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Reliable energy recovery in an existing municipal wastewater treatment plant with a flow-variable micro-hydropower system

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ABSTRACT

A micro-hydropower (MHP) system with a flow-variable turbine was tested for over one year to investigate its applicability for small-scale municipal wastewater treatment plants (WWTP) with severe flow fluctuations. The applied MHP was designed as a semi-Kaplan, equipped with only adjustable turbine blades without guide vanes, hence it is simple in its mechanical structure and is inexpensive while providing high-level performance. To exploit as much hydro-energy as possible, a maximum water level tracking control scheme in the forebay tank was employed and the turbine blade angle was accurately adjusted corresponding to the oncoming flow rate, which allows water to hit the blade in the best direction for maximum efficiency. Despite its micro-scale (12.3 kW at design conditions of 4.30 m net head and 0.35 m^3/s flow rate), the applied MHP can work stably over a wide range of flows from 57% to 123% of the rated design flow, with the highest turbine efficiency of 91.3% and its corresponding overall electric efficiency of 80.3%. Even as the flow rate decreases to 23% of the design flow, the turbine still runs but at relatively lower efficiencies. Because of wide flow adjustability, the tested MHP can generate power even at extreme flow rates so that an almost complete amount (95.8%) of WWTP's total effluent was used to produce 68.1 MW h annually. In addition, as compared with similar WWTP-based hydropower systems in South Korea, the tested MHP achieved 1.78–2.80 times higher normalized electricity in both flow rate and net head, indicating a more efficient use of the flow and head. These results should draw new interest in the WWTP-based MHP, which was considered unfeasible in the past in Korea due to its low efficiency.

1. Introduction

A municipal wastewater treatment plant (WWTP) plays an important role in protecting human health and the environment by reducing pollutant emissions into bodies of water. However, WWTPs consume considerable amounts of energy and emit substantial greenhouse gases (GHG), and their energy demands are increasing as a consequence of more stringent and energy-intensive treatment standards and technologies [1,2]. For example, compared with the conventional activated sludge process for carbon removal in the past, membrane bioreactors in many WWTPs consume several times more energy to achieve a better effluent quality by removing carbon, nutrients, and other emerging pollutants. In South Korea, WWTPs alone consume 2800 GW h of electricity annually, comprising up to 0.5% of national total energy consumption, and their electricity demand is increasing continuously by 7.2–11.1% per year [3]. However, unfortunately, almost all (>99.2%) of the energy consumed in WWTPs has been supplied from the external public electricity grid, indicating a low-energy self-sufficiency of less than 0.8% (as of 2010). As a result, electricity costs are a huge burden on WWTPs in Korea, typically accounting for 20% of the total annual operating cost of 0.95 billion USD.

The WWTPs in many countries, including Korea, are unsustainable in their current form because of considerable amounts of energy consumption and GHG emissions associated with the various treatment processes. The wastewater treatment industry is an energy-intensive sector, and the WWTP itself is commonly reported as the largest single energy consumer in a small- or medium-size city. Thus, there is increasing global pressure on the WWTP sector to find a more sustainable way of supplying energy by employing various renewable energy productions and

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Nomenclature

WWTPs	municipal wastewater treatment plants	Q	flow rate
GHG	greenhouse gas	H	head
SHP	small-hydropower	η_t	turbine efficiency
MHP	micro-hydropower	η_g	generator efficiency
P_{th}	theoretical power output in W	η_s	overall system efficiency
P_{mech}	mechanical power output in W	τ	shaft torque in N-m
P_{act}	actual electric power output in W	Ω	rotation rate in rad/s
g	gravitational constant (9.81 m/s^2)	N_s	specific speed

energy-saving technologies [4–6]. To cope with this pressure along with climate change concerns, the Korean government has set up an ambitious goal to change current WWTPs into an energy self-sufficient or even energy-producing facilities. To accomplish this visionary goal, the Korean Ministry of Environment has been promoting the policy targeting WWTPs' energy independency of 30% by 2020 and 50% by 2030 under an investment plan of 3.5 billion USD.

Among various renewable technologies such as photovoltaics, small-hydropower (SHP), biogas, thermal recovery from wastewater, geothermal, wind power, etc., micro-hydropower (MHP) is considered a cost-effective, environmentally friendly option because it can run almost year-round regardless of weather conditions and thus is much more energy-efficient than either solar or wind power [7,8]. It also has competitive advantages such as long-lasting asset life, low maintenance costs, and no environmental impact [9–11]. In particular, in the case of employing MHP in an outfall of WWTP, capital costs are substantially reduced because of minimized civil work by using existing infrastructures. Also, unlike river- or dam-based SHP, it does not cause any conflicts such as river ecosystem destruction or migratory fish interference [12,13]. However, MHP technology has been less studied than large scale hydropowers and is still at the developmental stage [14]. In 2010, the Korean government predicted 11 GW h as the amount of annually exploitable hydropower potential from 15 WWTPs having a relatively higher net head (>2 m) and sufficient daily influent (>20,000 m^3) [3]. However, the potential is much greater than this expectation because many WWTPs in Korea, considered technically unfeasible for exploitation in the past due to low net head, can harness hydro-energy with the advent of high-efficiency turbines. Nonetheless, Korea has very little experience with WWTP-based hydropower generation with no successful records: only eight sites have employed MHP out of the existing 540 WWTPs. The major reason for this low application is that most formerly installed MHPs have a lower flow-flexibility and thus cannot operate under severe diurnal and seasonal flow variation conditions that are common in WWTPs. Therefore, during a long period of low-flow time, many installed MHPs often remain idle without generating electricity while simply passing the effluent through the turbine. Likewise, considerable surplus flow is also wasted through the bypass when a WWTP's effluent is greater than the turbine maximum discharge, which is indeed a waste of valuable resources and thus leads to a significant amount of wasted electricity. Those constraints have restricted public interest in MHP application in WWTPs, but have not been considered by many previous researches. In particular, when considering small WWTP application, it is very important that MHP should be designed to cope with such extremely low or high flows because those plants are typically exposed to wide flow variations.

To solve the problems related to these constraints, for the first time, a demonstration project employing a flow-variable turbine has been investigated since 2013 as a Korean government-supported program, which ensures a stable production of electricity all-year-round without any waste of effluent. Hence, this study aims to present a successful operational strategy and performance obtained from the newly designed micro-hydropower system capable of working under wide flow fluctuation in WWTPs.

2. Materials and methods

2.1. Test-bed WWTP description

To investigate the feasibility of energy recovery through a flow-variable MHP, Kiheung Respia WWTP, in Yongin, South Korea, was selected as the test-bed for this study because it is a typical medium-size WWTP (a design capacity of 30,000 m^3/d) with severe flow fluctuations. Many types of renewable energy technologies including a MHP have been applied in this test-bed to develop more affordable, diverse options for WWTPs. In this study, effluent outfall was chosen as the most suitable location for a MHP installation because it offers the highest available head (4.3 m) and the best cost-effectiveness in the WWTP (Fig. 1). The developed MHP consists of a small effluent forebay tank, penstock, micro-turbine, self-induction generator, system bypass, and flow sensors. In this MHP concept, treated effluent is diverted from the outfall pipeline into the forebay tank and then flows down through the pressurized penstock to the turbine unit before discharging into the receiving water body. MHP operations should not interfere with the primary wastewater treatment function of the existing facilities prior to the MHP. Therefore, a shunted section was also incorporated as a bypass to guarantee non-interrupted operation of WWTPs, whether or not the MHP is operational in such cases of turbine shutdown or excessive discharge flows.

2.2. Flow-variable micro-hydropower system

The applied flow-variable turbine was a semi-Kaplan, a variant of Kaplan, which only has adjustable blades inside a tube but no inlet guide vanes (runner diameter = 462 mm and specific speed of the turbine = 503.5). In terms of water flow direction, it is a vertical-axis turbine where the flow direction is parallel to the driveshaft through the runner blades, and thus can be an advantage in space-constrained WWTPs' outfall due to its smallest footprint requirement. Depending on the influent flow rate, the turbine blade angles are also adjustable, from a flat profile for low flow to a heavily pitched profile for high flow; thus, the amount of flow that can pass through the turbine can be regulated. This adjustable blade scheme enables turbine work within a wide flow range with high efficiency.

In this system, turbine blade operating components such as an oil servomotor are located outside so that they are easily accessible for maintenance without dismantling the facility, which is the most primary need for the operators. Also, a specially shaped conical draft tube (half angle = 4.2°) that draws water from the turbine