PostDoc Journal
Vol. 2, No. 5, May 2014

Journal of Postdoctoral research
www.postdocJournal.com

Integration of wastewater source heat pump and solid-state anaerobic digestion for residential waste treatment and energy production

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Abstract

Recovering energy from waste is gaining growing interest worldwide. The tremendous amount of residential waste, e.g. wastewater and food waste, spurs researchers to develop appropriate waste management methods and energy recovery technologies. Wastewater source heat pump (WWSHP) and solid-state anaerobic digestion (SS-AD) are well established methods for treating wastewater and organic waste. This study proposes a novel combination of these two technologies to handle residential wastewater and solid waste. In the proposed integrated system, WWSHP recovers heat from residential wastewater and then supply heat to SS-AD so that keeps the digesters at a desired operation temperature. The digester uses residential solid waste as feedstock to produce biogas, which is a renewable energy carrier. A case study taking a 1000-resident community as an example showed that the total electricity generated from this system can supply 8% of the community and also provides 1.53×10^{12} J useful heat per year which can greatly reduce building energy consumption.

Keywords : renewable energy, solid-state anaerobic digestion, wastewater source heat pump , waste management

Introduction

Waste heat recovery is of considerable significance to energy conservation and environmental protection. Wastewater source heat pump (WWSHP) is a device that recovers waste heat from residential or industrial wastewater [1], and then uses the recovered heat to warm up indoor air or domestic water so that reduces building energy consumption [2]. The first generation of WWSHP was developed in Norway in the 80s, and gained extensive attention thereafter. For instance, a WWSHP system that recovers heat from urban sewage was established in Sweden and has a capacity of 3.3 MW [3]. In fact, 40% of residential buildings in Sweden have a heat-pump-based heating system, and 10% of them are WWSHP. WWSHP systems were also adopted in wastewater treatment plants [4]. Up-to-date, WWSHP is known for its merits including 1. WWSHP has a higher energy efficiency when compared to other heaters such as electric boiler, gas boiler, oil and coal boiler [1]; 2. WWSHP has a higher coefficient of performance (COP=4.0–4.6) than other source heat pumps such as air source heat pump (COP=2.8–3.4) and ground source heat pump (COP=3.3–3.8); and 3. WWSHP is an environmental-friendly technology that emits no air pollutants.

Anaerobic digestion (AD) is a collection of processes by which microorganisms break down organic materials, such as carbohydrates, fats, and proteins, in the absence of oxygen and produce biogas [5]. Methane is a major component in the produced biogas, companied with other gases such as carbon dioxide, ammonia, and hydrogen sulfide. A typical anaerobic digestion process includes four steps: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. Based on the total solid (TS) content, AD can be categorized into liquid AD (L-AD) that handles TS less than 15% and solid-state AD (SS-AD) that handles feedstocks with 15–40% TS. Consequently, SS-AD can have higher organic loading rate, smaller reactor volume, less energy demand for heating, and higher volumetric methane productivity, when compared to L-AD. Most anaerobic digesters are operated at temperatures lower than 20℃ (psychrophilic), 30–40℃ (mesophilic), or 50–60℃ (thermophilic). A major problem of AD at psychrophilic temperatures is the relatively low methane yield and the strong influence of temperature on the activity of microbial consortia [6]. Majority of commercial AD are operated at mesophilic temperatures, and thermophilic AD is attracting more and more interest in recent years, due to its ability to shorten retention time, to enhance degradation of lignocellulosic biomass, and to destruct pathogens. A variety of wastes have been used as SS-AD feedstocks, including food and agricultural wastes [7-9]. For instance, food waste, fruit–vegetable waste, and dewatered sewage sludge were co-digested in a mesophilic AD and achieved a high biogas production rate of 4.25 m^3 per m^3-digester per day at a hydraulic retention time of 20 days [10]. Based on this methane yield, one tonne (dry basis) of such feedstock can generate about 17,000 MJ of energy or equivalently 4,700 kWh of electricity. According to the AgSTAR report, one typical anaerobic digester using livestock manure as feedstock can produce approximately 3 million kWh of electricity per year, which is enough to supply more than 200 homes [11]. Besides, these feedstocks are usually available with a very low cost or even can be collected with a tripping fee, thus making SS-AD economically favorable.

Integration of two or multiple energy conversion and production technologies has been widely studied. One good example is the integrated energy system at a wastewater treatment plant in Maine [12], in which wastewater sludge was collected as L-AD feedstock and heat captured by solar panel was used to keep digesters warm. Inspired by this project and concerned by the growing residential wastewater and solid waste, we proposed the concept of integrating WWSHP and SS-AD to treat residential wastes (i.e. wastewater and organic solid waste) and to produce electricity and useful heat.

Integration of WWSHP and SS-AD

Basic concept

The proposed system integrates WWSHP and SS-AD to handle two types of residential waste, the wastewater and solid waste (Fig. 1). Wastewater could come from washing sinks and bath tubs, while solid waste is mainly food processing waste and food residuals. The temperature of wastewater is usually in the range of 10–15°C in winter and 15–25°C in summer, which is favorable for heat extraction using WWSHP. The heat supplied by WWSHP can then be used to keep the temperature of SS-AD at the desired level, either at a mesophilic condition (30–40℃) or a thermophilic condition (50–60℃). Generated biogas can be burned in a combined heat and power (CHP) unit to provide electricity and useful heat. The generated heat can be used for space heating. After the treatment, wastewater still needs to be treated in a wastewater treatment plant (WWTP), while the digestate coming out of the SS-AD has the potential to be used as a fertilizer for land applications, or can be processed in a composting facility.

Energy balance

The energy balance is examined with the wastes generated in a 1000-resident community. To facilitate the energy balance calculation, the following assumptions are made:

a. Wastewater generation is 50 gallon (0.189 m^3) per day, or 69 m^3 per year for each resident [13];
b. Wastewater temperature is 13°C in winter, 20°C in summer and 17 ℃ in spring and fall [14];
c. WWSHPs averaged COP is 4.2 in winter, 4.6 in summer and 4.4 in spring and fall, respectively [15]. The wastewater

temperature drop after heat extraction is 5^{o}C, meaning that wastewater temperature drops from 13 ^{o}C to 8 ^{o}C in winter, from 20 ^{o}C to 15 ^{o}C in summer, and 17 ^{o}C to 12 ^{o}C in spring and fall;

d. Annual solid waste generation is 1.8 tonne for each resident [16], and 50% is digestible;
e. Solid content of the residential solid waste is 20%, which is typical and favorable for SS-AD [17];
f. SS-AD is operated at 37 ^{o}C, as mesophilic condition is most commonly selected;
g. Energy yield rate is 17,000 MJ per dry tonne residential solid waste [10];
h. Heat transfer efficiency from WWSHP to SS-AD is conservatively assumed to be 50%;
i. CHP converts 35% of input energy to electricity and 50% to useful heat [18, 19];
j. Average heat required for SS-AD operation is 13% of total energy carried in produced biogas [20];

Heat recovery using WWSHP

Based on the above assumptions, the amount of heat that can be extracted from wastewater can be calculated using Eq. 1.

$$Q_w = c_p \cdot m \cdot \Delta t = 3.97 \times 10^9 \text{ J/d} \quad (1)$$

Where,
Q_w: heat extracted from wastewater, J/d;
c_p: heat capacity of wastewater, 4200 J/(kg•^{o}C);
m: weight of wastewater, kg;
Δt: wastewater temperature drop, ^{o}C.

COP is defined by Eq. 2. The amount of heat supplied by WWSHP can be calculated using Eq. 3.

$$\mathrm{COP} = \frac{Q_{su}}{W} = \frac{Q_{su}}{Q_{su}-Q_w} \quad (2)$$

$$Q_{su} = \frac{COP \cdot Q_w}{COP - 1} \quad (3)$$

Where,
Q_{su}: heat supplied by the WWSHP, J/d
W: WWSHP power input, kWh/d

The results for winter, summer, and spring/fall are summarized in Table 1.

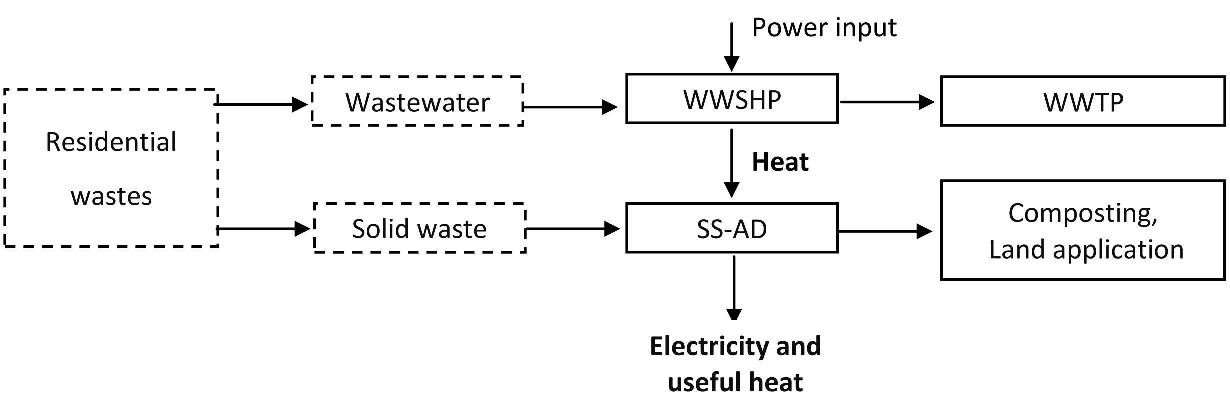

Figure 1. Diagram for integration of WWSHP and SS-AD.

Table 1. Summary of WWSHP operation parameters in four seasons

Season	Item	Unit	Value
Winter	Volume of wastewater discharged from building	m^3	189
	Wastewater temperature before heat extraction	℃	13
	Wastewater temperature after heat extraction	℃	8
	COP of WWSHP system	N.A.	4.2
	Heat supplied by WWSHP	J/d	5.21×10^9
Summer	Volume of wastewater discharged from building	m^3	189
	Wastewater temperature before heat extraction	℃	20
	Wastewater temperature after heat extraction	℃	15
	COP of WWSHP system	N.A.	4.6
	Heat supplied by WWSHP	J/d	5.07×10^9
Spring/fall	Volume of wastewater discharged from building	m^3	189
	Wastewater temperature before heat extraction	℃	17
	Wastewater temperature after heat extraction	℃	12
	COP of WWSHP system	N.A.	4.4
	Heat supplied by WWSHP	J/d	5.14×10^9

Electricity and useful heat generated from SS-AD

Total amount of energy generated from solid waste is:
17,000 MJ/dry-tonne TS × 1.8 tonne/yr.person × 50% × 20%TS × 1000 person = 3.06×10^{12} J/yr

Total heat needed for SS-AD is:
3.06×10^{12} J/yr × 13% × (1yr/365d) = 1.09×10^9 J/d
Valid heat supplied by the WWSHP in winter is: 5.21×10^9 J/d × 50% = 2.62×10^9 J/d, which is more than what the SS-AD needs. Likewise, heat generated from WWSHP covers SS-AD demand in summer and spring/fall.

If only consider using biogas for energy production, the net energy gain from this integrated WWSHP and SS-AD system can achieve 3.06×10^{12} J/yr. By using a CHP unit, the electricity and useful heat output can be calculated as following:

Electricity output is: 3.06×10^{12} J/yr × 35% × (1 kWh/3.6×10^6 J) = 2.98×10^5 kWh/yr
Useful heat output is: 3.06×10^{12} J/yr × 50% = 1.53×10^{12} J/yr

The produced electricity is enough to supply more than 20 homes. Assuming 4 people in a family, the generated power can supply 80 people, or 8% of the total residents in this community. The generated useful heat can be used for residential space heating, which can greatly reduce residential power consumption.

Application of this integrated systems

This system handles two types of wastes and has a great potential for community applications. Besides that, it can be built nearby wastewater treatment plants where the large amount of treated effluent can be used as a heat source for WWSHP and a large scale SS-AD can be installed to treat either municipal or industrial organic waste.

Concerns about this system are mainly related with the collection of wastewater, possible problems caused by the temperature decrease of wastewater, and the stability of the SS-AD. As the system is targeting small-scale communities, the supply of wastewater and solid waste could be unstable, which would negatively affect the system performance. The decrease of wastewater temperature after heat extraction may lead to condensation of particles in the pipelines, although the effect is minor and can be minimized by absorbing ground heat during transfer process.

Conclusions

This study proposes a concept of integrating WWSHP and SS-AD to treat residential wastes and to produce electricity and useful heat. The case study based on a 1000-resident community shows that the heat recovered from residential wastewater using WWSHP can meet the heat demand of SS-AD that utilizes residential solid waste as feedstock. Theoretically, by using a CHP unit, the biogas produced from SS-AD can generate 2.98×10^{5} kWh electricity per year that covers more than 8% of residents in this community and at the meantime provides 1.53×10^{12} J of useful heat per year.

Acknowledgement

The authors would like to acknowledge ASHRAE (Project RP-1677) and the 12th Five-Year science and technology support program (No.2012BAJ06B02, and No. 2013BAJ12B03) for providing financial support. Appreciation also goes to Dr. Yebo Li from The Ohio State University and Dr. Xinlei Wang from the University of Illinois at Urbana-Champaign for their guidance.

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