Design and Thermodynamic Analysis of Waste Heat Recovery System of Sludge Hydrothermal Carbonization

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Abstract. This paper proposes a new type of sludge hydrothermal carbonization waste heat recovery system, which transfers the heat in the sludge hydrothermal carbonization to the combustion air of the boiler through total heat exchange to achieve waste heat recovery. The waste heat recovery system makes full use of the heat in the steam and improves the calorific value of the sludge entering the incinerator. With the increase of combustible matter content in sludge, the exergy efficiency of waste heat recovery system increases. Due to the improved steam quality and the use of small turbines to do work, the operating economy is improved.

Key words. Sludge, carbonization, waste heat recovery, thermal calculation.

1. Introduction

In recent years, energy shortage and environmental deterioration have become one of the important factors restricting social and economic development and affecting people's quality of life. In the face of the increasingly prominent energy crisis and environmental crisis, energy conservation and emission reduction have become the focus of today's society. In industrial production, there are a lot of waste heat resources [1]. If these waste heat can be effectively recycled, it will not only save energy, but also reduce thermal pollution of water bodies. At present, there is a large amount of low-grade heat energy that can be reused in production and life, such as sewage, groundwater, seawater, etc. A heat pump can obtain low-grade heat from air, water or soil, and is a device that uses a compressor to achieve grade-boosting. With the development of social production, the use of heat pumps to provide heat has become a major heating method. Scholars at home and abroad have done a lot of research work on heat pump technology, using various measures to improve the COP value of heat pumps and achieve low energy consumption. In this paper, the thermodynamic characteristics analysis of the overall process of sludge hydrothermal carbonization and waste heat recovery is carried out.

analysis.

2. Thermal system

2.1. Conventional sludge carbonization system

A conventional sludge carbonization system is shown in Figure 1 (the picture is quoted from Combustion characteristics of sewage sludge in an incineration plant for energy recovery). The wet sludge enters the dryer through the sludge conveying system. In the dryer, the saturated steam generated by the waste heat boiler transfers heat to the wet sludge. After the wet sludge is heated, the water in it evaporates to form dry sludge [2]. The mud is sent to the incinerator through the conveying system, while the steam condenses into liquid water. The high-temperature fluidizing air that supports combustion is sent into the incinerator hearth by the air distribution device, and the natural gas for auxiliary combustion is sprayed into the incinerator from the dense phase area of the hearth by the auxiliary burner, and the dry sludge is burned and burnt out in the furnace.

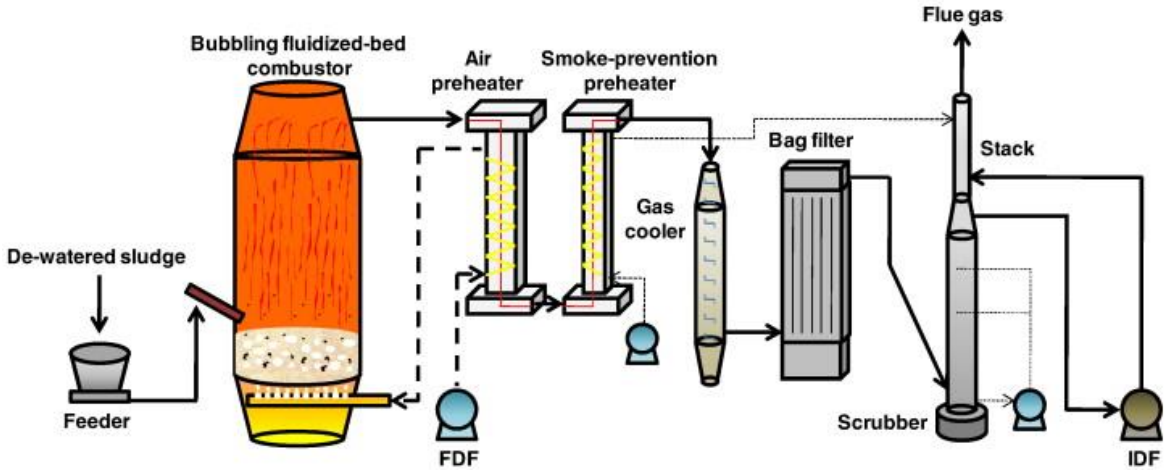


Figure 1. Conventional sludge incineration and waste heat recovery system

2.2. New sludge carbonization system

In the conventional sludge carbonization system disposal process, in order to ensure the steam demand of the sludge dryer and the temperature demand of the fluidizing air required by the incinerator, the air preheater is usually placed before the incinerator, and the flue gas passes through the incinerator [3]. After the air preheater, it enters the waste heat boiler. In the air preheater, the high temperature flue gas is used to heat the air at room temperature, and there will be a large heat exchange temperature difference between the hot medium and the cold medium. After the heat exchange of the air preheater, the high-quality heat consumption is more, and the heat exchange temperature difference in the waste heat boiler is also large, and the steam in the waste heat boiler cannot reach higher parameters. Quality heat is not fully utilized. Based on this, a cascade utilization of high-temperature flue gas is proposed to recover the heat in the flue gas. The process of the proposed new waste heat recovery system based on sludge carbonization is shown in Figure 2 (the picture is quoted from https://www.sludgeprocessing). .com/features/sludge-to-energy-recovery-methods-an-overview/).

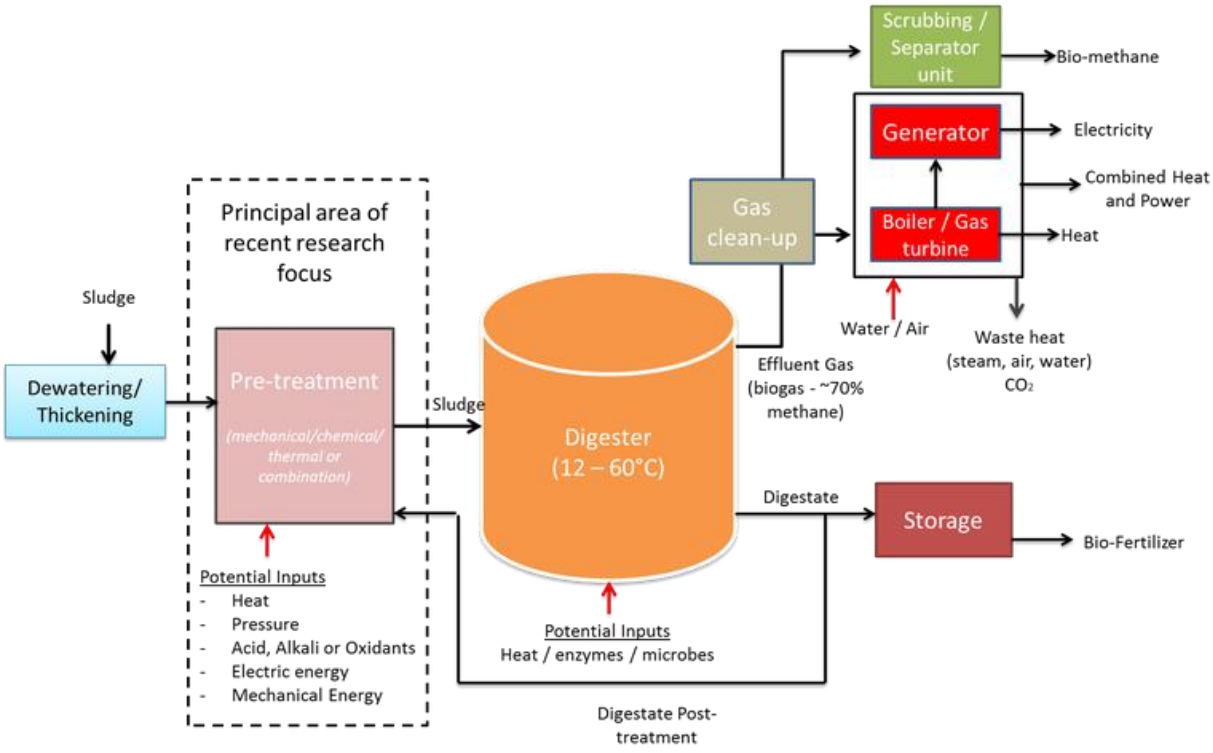


Figure 2. New waste heat recovery system based on sludge carbonization

In the system flow shown in Figure 2, the wet sludge is sent to the dryer after passing through the conveying system, and the wet sludge in the dryer absorbs the latent heat in the saturated steam and evaporates part of the water therein. A heat recovery unit is installed after the dryer to absorb the sensible heat in the hot water after the sludge is discharged from the dryer, and the calorific value of the sludge is further improved. Then the sludge enters the sludge incinerator, and the sludge is heated in the hot air It is completely incinerated under the action of heat carrier (quartz sand). The flue gas after incineration first enters the high-temperature waste heat boiler. The steam side of the high-temperature waste heat boiler inputs the saturated steam heated by the low-temperature waste heat boiler [4]. After heating, the steam becomes superheated steam and enters the steam turbine to do work. After that, the flue gas from the high-temperature waste heat boiler enters the air preheater to heat the cold air, and the cold air is heated and sent to the sludge incinerator as fluidized air. Then the flue gas enters the low temperature waste heat boiler, and the feed water of the low temperature waste heat boiler is heated into saturated steam. The saturated steam is divided into two parts, one part is used for the steam of the dryer, a throttle valve is set at the steam inlet of the dryer to adjust the steam quality required by the dryer, and the other part is passed into the high temperature waste heat boiler. The superheated steam is condensed by the air cooler after the steam turbine does work to produce electricity, and the condensed water is mixed with the hot water at the outlet of the dryer and sent to the low-temperature waste heat boiler as feed water.

3. Thermodynamic Model

When establishing the thermodynamic analysis model, the sludge treatment capacity is calculated as 1000kg per batch. After hydrothermal carbonization, one or two-stage flash evaporation is connected in series, and the steam is successively introduced into the preheating tank to mix with the materials in the tank [5]. The wet sludge in the dryer absorbs the latent heat in the steam, the moisture content is reduced from 75% to 60%, the quality of the sludge changes to the change of water quality and a small amount of odor is evaporated, the steam side of the dryer, the saturated steam is released Latent heat, becomes hot water, energy consumption during drying Q_{evp}:

$$Q_{evp} = m_w[\gamma_w + (t_o - t_i)c_w] \tag{1}$$

In the formula: Q_{evp} is the energy consumption in the drying process, $kJ;\gamma_w$ is the latent heat of vaporization of water, $kJ/kg;c_w$ is the heat capacity of water, $kJ/(kg \bullet K);t_o$ is the temperature of the sludge outlet, $K;t_i$ is the inlet temperature of the wet sludge, and $K;m_w$ is the temperature of the evaporated water. quantity, kg/s , its calculation formula is:

$$m_w = m_s\left(\frac{1}{1-\omega_i} - \frac{1}{1-\omega_o}\right) \tag{2}$$

In the formula: m_s represents the mass flow rate of wet sludge, and $kg/s;\omega_i,\omega_o$ represents the moisture content of the wet sludge entering and leaving the dryer [6]. Based on the balance formula of energy calculation in the dryer, during the calculation process of the sludge heat recovery unit, the heat required for the sludge to evaporate water is obtained from the sensible heat of the hot water, which is the temperature drop from 120°C. The heat to 70 ℃, and then inversely calculate the moisture content ω_o of the sludge from the outlet of the heat recovery unit. The dried sludge in the incinerator is subjected to combustion reaction under the action of high temperature fluidized wind. The energy balance calculation formula in the incinerator is:

$$Q_s + Q_s^{'} + Q_a + Q_b = Q_f + Q_{ash} \tag{3}$$

In the formula: Q_s is the low-level heat carried by the sludge, $kJ;Q_s$ is the physical sensible heat carried by the sludge, $kJ;Q_a$ is the heat carried by the fluidizing air, $kJ;Q_b$ is the heat loss of incomplete combustion, $kJ;Q_f$ is the heat carried by the incinerator flue gas, $kJ;Q_{ash}$ represents the heat carried by the slag discharge of the incinerator, kJ .

Q_s can be obtained from the mass of the dry sludge and the calorific value of the dry basis of the sludge, $Q_s^{'}$ is the sensible heat carried by the sludge, and the mass flow of the fluidizing air is calculated according to the classical formula (4) for calculating solid waste combustion in the project. The heat exchange between the discharge material and the batching tap water belongs to the natural convection heat exchange process. According to the heat balance equation, Newton's cooling law, natural convection differential equation and Fourier heat conduction law, the heat exchange equation can be obtained as follows:

$$\frac{Q}{\tau}=\phi_1+\phi_2=\int_0^{35-10}h_1A_1d\Delta t_1+\int_{t_2-t_\infty}^{t_1-t_\infty}h_2A_2d\Delta t_2 \tag{4}$$

$$h=\frac{\lambda cpr^n}{l}\left(\frac{ga_v l^3}{v}\right)\Delta t^n \tag{5}$$

$$\phi_1=A_1\frac{\lambda cpr^n}{l}\left(\frac{ga_v l^3}{v}\right)^n\int_0^{35-10}\Delta t^n d\Delta t \tag{6}$$

In the formula: Q is the heat provided by the sludge water, $J;\phi_1$ is the heat exchange between the feed liquid and water, $W;\phi_2$ is the heat dissipation from the sewage treatment device to the environment, $W;\tau$ is the heat exchange time of the heat exchanger, $s;\Delta t$ is the heat exchange temperature difference, $^{\circ}C;l$ is the qualitative dimension, the height of the inner water tank, $m;A_1,A_2$ is the outer surface area of the inner and outer water tanks, $m^2;c,n$ is the formula coefficient, and the values of c and n in different temperature difference ranges are shown in Table 1.

Table 1. Values of formula coefficients under different working conditions

Δt/℃	n	c	Flow state
16-27	1/3	0.11	Turbulence
2.5-16	0.39	0.0282	Over
0-2.5	1/4	0.59	Laminar flow

4. System Simulation Design

MATLAB/Simulink is used to simulate the heat pump system. Since the heat pump system is a nonlinear, large delay, and strongly coupled system, two sets of single-input and single-output control methods are used. The system is a condenser fan and an expansion valve, and the operating frequency of the condenser fan is determined as input, expansion valve outlet temperature as output.

Figures 3 and 4 show the effect of the hydrothermal reaction temperature on the preheating temperature of the hydrothermal feedstock and the operating energy consumption of the hydrothermal reaction, respectively (images are quoted from Effect of hydrothermal condition on the formation of multi-component oxides of Ni-based metallic glass under high temperature water near the critical point). Analysis of Fig. 3 shows that when the hydrothermal reaction temperature is increased, the slurry waste heat recovered by flash evaporation can preheat the sludge feed to a higher temperature. This is because the feed temperature of the flash tank increases and the flash superheat degree

increases. The resulting amount of steam is higher; the hydrothermal feed preheat temperature for the secondary flash system is higher than for the primary flash system, but the difference is not significant.

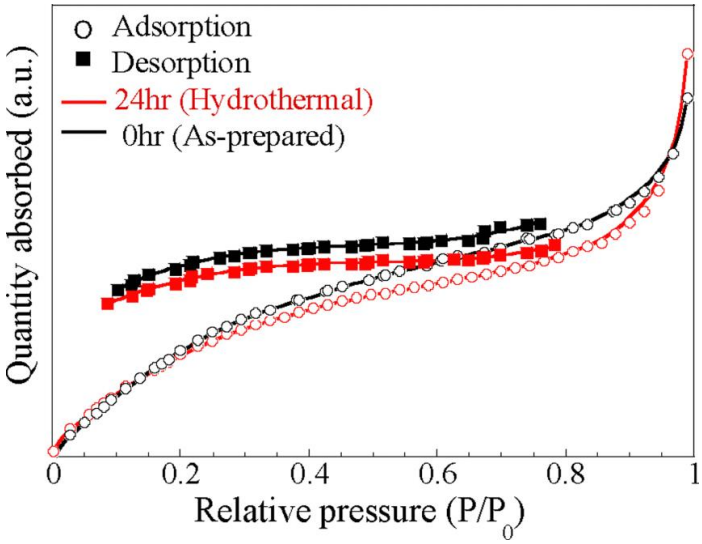


Figure 3. Variation of hydrothermal feed preheating temperature with hydrothermal reaction temperature

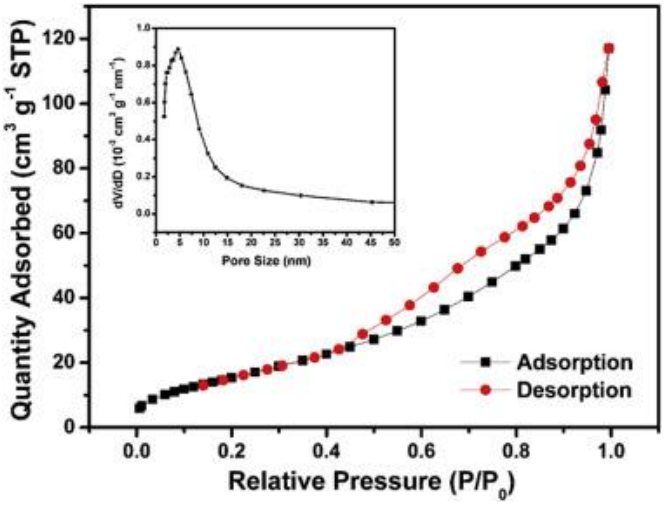


Figure 4. The variation law of the operating energy consumption of the hydrothermal reaction with the temperature of the hydrothermal reaction

The improved new sludge carbonization system makes use of the sensible heat of the condensed water in the dryer by setting the heat recovery unit, and the heat of this step is used to heat the sludge at the outlet of the dryer, which can effectively improve the sludge entering the furnace. Calorific value. In the waste heat taxation system, by setting up two-stage waste heat boilers, the waste heat boiler in the low temperature section heats the feed water to a saturated state, part of the saturated steam is used for steam supply for the dryer, and the other part is sent to the waste heat boiler in the high temperature section. The flue gas heats this part of the steam to a superheated state, and the superheated steam is sent to the steam turbine to generate power. Setting an air preheater between the high temperature section and the low temperature section can effectively reduce the heat exchange temperature difference between the flue gas and the fluidizing air in the air preheater. Due to the increase in the content of combustible substances in the sludge, the heat carried by the flue gas after the sludge incineration also increases accordingly. Under the conditions of satisfying the same steam and air temperature, the temperature drop in the flue gas decreases correspondingly, and the entire waste heat recovery process is reduced. In the system, the heat exergy input by the flue gas also becomes smaller. For the conventional waste heat recovery system and the waste heat recovery

system proposed in this paper, the exergy efficiency increases with the increase of the combustible matter content.

5. Conclusion

The use of waste heat recovery unit to achieve sludge water temperature improvement can not only improve the stability of the sludge water treatment plant, but also save the cost of chemicals. The operation cost in winter will increase by about 16.4% after the temperature increase measures are adopted. The heating rate of the biochemical tank is basically linearly related to the power consumption of the waste heat recovery unit. It is recommended to explore and optimize the balance point of water temperature and chemical consumption, and find the minimum water temperature condition to ensure that the sludge water treatment effect is stable enough, and achieve the lowest power consumption and chemical consumption.

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