Optimization and feasibility analysis of pico-hydro generation system used in small agricultural pipe network

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Abstract—Remote monitoring and control of irrigation can be realized by using agricultural automatic irrigation technology. Power supply is important to ensure the normal operation of automatic irrigation monitoring and control system. Using pipeline water flow as the energy source could solve the problem of power shortage outside the city. In order to fully utilize the water flow energy, we proposed a pico-hydro generation system in this paper, including the optimized power generation module and its peripheral circuit. Firstly, different structures of 3-D impeller models are constructed. These models are analysed and compared with each other using computational fluid dynamics (CFD) and the optimized impeller model is selected. Finally, the peripheral circuit is designed based on the hydraulic turbine output using the optimized impeller structure. The results show that the impeller model with 7 blades, each of which is with the angle of 53°, has a stable flow pattern. And the water energy utilization efficiency is as high as 82.1%.

1. Introduction

Agricultural automatic irrigation technology is very important for agricultural production efficiently. Its core part is the automatic monitoring and control system, which uses a variety of sensors and controllers, such as flow meters, soil temperature and humidity sensors, core controllers, and communication equipment [1]. All these equipment work together to control the irrigation water flow. As the farmland area expands, the automatic irrigation monitoring and control system becomes more and more important.

Power supply is the key point to ensure the normal operation of automatic irrigation monitoring and control system. Using battery limits the working time of the whole system. Battery replacement also increases the labor cost and replaced battery is unfriendly to our environment. Using new energy sources like solar and wind power is very green. However, the construction cost is very high.

Therefore, using pipeline water flow as the energy source can be a good solution of the power shortage outside the city. Meanwhile, it is environment-friendly. Researchers from Turkish-Cyprus used a small piezoelectric wafer as a core part to generate electricity using water pressure [2], [3]. Researchers from the University of Cartagena Technology proposed the use of standard centrifugal pumps operated in reverse mode as hydraulic turbines to generate electric power in water distribution networks. By comparing different methods, they calculated the maximum power coefficient for the
model operation [4]. Researchers from Korea Maritime University placed the turbine behind the pressure reducing valve in the urban pipeline. Electricity could be generated because of the pressure difference before and after the pressure reducing valve. The hydraulic turbine model was optimized by changing the quantity and angles of the blades. It finally achieved 300 W output power and 48% efficiency with the blade angle of 30° [5]. In order to improve the utilization efficiency of water energy, researchers from University of Technology Mara Power Engineering Research Center in Malaysia proposed that the rotation of the impeller could be accelerated by increasing the number of the blades. Also, they thought that the power generation could be increased by adding more magnetic coils for the generator [6].

The purpose of this paper is to design a pico-hydro generation system based on the principle of hydraulic turbine and computational fluid dynamics (CFD). The structure of the impeller is optimized by studying the output results of the impellers with different number and angles of blades. According to the output power of hydraulic turbine, the peripheral circuit of the system is designed and its feasibility is analyzed.

2. Overall Architecture of The System
Pico-hydro generation system mainly consists of three parts. They are power generation module, system circuit and energy storage & load module, which are shown in Fig. 1.

![Overall structure of pico-hydro generation system](image)

2.1. Power generation module
The power generation module includes the hydraulic turbine and the permanent-magnet DC generator. Pipeline water drives the hydraulic turbine impeller to convert the water energy into the mechanical energy. The rotating shaft of the hydraulic turbine drives the rotor of the generator to convert the mechanical energy into the electric energy. When the power generation module works, the operation speed of the hydraulic turbine is fluctuated with different impeller structures, water pressures and water speeds [7], [8], resulting in unstable output voltage. In order to have a stable voltage, the output needs to be transformed through the system circuit before use.

2.2. System circuit
The system circuit includes the control circuit and the DC-DC conversion circuit. The DC-DC conversion circuit converts the unstable DC voltage from the generator into stable output voltage according to the duty ratio from the control circuit. The main purpose of the control circuit is to adjust the duty ratio according to the input unstable DC voltage. It detects the output voltage and the output current of the generator through the voltage and current sensor. Then the Micro Controller Unit (MCU) in the control circuit adjusts the duty ratio of the switching tube to match the load of the system, so that the system can work at the maximum power output [9].
2.3. Energy storage & load module
The energy storage & load module includes the battery and the inverter. This module plays the role of load balance and energy regulation in the system [10]. It uses 12 V/24 Ah lead-acid battery as the energy storage part. The battery is internally connected with the system circuit and externally connected with the load for externally power supply. The DC load can be supplied through the battery under the control strategy. The AC load can be supplied through the inverter, which converts the DC power into AC power for the load.

3. System Circuit Design
The power of the hydraulic turbine will fluctuate according to the change of water flow speed, thus affecting the output of the generator. In order to ensure the stable output of the system, it is necessary to design the system circuit to track the output of the generator. According to the output of the generator, the load is adjusted to achieve the power adjustment [11]. The system circuit design mainly includes DC-DC conversion circuit design and control circuit design.

3.1. DC-DC conversion circuit design
There are many different types of DC-DC conversion circuits, which can be divided into Buck circuit, Boost circuit, Buck-Boost circuit and Cuk circuit according to the functions of the converter [12]. Because the output voltage of the generator in this system is bigger than the input voltage of the battery and equipment. As a step-down converter, the Buck conversion circuit is chosen to convert the unstable output voltage of the generator into a lower stable output voltage. Fig. 2 is the Buck conversion circuit. The main components of the circuit are switching tube T, flywheel diode D, energy storage inductor L, output filter capacitor C, and load resistor R. U0 is the DC input power supply and UR is the output voltage.

![Fig. 2 Buck conversion circuit](image)

3.2. Control circuit design
The control circuit is composed of the voltage and current detection circuit, the MCU and the driving circuit. When the pico-hydro generation system works with Maximum Power Point Tracking (MPPT), it is necessary to collect the voltage and current of the generator and the battery in real time. Then the MCU outputs Pulse Width Modulation (PWM) signal through the program, and the duty ratio is changed to control the voltage [13].

Considering that the power generation is limited and the system needs to be used in the field environment, the low power MCU is selected. The system uses STM32F103C8T6 microprocessor as the MCU of the control circuit and ACS712 current sensor for current detection. The current detection circuit is shown in Fig. 3. For the voltage detection circuit, LM358-2 operational amplifier is used as the main component. The voltage detection circuit is shown in Fig. 4.
Because the PWM signal sent by the MCU is not capable of driving, it is necessary to design a driving circuit to amplify the signal to drive the MOS tube. This paper uses the IR2104 driver IC and designs the peripheral circuit to achieve the function of the circuit. The driving circuit of the system is shown in Fig. 5.

4. Optimization of Power Generation Module
This paper combines with the working characteristics of the small pipeline hydraulic turbine, and considers the factors of manufacturing and cost, the blade structure is designed according to the blade structure of the traditional impulse hydraulic turbine. Firstly, the 3-D model of the impeller is established by changing the angles and the quantity of the blades. Secondly, the impeller model is set using pre-processing, which includes fluid domain establishment, boundary region naming and mesh division. Thirdly, the CFD software is imported for simulation. Finally, the optimal impeller model is selected through comparative analysis [14].

4.1. The establishment of the hydraulic turbine model
This paper mainly aims at the design of the power generation system of the low and middle pressure irrigation pipeline. The diameter of the pipeline is 100 mm, the flow rate of the pipeline is 1.5 m/s, and the water pressure of the pipeline is 200 kPa.

The impeller structure is designed according to the design method of the traditional impulse hydraulic turbine impeller. 45°, 50°, 55° and 60° are selected as the rotation angles of impeller, and the impeller models with 4-10 blades are designed respectively. Structural parameters of impeller are shown in Table.1.

| Parameter                  | Numerical Value |
|----------------------------|-----------------|
| Diameter of impeller /mm   | 80              |
| Diameter of central shaft /mm | 10             |
| The maximum thickness of blade /mm | 6             |
| The minimum thickness of blade /mm | 1             |

4.2. Simulation calculation
The dynamic mesh calculation model is used for simulation calculation to obtain the output of the hydraulic turbine. The simulation calculation parameters are shown in Table.2.

In the boundary motion of CFD, the motion form of the boundary needs to be defined. For some simple motions, they can be defined using a profile file. And for complex motions, they can be described using a UDF file.

In this paper, 6DOF UDF is used to define the motion form of the impeller. 6DOF UDF is a six degrees of freedom dynamic mesh model, which is mainly used to calculate the displacement of the model surface. According to the properties of the model itself, the model movement form is defined by the translation and rotation of the model in the three-axis direction [15].

In order to use the coupling calculation for the impeller, 6DOF function and rigid body equation are used to solve the motion state of the impeller.
5. Power Generation Simulation Experiment

5.1. Analysis of steady-state simulation results

The curves of blade number and head loss are shown in Fig. 6. They show that under the same blade profile and the same blade angle, the head loss in the flow field increases with the increase of the number of blades. When the number of blades is more than 4, with the increase of the number of blades, the increment of head loss is small and tends to be stable. When the number of blades is 4-6, the head loss increases significantly with the increase of the number of blades. And the head loss decreases in the 7 and 9 blades. On the whole, the head loss shows an increasing trend, and the head loss is less than 0.5 m within the test range.

The curves of blade number and output power are shown in Fig. 7. As can be seen in Fig. 7, the trend of impeller output power is the same as the trend of head loss, and the overall trend of output power is an increasing trend. The output power of the system is 20 W to 45 W, and the overall output power has a significant increase at the angle of 52°. When the number of blades is more than 8, the output power tends to be stable or slightly decreased.

Table 2: The simulation calculation parameters

| Parameter                  | Value                      | Parameter                  | Value                      |
|----------------------------|----------------------------|----------------------------|----------------------------|
| Time model                 | Transient                  | Outlet pressure /kPa       | 200                        |
| Turbulence model           | RNG                        | Dynamic mesh               | Smoothing & Remeshing      |
| Watershed medium           | Liquid water               | Spring coefficient         | 0.65                       |
| Inlet velocity /m·s        | 1.5                        | barycentric coordinates    | (0,0,0.010137)             |
| Intensity /%               | 6                          | Type of impeller wall      | Rotating rigid body        |
| Hydraulic Diameter /m      | 0.1                        | Solving algorithm          | Simple                     |
| Time step size /s          | 0.00025                    | Number of time steps       | 30000                      |

Fig. 6. The relationship between the number of blades and head loss

Fig. 7. The relationship between the number of blades and output power
Fig. 8. The relationship between the number of blades and hydraulic efficiency

Fig. 8 shows the curves of hydraulic turbine blade number and hydraulic output efficiency. For the same blade rotation angle, the efficiency is the highest when the number of blades is 5. In the structure with 5 blades, the efficiency at the angle of 50° is the highest, which can reach 95%. The output efficiencies of other impeller structures are less than 90%, and when the number of blades is 5 and 7, the output efficiencies are relatively high at the same rotation angle. On the whole, the output efficiency of the whole system decreases with the increase of the number of blades.

According to the similarity theory of impeller, the speed ratio of impeller can be used as an important parameter to compare the impeller design under the same series [16]. By comparing the speed ratio of the impeller, the performance of the impeller under different structures can be analyzed. As can be seen in Fig. 9, when the blade angle is constant, the speed ratio of the impeller decreases with the increase of the blade number. The speed ratio decreases the most when the blade number increases from 4 to 5. Thereafter, the decrement of the speed ratio decreases with the increase of the blade number. When the blade number is 7, the speed ratio is unchanged. When the blade angle is 52° and the blade number is 4, the speed ratio of impeller is the maximum, which is about 653.6; when the blade angle is 55° and the blade number is 8, the speed ratio of impeller is the minimum, which is 386.1.

Furthermore, it can be seen in Fig. 10 that the speed ratio decreases when the blade angles increase, but the decrease is not linear. When the blade number is from 4 to 5, the speed ratio is the maximum. When the blade number is 8, the speed ratio of the impeller fluctuates in a small range. Therefore, it can be indicated that the speed performance of impeller reaches the best at this angle, and increasing the blade number continuously cannot improve the hydraulic performance of the impeller.
According to the speed ratio of the impeller, the performance of the impeller under this structure can be compared, and the impeller structure under other pipeline types can be designed by using the similarity theory of hydraulic turbine. Considering the hydraulic output capacity and the speed ratio of the impeller comprehensively, the impeller structures with 6 and 7 blades, each of which is with the angles of 52° and 53°, are selected as the pre-selected impeller structure.

5.2. Flow field analysis
The water flow state affects the stability of the pipeline water, so the disturbances of the impeller rotation to the internal flow field can be analyzed by observing the path lines and the vortex cores at the impeller tail.

The vortex ropes of the impellers with 6 and 7 blades, each of which is with the angles of 52° and 53°, are respectively shown in Fig. 11 to Fig. 14. The path lines of the impellers with 6 and 7 blades, each of which is with the angles of 52° and 53°, are respectively shown in Fig. 15 to Fig. 18. The following conclusions can be drawn from the figures:

By observing the vortex rope distribution diagrams of the tail section of the impeller, it can be seen that the vortex ropes of the near tail of the impeller are clearly distributed, and the rotation trend of the impeller can be clearly seen. When the impeller rotates, the flow velocity at the tail of the blades increases sharply, and the back-flow is obvious. The tail of the impeller central shaft forms a low-level vortex area. By comparing the path line diagrams, it can be seen that multiple rotation vortex zones are formed at the tail of the blades, and there is a streamline rotation zone inside the center. Near the tail of the impeller, the rotation of impeller interferes severely with the water flow and the water flow is chaotic. The comparison of the four impellers shows that the vorticity here reflects a situation similar to that of the path line.

With the increase of the distance from the impeller, it can be seen that the swirling flow at the tail of the blade decreases, and the low-speed vortex area at the center increases and gradually becomes a circular rotation area. The disturbance at the tail of the blade decreases with the increase of the distance from the tail of the impeller. At 100 mm, it can be observed that a stable flow velocity area has been formed near the wall. The center part of the pipeline gradually formed a rotating vortex, and the hollow vortex appears in the vortex center. A vortex area is formed in the steady flow area between the center and the wall surface, where irregular vortices can be observed.
Fig. 13 Vortex rope of 6 blades and 53° rotation angle

Fig. 14 Vortex rope of 7 blades and 53° rotation angle

Fig. 15 Path lines of 6 blades and 52° rotation angle

Fig. 16 Path lines of 7 blades and 52° rotation angle

Fig. 17 Path lines of 6 blades and 53° rotation angle

Fig. 18 Path lines of 7 blades and 53° rotation angle
When observing 150 mm from the section, it can be seen that the water flow at the wall surface is stable, and the central hollow velocity area disappears, but the central vortex area still exists and there are vortices. The vortices of the four impellers are observed, the impeller with 6 blades, each of which with is the angle of 52°, also has a hollow vortex area and swirls around it. Under the impeller structure with 6 blades, each of which is with the angle of 53°, and the impeller structure with 7 blades, each of which is with the angle of 52°, the hollow swirls disappear, and three swirl areas appear in the vortex area. Under the impeller structure with 7 blades, each of which is with the angle of 53°, the central vortex area still exists, but there are only 2 swirling areas. Therefore, compared with the pipeline flow conditions under other impeller structures, this impeller structure has fewer vortices and more stable flow pattern.

In order to meet the hydraulic output power is 35 W, the head loss is no more than 2% and the efficiency is higher than 80%, and considering the flow field at the tail of the impeller, the impeller model with 7 blades, each of which is with the angle of 53°, is selected as the impeller of the hydraulic turbine. Under this impeller structure, the speed of hydraulic turbine is 580 r/min, the output power is 37.9 W, the head loss is 0.379 m, and the output efficiency is 82.1%.

6. Conclusion
In this paper, the pico-hydro generation system is optimized and the feasibility is analysed. The angles and the number of blades are taken as independent variables, the impeller is simulated using CFD theory. The simulation results show that the speed of the designed blade changes linearly with the increase of the blade rotation angle in the pipeline with a flow rate of 1.5 m/s and a pressure of 200 kPa; However, when the rotation angle is constant, the speed remains unchanged with the increase of the number of blades. The steady-state simulation results show that when the number of blades is 8, the hydraulic performance of the impeller cannot be improved by increasing the number of blades.

In conclusion, the impeller model with 7 blades, each of which is with the angle of 53°, is selected as the impeller of the power generation module. Using this impeller model, the vortex is less, the flow pattern is stable, and the influence on the pipeline flow is the least. The output results show that the hydraulic turbine speed is 580 r/min, the output power is 37.9 W, the head loss is 0.379 m, and the output efficiency is 82.1%. The optimized pico-hydro generation system can utilize the pipeline water energy with maximum efficiency under the specific working condition. With the intelligent system circuit, the system has the ability to continuously supply stable power for the automatic irrigation monitoring and control system.

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