Applied Energy 179 (2016) 565–574

Contents lists available at ScienceDirect

Applied Energy

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

Flexible and stable heat energy recovery from municipal wastewater treatment plants using a fixed-inverter hybrid heat pump system

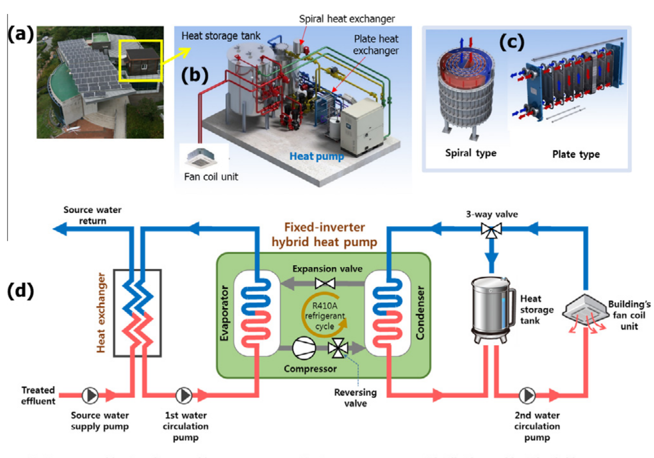
Kyu-Jung Chae [a,*], Xianghao Ren [b]

[a] Department of Environmental Engineering, College of Engineering, Korea Maritime and Ocean University, 727 Taejong-ro, Yeongdo-gu, Busan 606-791, South Korea
[b] Key Laboratory of Urban Stormwater System and Water Environment, Ministry of Education, School of Environment and Energy Engineering, Beijing University of Civil Engineering and Architecture, Beijing 100-044, PR China

HIGHLIGHTS

- Specially designed fixed-inverter hybrid heat pump system was developed.
- Hybrid operation performed better at part loads than single inverter operation.
- The applied heat pump can work stably over a wide range of heat load variations.
- Heat energy potential of treated effluent was better than influent.
- The heat pump's COP from the field test was 4.06 for heating and 3.64 for cooling.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 7 April 2016
Received in revised form 5 July 2016
Accepted 9 July 2016

Keywords:
Energy self-sufficiency
Heat pump
Fixed-speed compressor
Inverter-scrolled compressor
Sewage treatment plant
Heat recovery

ABSTRACT

Among many options to improve energy self-sufficiency in sewage treatment plants, heat extraction using a heat pump holds great promise, since wastewater contains considerable amounts of thermal energy. The actual heat energy demand at municipal wastewater treatment plants (WWTPs) varies widely with time; however, the heat pumps typically installed in WWTPs are of the on/off controlled fixed-speed type, thus mostly run intermittently at severe part-load conditions with poor efficiency. To solve this mismatch, a specially designed, fixed-inverter hybrid heat pump system incorporating a fixed-speed compressor and an inverter-driven, variable-speed compressor was developed and tested in a real WWTP. In this hybrid configuration, to improve load response and energy efficiency, the base-heat load was covered by the fixed-speed compressor consuming relatively less energy than the variable-speed type at nominal power, and the remaining varying load was handled by the inverter compressor which exhibits a high load-match function while consuming relatively greater energy. The heat pump system developed reliably extracted heat from the treated effluent as a heat source for heating and cooling purposes throughout the year, and actively responded to the load changes with a high measured coefficient of performance (COP) of 4.06 for heating and 3.64 for cooling. Moreover, this hybrid operation yielded a performance up to 15.04% better on part loads than the single inverter operation, suggesting its

* Corresponding author.
E-mail address: ckjdream@kmou.ac.kr (K.-J. Chae).

http://dx.doi.org/10.1016/j.apenergy.2016.07.021

effectiveness for improving annual energy saving when applied to highly load-fluctuating real WWTPs. To improve the overall efficiency of the heat recovery system, although the heat pump is the largest energy-consuming component, taking up 56.0–68.5% of the total energy, new efforts to develop a novel design are also needed to make the heat exchanger more energy-efficient.

1. Introduction

Municipal wastewater treatment plants (WWTPs) have been consuming vast amounts of fossil fuel energy at a continuously increasing rate, resulting in the corresponding emission of greenhouse gases. This phenomenon has stimulated great interest in making WWTPs more sustainable by producing more energy with renewable technologies such as photovoltaics, micro-hydropower, and sewage heat recovery. Among these diverse renewable technologies applicable for WWTPs, heat recovery using a heat pump from domestic wastewater can play an important role, since wastewater contains considerable amounts of thermal energy. Domestic wastewater (sewage) is a promising and cost-effective source of heat energy for heating and cooling purposes [1–7]. In the average city, approximately 40% of the heat produced in residential buildings is wasted to the sewage system [3], and 1.16 kW h of heat energy can theoretically be extracted by cooling 1 m^3 of wastewater by 1 °C [4]. Compared with other low-grade heat sources, sewage has competitive advantages, such as abundant quantity, an almost constant supply from residential areas throughout the year, a small variation in temperature, typically ranging from 10 °C to 25 °C, and a high heat density [1,3,5]. Moreover, it is warmer in winter and colder in summer than the ambient air temperature, and so can act as an efficient source for recovering heat with a heat pump.

A heat pump is a heat-transferring device from a low-quality heat source (sewage, air, ground, etc.) to another requiring heat, working on an electrically driven vapor compression and absorption cycle [8–12], while consuming substantially less energy than conventional heating and cooling systems [13]. In general, a heat pump consists of a compressor, an expansion valve, an evaporator, a condenser, and other auxiliary components, and can make use of temperature differences between different media by employing a refrigeration cycle [3]. A heat pump works as a heater in winter but can also function as a cooler in summer, by simply reversing the direction of the working fluid in the refrigerant circuit via a reversing valve.

Heat recovery via a wastewater source heat pump (WWSHP) has become increasingly popular over the past two decades, thanks to its energy saving potential and environmentally friendly features [7,14,15]. Hepbasli et al. [3] and Culha et al. [7] comprehensively reviewed the features of various previously developed WWSHP systems, adapting different types of heat pump equipment, heat exchangers, source wastewater, application capacity, and refrigerants. According to their review, the performance of WWSHP systems is directly affected by the temperature of the wastewater and varies depending on the type of heat pump applied. The most frequently used types of refrigerant and heat exchanger are R134A and shell-and-tube, respectively, and the coefficient of performance (COP) values of the reviewed WWSHPs are in the range of 1.77–10.63 for heating and 2.23–5.35 for cooling [3,7]. The prevention of fouling in WWSHP systems is an important issue, especially when using high solid- and fiber-laden untreated wastewater as the source water. Therefore many attempts have been made to mitigate this problem by finding a novel design that incorporates anti-fouling technology or an automatic cleaning device. For instance, Zhao et al. [16] designed an urban WWSHP system incorporating a filth block device for efficient filtering of wastewater-embedded impurities. Shen et al. [17] developed a novel dry-expansion, shell-and-tube evaporator with defouling function for WWSHP, and reported 3.1 times greater heat transfer coefficient compared with a conventional immersed evaporator.

At present, more than 500 facilities around the world have applied the WWSHP technology, with thermal capacity ranging between 10 kW and 20 MW [3]. In Korea, however, the WWSHP has not been employed as widely as it should be, because exploiting heat from the wastewater was considered economically unfeasible in the past, owing to many relevant constraints. Even in the WWTPs where the heat recovery system is being used, the extracted heat is merely consumed inside the plant itself for space heating and cooling, rather than being transferred offsite or sold. The critical reason for this low application is the mismatch between the plant's real heat needs and the available capacity of the WWSHP, owing to severe diurnal and seasonal fluctuations in thermal energy demand in WWTPs. For instance, the heating or cooling demands in the WWTPs vary over a wide range during the day and also over the year, depending on occupancy, ambient conditions, seasons, and so on. Moreover, because most urban WWTPs are situated far from residential areas or the city center, the offsite transfer of the exploited heat for use in urban districts is not reasonable, because of a huge delivery loss. Insufficient use of the recovered heat in the spring and fall is another constraint limiting WWSHP installation. During these seasons, the recovered surplus heat could be considered for heating up anaerobic digesters, but many WWTPs (especially in small plants < 10,000 m^3/d) do not have digesters, making this option equally impractical. In this circumstance, the conventionally used fixed-speed heat pump, controlled by on/off cycling, causes switching off under light load conditions and leads to the compressor being repeatedly turned on and off, which consequently diminishes the heat pump's performance and lifespan. Therefore, during the mismatch period between supply and demand, conventional fixed-speed heat pump systems run intermittently with low efficiency and often remain idle. Accordingly, WWSHP systems should be designed to be able to cope with the wide heat load variation that is common in many WWTPs.

To solve this problem, a specially designed, fixed-inverter hybrid heat pump system was developed and tested for over three years in a real WWTP. It consists of a fixed-speed compressor, which runs more efficiently than an inverter-scroll compressor at its rated load condition and is thus potentially able to cover the base-load that is essentially required at any time, and a variable speed compressor with an inverter to match fluctuating heat loads. To the authors' knowledge, there are few reports on efforts to enhance the reliability of a sewage heat recovery system by adapting a fixed-inverter hybrid heat pump, although many comprehensive reviews [3,7–9,11,15] and studies have been conducted on: (i) improving heat pump performance by employing multistage cycle designs [18], new refrigerants [19,20], and a novel evaporator [17], (ii) exploiting utilization in a wide range of applications, such as hybrid with solar power [10,21,22] and desalination [23], and (iii) improving the system's reliability with fouling-preventing devices [16,24,25]. Hence, this study aims to present the performance of the newly designed heat recovery system employing