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Research Status and Trends of Ultra-Low-Head Water Resources and Hydropower Turbines

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Abstract: China is rich in hydropower resources and developing hydropower technology is the best choice for increasing the supply of renewable energy, optimizing the energy structure, and alleviating environmental problems. This paper focuses on the rich micro-head resources of China and analyzes the demand and application characteristics of these micro-head resources, such as rivers, canals, reservoirs, power plant tailings, piped water supplies, municipal wastewater, and marine energy. We analyze two types of micro-head hydropower turbines that are suitable for open and closed watersheds, which provides a basis for the design of micro-head hydropower turbines and the study of their flow characteristics and mechanisms. This paper discusses the research trends of micro-head resource evaluation and hydropower turbines, and provides various suggestions for future research.

Keywords: ultra-low-head water resources; hydropower turbines; open watershed; closed watershed

1 Introduction

With the current shortage of global energy, aggravation of climate change, and increased focus on ecological environments, accelerating the development of renewable energy, ensuring the security of ecological environments, and supporting the sustainable development of a social economy have attracted significant attention around the world. Currently, the energy popularity rate and per-capita energy consumption of China are relatively low and energy shortages have become a major obstacle to the economic development of the country. According to the *13th Five-Year Plan for Renewable Energy Development* of China, the proportion of renewable energy supply to primary energy supply in China should increase to 15% in 2020 and 20% in 2030 [1]. Hydropower is the second largest energy source after coal. It is a clean energy source that accounts for the largest portion of renewable energy in China. China is rich in small hydropower resources, which exist in 1500 counties throughout the country. Approximately 600 counties are mainly powered by small hydropower resources, which has solved electricity consumption problems for more than 20 million people. The potential development capacity of small hydropower (hydropower stations with installed capacity $\leqq$ 50 MW) in China is 1.28×10^8 kW. At the end of 2015, a capacity of 7.5×10^7 kW had been developed, constituting a development rate of 58.6% [2]. Therefore, the development of small hydropower technology is in line with the national renewable energy development strategy, which is the best choice for China to optimize its energy structure, ensure energy security, and alleviate environmental problems.

A micro-head is a hydraulic resource with a water head between 0–3 m with the potential for hydroelectricity generation. However, based on the low value of their economic development, micro-heads have not attracted significant attention [3]. However, micro-head resources in China are widely distributed

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and have unique development advantages compared to conventional hydropower resources. They are rich and diverse with significant development potential. They are convenient to access, have simple structures, and facilitate secondary energy recovery and savings investment. The resources of canals, pipelines, tail water, and other micro-heads are stable and predictable. Finally, there is no need for water storage regulation and micro-heads have a small impact on the environment.

The hydraulic turbine is the most important piece of equipment for determining the efficiency and output of a power station. Currently, there are two main methods to design turbines for micro-head hydropower stations. The first is the design method utilized in conventional low-water-head systems. The design of conventional hydropower stations considers the potential energy of water as the core parameter and the cost is largely determined by the head. The lower the head, the poorer the economy. Only two types of turbines, namely axial flow and tubular flow turbines, can be utilized water head ranges as low as 2–3 m. However, from the viewpoint of practical operation, the full-tubular turbine generator set and integrated bulb-tubular units utilized in low-head power stations are not fully applicable to the operation of micro-head stations. The second design method focuses on zero-head generators. Such turbines are typically utilized in natural rivers, tidal currents, ocean currents, artificial watercourses, and other channels with sufficient flow speeds. The essential difference compared to a conventional turbine is that the kinetic energy of water is first converted into mechanical energy and then converted into electric energy by a generator. This type of turbine is simple in structure and typically installed in open water areas with large amounts of discarded water. However, its theoretical efficiency limit is only 59.3%. Compared to an inner-flow turbine with the same capacity, such turbines are larger in size, higher in installation cost, and more difficult to maintain [4].

One can see that there is no mature turbine design that can be applied to power generation for 0–3-m micro-heads. This issue has become a technical bottleneck restricting the development of micro-head hydropower. Therefore, it is necessary to analyze the resource demands and application characteristics of micro-heads and propose a design methodology for two-type micro-head hydropower turbines that are suitable for open and closed watersheds. Such designs for micro-head turbines should incorporate both dynamic and potential energy.

2 Research status of the development of micro-head resources

Many of the world's untapped rivers and streams contain abundant micro-head resources. It is feasible to make use of such resources to generate electricity with simple on-site-installed hydraulic units. A study by the US Electric Power Research Institute found that the technically recoverable energy from rivers in the United States is 119.9 TW·h [5]. By utilizing velocity turbines [6], water flow (anhydrous heads) can be utilized to generate electricity. The velocity and depth of water flow determine the available hydrodynamic energy and size of the turbine.

For micro-head power generation, when the flow velocity of a canal or other artificial channels is greater than 1.5 $m \cdot s^{-1}$, the energy conversion is ideal, controllable, measurable, and relatively clean. The development of hydrodynamic energy in existing canal systems, such as the Roza Canal in Washington State, is supported by the United States Wind and Hydro Technology Office [7]. Taiwan of China [8] and Laos [9] have constructed micro-hydropower systems based on irrigation water in agricultural canals. Generally, it is feasible to utilize kinetic energy to generate electricity when there is sufficient water velocity in a canal or other artificial channel. The faster the flow of water, the greater the potential for generating electricity. In some pumping stations, a pump can be utilized as a hydraulic turbine to generate electricity under special circumstances. For example, in the main irrigation canal of Jiangdu in China, when the inflow of the Huaihe River is very large, the pump unit can produce 3 MW of electricity by acting as a turbine.

There are many surplus water heads created by industrial-cooling water-circulation systems, and the waterworks and water supply pipelines for hydropower stations. In [10], an example focusing on excess pressure in the range of 39~147 KPA in a cooling tower pipeline was detailed. An improved Francis turbine was installed in the cooling system to recover wasted energy. A 300-kW small hydraulic turbine unit was studied in [11], which can be utilized to replace the pressure-reducing valve in the water supply system of a hydropower station. In many water treatment plants, excess pressure in water diversion pipes can also be utilized to generate electricity. The pressure of a system can be controlled by adopted a small hydraulic system in the water supply network. However, when utilizing potential energy in urban water supply networks, care must be taken to avoid negatively impacting water quality. Additionally, bypass lines can be added to prevent accidents and avoid affecting the normal water supply.

Although the implementation of hydroelectric power in sewage plants is still in the early stages of development, with the emergence of the new low-water turbine system technology, the water energy in such facilities is becoming increasingly relevant. Since 2002, the Deer Island sewage-treatment facility in Boston, Massachusetts has been recovering energy from the water flowing out of the plant [12]. The plant installed two sets of 1-MW hydroelectric generating units, which generating more than 6×10^6 kW·h of power and save 600-thousand US dollars per year. At a sewage-treatment plant in Milbury, Massachusetts with an effective water head of 1.7 m and average discharge of 1.4 $m^3 \cdot s^{-1}$, a similar system can generate approximately 20 kW of electricity. Generally speaking, there are two main schemes for installing hydraulic devices near sewage-treatment plants.

The first is to install devices upstream from a plant. In this case, turbine components must be more corrosion resistant and the inlet of the diversion pipe must be equipped with a trash screen. In the second scheme, hydroelectric generating sets are installed downstream from a plant, where the water flow into the hydraulic turbine is cleaner, meaning the corrosion resistance requirements for the components are reduced. However, such systems run into problems in terms of space restrictions.

There is a considerable amount of hydrodynamic energy left in the water at the bottom of a traditional hydropower station, either as a compensation flow or flow from the draft tube [13]. The harnessing of these currents to generate electricity will result in lower flow rates, thereby reducing the erosion of hydraulic structures downstream. At the Wannapo Dam in southeastern Washington State, a number of flow fields in the wake of the dam can be visualized, which provides a useful reference point for site selection for hydraulic units [14]. The authors of [15] confirmed the feasibility of a small hydropower project at the Poringalkuthu, India hydropower station. In addition to generating energy from the wake of the station, the cooling water from the thermal power plant is utilized to generate electricity through a Kaplan hydro-generator.

Tidal energy contains both potential and kinetic energy, which are generated by tidal reservoirs and tidal current units, respectively. The theoretical potential energy of the Earth's tidal resources is estimated to be 8.8×10^{11} kW·h/a and the technically exploitable tidal energy is estimated to be 8×10^{10} kW·h/a [16]. The National Renewable Energy Laboratory estimated that the sum of all potential marine renewable energy sources in the United States may exceed the current national electricity demand. They also estimated that a total of 13 GW of new hydrodynamic technologies will be available by 2025, which will supply at least 10% of America's electricity demand [17]. There are many areas where potential current energy exists, including Ireland, Fiji, the Amazon River, English Channel, Strait of Gibraltar, Strait of Messina, and southern coasts of Iran and South Korea [18]. In China, rich tidal energy resources have excellent potential for development. More than 80% of the tidal energy in China is distributed across Fujian and Zhejiang. The southern waters of the Yangtze River Estuary are rich in tidal energy [19]. However, the development of tidal energy still faces challenges in terms of complex marine hydrodynamic environments, short equipment lifespans, difficult maintenance, difficult construction, and large investment.

In conclusion, existing research and applications demonstrate that micro-head hydraulic resources are widely distributed and have excellent potential for development. However, current research on the distribution of micro-head hydraulic resources in China is insufficient, meaning it would be very significant to identify and analyze the demand and application characteristics of micro-head resources, such as rivers, canals, reservoirs, industrial waste water, and marine energy.

3 Research status of micro-head power generation devices

It is very important to select suitable turbine types for the development of micro-head hydraulic resources. Traditional turbines can be divided into impulse turbines and reaction turbines, which can be subdivided into the following categories: impulse turbines, diagonal turbines, cross-flow turbines, mixed-flow turbines, axial-flow turbines, and tubular turbines. Additionally, there are more than 20 relatively new types of turbines that can convert water energy into electric energy. These new types of turbines can be divided into lift types and resistance types. This classification is based on the principle force acting on the turbine blades and the relationship between the flow direction and rotating shaft of the turbine, which is either horizontal or vertical.

3.1 Traditional micro-head hydraulic turbine

One of the main methods utilized in turbine selection is to refer to diagrams for turbine selection and compare the technology and economy of various turbines. A turbine selection table can provide reference information for turbine type determination at a specific location and help manufacturers verify that a particular turbine is present at that location. It has been reported that some Francis turbines with simplified structures can be utilized for water heads less than 3 m. A redesigned double-tap turbine can also be utilized in cases with no pressure head. The authors of [20] utilized relevant research results to create a turbine type selection chart that is suitable for micro-heads. The table considers both technical and economic feasibility. Additionally, even when the head is lower than 0.5 m or the flow rate is lower than 0.5 $m\cdot s^{-1}$, there are still available turbine types.

Generally speaking, open-channel Francis turbines are rarely utilized in micro-head applications. When the flow rate is less than 1 $m^3\cdot s^{-1}$, the size of a Francis turbine becomes too small and the number of blades becomes too large, meaning it is difficult and costly to produce such turbines. For the same micro-head, compared to a Kaplan turbine, a Francis turbine has poor flow capacity and lower output power. For wide ranges of water-head or flow-rate fluctuations, Francis turbines have good stability and high efficiency, making them superior to propeller turbines. Because of their dual regulating ability (the runner blade and runner can both be adjusted), Kaplan turbines also achieve good performance over a wide range of water heads and flow rates. However, the blade adjustment mechanism for such turbines is complex and requires proper mounting space in the runner hub. Therefore, Kaplan turbines are expensive, making them more suitable for large flow rates and low water heads based on economic reasons. Propeller turbines is well suited to micro-head applications, but their optimal operating ranges are relatively limited. In the case of micro-heads, tubular turbines are a good choice because water flows straight through the turbines, the flow rate is large, and the hydraulic loss is small.

For a station with smaller total flow, a single-regulated or unregulated tubular turbine can be utilized instead of a double-regulated turbine to reduce system complexity and cost. Additionally, the geometry and number of guide vanes and runner blades can be appropriately simplified to reduce the manufacturing costs of Kaplan turbines and tubular turbines. In [21], an optimized design for a two-way bulb tubular turbine for the Jiangxia tidal power station (water head range of 1.2–5.5 m) was presented and the efficiency of forward and backward generation was improved by 6%. In [22], an ultra-low-head pit turbine for a 2-m head was proposed. In recent years, turbines with very low head requirements have been proved to be suitable for micro-head operation. Such turbines represent a new type of axial flow turbine.

A traditional cross-flow turbine is driven by a jet and can be utilized for a wide range of water heads (5–200 m). The optimal efficiency of a cross-flow turbine is slightly lower than that of an axial-flow turbine or mixed-flow turbine. However, the efficiency curve of a cross-flow turbine is flat under variable load conditions and its structure is simple. Such turbines also have self-purification abilities [23]. Additionally, cross-flow turbines become more efficient in semi-submerged or fully submerged applications, where the conversion of electrical energy is more efficient. Therefore, cross-flow turbines may be an ideal water energy converter solution for micro-heads.

3.2 A new type of micro-head hydropower turbine

Germany has recently developed a new type of turbine called the Archimedes helical turbine. One of the important advantages of spiral turbines is their tolerance to debris. Archimedes helical turbines have excellent power generation potential, a small environmental impact, and low rotational speed. Additionally, this type of turbine has relatively simple structural requirements [24]. In [25], through multi-objective analysis, the authors determined that Archimedes spiral turbines are the most suitable solution for low-head energy generation. However, the large size of Archimedes spiral turbines makes transportation and installation difficult.

In [26], a direct- and reverse-rotating double-runner turbine suitable for a 0.5–3-m head range was developed. The Wave Dragon floating-wave electric field was established in Denmark [27]. The Wavebob wave-energy electric field was established in Ireland [28]. The US Hydropower Green Energy Corporation and US Army Corps of Engineers have developed a flow turbine for small hydropower stations on the Mississippi River. A Gollov spiral turbine has been installed on the coast of the Uldolomok Strait in South Korea [29]. The Singapore Atlantis Company has developed an underwater fixed-pitch turbine with a designed velocity of 2.6 $m \cdot s^{-1}$. They also developed a hydraulic turbine with a diversion cover, which has been successfully installed and tested [30]. In Guanshan, China, a floating double-rotor vertical-axis turbine, cycloidal runner, two-blade horizontal-shaft impeller, and other devices have tested through real waterway tests [31]. In [32], a rectangular tidal-current turbine was studied and a novel type of vertical-axis power-conversion device was proposed, which was suitable for medium- and low-velocity water.

For very low or zero water heads, a flow turbine is driven by free-flowing water. This type of turbine is typically utilized in natural rivers, tides, tidal currents, artificial waterways, and other areas with adequate flow speeds. Such hydrodynamic systems can convert the energy of flowing water into electric energy and provide greater power output by deploying multiple units, similar to wind farms. Additionally, the institutional requirements for these systems are minimal. However, their relatively low efficiency, cavitation performance, high installation cost, and maintenance difficulty are significant obstacles to advancing hydrodynamic technology.

4 Trends and recommendations

In summary, current micro-head power generation systems mainly utilize kinetic energy by converting current flow velocity into mechanical energy for electric power generation. Conventional turbines have many shortcomings in terms of micro-head power generation. Therefore, it is necessary to deeply study the application of hydraulic power plant to micro-heads and propose design methodologies and performance research schemes for micro-head hydropower prime movers.

The international community has gradually acknowledged the value of micro-head resources and there are various typical cases of micro-head applications, such as canals, sewage-treatment plants, and dam runoff. However, there are no comprehensive statistics regarding the overall distribution of micro-heads. There are also no clear descriptions of the types of resources or characteristics and applicability of devices. Therefore, there is no clear understanding of how much economic value micro-head resources can generate, which in turn affects the investment of funds and technologies in this field and restricts the pace of development and utilization of micro-head resources. First, we should sort and classify micro-head resources, summarize their characteristics at home and abroad, and classify design schemes to analyze overall scheme design, system-integrated design, and economic impacts. It is important to attract the attention of researchers and investors in related fields to promote the development of micro-water-head hydropower technology.

Currently, most research on micro-head hydro turbines is focused on conventional pressure hydraulic turbines or zero-head hydraulic turbines, where some parameters and components have been improved to adapt to the characteristics of ultra-low heads or the invention and innovation of a single turbine type. There is still no complete design theory or methodology for analyzing “pressure head” or “velocity head” characterizes, meaning the field is still in the early stages of theoretical design and will require significant development to match the mature technology of conventional hydroelectric power generation systems. The development of micro hydropower is currently very restricted. Design theories and methodologies for micro-head turbines combining dynamic energy and potential energy must be established in conjunction with the theory of vanadium and method of vane momentum to lay a theoretical foundation for the improvement and development of micro-head turbines.

5 Conclusions

The development of micro-head hydropower technology is keeping pace with the national renewable energy development strategy of China. Such technology is the best choice for China to optimize its energy structure, ensure energy security, and alleviate environmental problems by leveraging the demand and application characteristics of micro-head resources, such as rivers, canals, reservoirs, power plant tailings, piped-water supplies, municipal wastewater, and new marine energy. This paper discussed two types of micro-head hydraulic turbines that are suitable for open and closed watersheds, and presented preliminary analysis of the design methodologies for micro-head turbines combining dynamic and potential energy. This paper provides a technical foundation for the innovative design of small micro-head hydropower plants.

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