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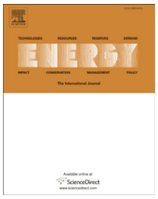

Development of inline hydroelectric generation system from municipal water pipelines

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ABSTRACT

It is a challenging work to ensure reliable power supply for the data monitoring and control devices of modern water supply networks in urban environment due to limited underground space and transportation restriction. In this study, a novel inline hydroelectric generating system (IHGS) was developed to harness the potential energy of the water flow onsite and provide power for data monitoring system of main water pipelines. Specifically, a drag-type turbine was designed for medium size pipelines and a lift-type turbine for large size pipelines, and a hybrid energy storage system which combine battery and supercapacitor was developed to store excess energy and stabilize power supply for the off-grid IHGS, and a control system with remote monitoring software was developed to manage the whole system. The main work presented in this paper includes theoretical study, computer simulation, prototype design, and experimental tests. The results demonstrate that this development can solve the power supply problem of the data monitoring systems, while there are still significant opportunities for further research such as cost-benefit analysis, long-term system monitoring and assessment.

1. Introduction

Hong Kong has a network of water mains totaling more than 7,800 km, most of which are underground [1]. About half of these water mains were laid some 30 years ago, the deterioration of pipes with age has resulted in 25% of the fresh water supply lost solely because of pipe leakage [2,3]. Therefore, currently the water supply network is comprehensively monitored by devices, such as pressure meter, flow meter and wireless data transmitters, to reduce leakage and maintain water supply quality. However, a reliable and continuous power supply solution for those data monitoring system is still a challenge due to limited underground space, transportation restriction, or remote location without power grid [4]. As a result, these devices are usually powered by rechargeable batteries, which require high cost and frequent replacement, thus making it not technically and economically viable [4–8]. On the other hand, to guarantee consistent water supply throughout the urban area, the pressure in the main pipeline is usually very high and even superfluous, thus making it promising to harness the untapped water head or small part of kinetic hydropower inside pipeline to provide power for the monitoring system [9]. Therefore, it becomes a key issue to offer enough power to ensure these numerous sensors to operate continuously and safely in developing monitoring systems for the water utilities [10].

To provide power for monitoring sensors using renewable energy, several existing energy supply solutions were developed and applied. For example, energy harvesting devices such as solar panel and wind generator for self-powered autonomous sensors were studied in Refs. [7,11–13]. However, pipeline sensors usually locate underground or restricted locations surrounded by the trees and buildings in urban areas, and thus it is really limited to provide reliable power using solar panels or micro wind turbines. Compared to electricity from solar and wind generator, the flow-induced vibration energy harvester [14,15] and piezoelectric power generator [16] has a micro size, whereas those devices are expensive due to their fabrication process and the electricity generated is quite limited, usually in the scale of μW, which can only be used for some very small energy consumers instead of data

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collection system which should be in the scale of W [17].

Alternatively, the flowing water in pipelines contains kinetic energy due to the water pressure fluctuation [18]. The flowing water is a renewable, pollution-free, continuous, and dependable energy source [19], and it can be converted into electrical energy by energy harvesters, which can be developed in any size and any scale, and therefore power generated from flow watering is applicable for in-pipe sensors or data collection systems [20]. Water supply system is one of the main man-made water infrastructures presenting potential for micro-hydropower [21]. The potential of energy recovery from water industry was evaluated in Ref. [22], and its economic issue was discussed in Refs. [23–26], and found that most can pay back their investment in a five to seven year time frame and enjoy a 30–40 year lifespan of the machine, demonstrating that there is an economical interest in micro-hydropower in water supply system. Small-scale hydro using excess of pressure, has long been recognized as an attractive form of renewable energy, is still under development, as some study estimated that this could be a high cost solution to apply in the water supply and wastewater systems [24,27]. The main reasons are (i) that there are no turbines in the market for low flows and low head like the ones is this type of systems and (ii) that the variability of flows during the day (and consequently, the low heads, low efficiencies and low power produced), makes this solution is not so reliable.

Examples of solutions and a number of case studies for the installation of micro hydro turbine in pipelines can be found in literature [28]. For example, Ampair et al. developed a kind of bulb hydro turbine in the pipe to generate the power for the wireless sensors [29], while the generator and some electrical components were immersed in the drinking water, and thus any improper waterproofing of this system will contaminate the drinking water. The hydro turbine is able to generate enough power, but it has a big size resulting in the difficulty of installing in pipelines [30]. Some other research [22,31–35] has been conducted to investigate the feasibility of using pump-as-turbine (PAT) in water distribution networks to substitute the pressure reduce valves and recovery energy for electricity generation, indicating that PAT is cost-effective and can work quite well although it has reduced efficiency [36]. However generally the pressure drop was higher than 0.05Mpa, which is beyond the allowable value in this project. An overview of the different types of in-pipe hydro systems available on the market for urban and building environment has been presented in Ref. [9]. Chang et al. [37] developed a micro-hydro turbine using ultra-fine power generation blades, and Yen et al. [38] invented the a hydroelectric generator with a horizontal guide blade wheel inside, while those turbines are only suitable for building water piping system with size in the range of 4–6 inches. One project was conducted in India to investigate the practicality of the potential hydropower generation from wastewater in high rise buildings, while this technology can only be used for in-situ greywater system [39]. The concept of hydro power generation in conduits is simple, while the in-pipe system presents special challenges and risks. Careful site assessment and planning are critical and more work should be done to improve the economic feasibility of this solution.

The possibility of using the micro-hydro turbine in main water supply system has been investigated in Refs. [35,40]. However, a water storage tank has to be placed on a high geographical position, which is not suitable for urban area. Moreover, A US company LucidPipe developed a novel in-line cross flow turbine system to extract the excessive head from water inside of water supply networks, converting it into renewable and low-cost energy [41], while LucidPipe is only suitable for the purposes of generating electricity in pipelines ranging from 24 to 96 inches. Furthermore, a trial inline vertical axis water turbine for small water pipelines (100 mm diameter only) was developed by our research group several years ago [42], and this prototype achieved satisfactory performance, expected to produce 700 kWh/year in the city's water main pipes [43]. However, the system cannot be used for medium and large size water pipelines, for example, 250 mm and 600 mm diameter. Besides in the academic literature there is lack of detailed fundamental studies about the system such as theoretical calculation of the potential power and evaluation of energy recovery potential from the water supply pipeline. Therefore, there is still a wide open area to carry on thorough research work, including physical design, simulation, prototype fabrication, optimization, experimental test, and conversion efficiency enhancement, to develop an appropriate in-pipe hydro turbine for main water pipeline monitoring system.

To solve the present problems as described above in power supply for monitoring systems of municipal water supply pipelines, a novel inline hydroelectric generating system (IHGS) was developed in this study to harness the potential energy of the water flow onsite and provide power for data monitoring system for its special application in the main water pipelines of 250 mm–600 mm diameter. This paper summarizes all research activities and deliverables in the development of the IHGS. The rest of this paper is organized as follows: the development of the hydro turbine for DN250 mm and DN600 pipeline is described in Section 2; the development of the hybrid energy storage system is outlined in Section 3; the development of control system and remote monitoring software is presented in Section 4; and the main conclusions are summarized in Section 5.

2. Development of energy harvesting device from water pipeline

Fig. 1 shows a schematic design of the IHGS, which harvests the needed small power insides the water pipelines and generate electricity for the monitoring system. This IHGS consists of an external hydroelectric generator and highly efficient hydro turbine which dips into flowing water and reclaims residual pressure. When water passes through, the turbine drives a central rotating shaft and a micro generator to produce electricity. Surplus power after meeting load can be used to charge the energy storage system for later use. The remote monitoring system is used to manage power output and stabilize power supply of the IHGS.

The general research methodology for the IHGS development is presented in Fig. 2, which is a combination of prototype design, computational fluid dynamic (CAD) simulation, lab test, field test, and modification for improvement. If the simulated performance of the proposed design can meet the target, i.e. power output and pressure drop limit, the prototype will be fabricated in a factory and then tested in our laboratory and onsite. In case of the simulated or tested performance cannot meet the target, the design will be modified and process will be repeated until it meets the requirement. Based on this methodology, two different inline hydroelectric generating systems were developed to harvest untapped water energy onsite from medium and large size pipelines (DN250-DN600).

2.1. Prototype design

The external view of the DN250 pipeline for turbine/generator installation is presented in Fig. 3a, the device consists of an external hydroelectric generator and highly efficient water turbine which dips into flowing water and reclaims residual pressure. When water passes through, the turbine drives a central rotating shaft and a micro generator to produce electricity. Fig. 3b shows the physical model of proposed drag-type hydro turbine, which includes the following major components: 12 vertical blades, bearing, coupling,