (notated as $B_j$) decreases as $W^y$ decreased. When $W^y$ decreased from 45% to 25%, $t_H$ would increase from 956°C to 1416°C which is comparable to that of coal combustion. At this time not only the auxiliary fuel can be saved, but also more water wall heat transfer surface can be installed in the furnace chamber to raise the steam production. Another benefit of MSW drying is the decrease of incomplete combustion loss $Q_4$ caused by increased heat value and the higher temperature in the furnace. So in figs. 5~6 both net heat recovery efficiency and steam production rate increase when MSW is dried with flue gas and steam. Even for Choice 4, the case with the highest heat loss of $q_2$, $\eta_j$ didn’t descend remarkably while steam production rate increased as MSW dried. For steam production rate is the index of heat recovery benefit, so it has proved that MSW drying always improves the heat recovery benefit, no matter what kind of heating medium adopted. The most important is that MSW drying improves the combustion, make stable and complete combustion possible and at the same time save the auxiliary fuel, which wasn’t taken into account in the above calculations. On the other side, for the dried MSW are easier to ignite and need less time to finish combustion process so the same incinerator can have a larger capacity. Generally, when theoretical combustion temperature is higher than 1000~1100°C the auxiliary fuel can be totally spared. Fig. 6 shows that when water content decreased to 38% the theoretical combustion temperature rises to 1100°C, so it is suggested water content in working MSW be less than 38% to avoid auxiliary fuel consumption.

5 Application of MSW drying and choice of heat exchanger networks

Presently in most of southern cities in China the low heat value of MSW is low because of high water content, but their combustible contents are normally higher than 50% in dry fuel. In this case MSW drying can help to increase the low heat value and the heat recovery efficiency. If the low heat value is the result of low combustible content in MSW, then MSW drying won’t help much and sorting should be conducted. From the above discussion, MSW drying can be
performed by using flue gas, hot air and steam as heating medium. From heat recovery efficiency and system analysis, Choice 3 corresponds to the highest heat recovery efficiency and highest steam production rate, especially for newly set up incineration plant, it is a better choice to use the total flue gas produced as drying medium and flue gas scrubber is designed for the cooled flue gas from MSW dryer. At the same time a high temperature flue gas scrubber should be equipped in the system to decrease dew point of flue gas. A possible problem concerning Choice 3 is that part of volatile may emit out when MSW contacting with hot gas. So experiments are necessary to decide the suitable temperature of flue gas contacting with MSW. Choice 4 is not a good one because of its negligible regain of heat recovery, increased heat transfer surface and the remain of evaporated moisture in the combustion air. Choice 5 is also a good one for the simplicity of the system and the separation of evaporated water from the incineration system. Generally, Choice 3 could be the most potential choice for new incineration plant and Choice 5 is the easiest modification to the existing incineration system in operation.

6 Conclusion

MSW drying can elevate theoretical temperature, improve ignition and combustion and save auxiliary fuel. Therefore it is a good method to improve incineration of MSW with high water content. Based on different method for MSW drying there are four choices for the heat transfer networks in the incineration system. With help of heat balance calculation of the whole system and thermal analysis of individual heat exchangers, it has been proved MSW drying can improve effective steam production. The best method for MSW drying is to use hot exhaust flue gas as heating medium, and Choice 3 in this paper is a suitable choice for heat exchanger network to new incineration plant. And to existing incineration plants Choice 5 is an easy modification although the increase of heat recovery is low, the combustion would be improved and auxiliary fuel could be spared. If air preheater is heated by flue gas instead of steam in heat exchanger network, it will always correspond to higher steam production rate, but at the same time high temperature gas scrubbing system should be adopted in the system to prevent erosion and corrosion as well as to degrade ash toxicity.

References