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The Possibility of Generating Electricity through the Installation of Microhydrogenerators in the Main Water Supply

Abdurakhim Taslimov [1], Asliddin Norqulov [2,a)], Feruz Raximov[2], Ma'ruf Karimov[1]

[1]*Tashkent state technical university named after Islam Karimov, Tashkent, Uzbekistan*
[2]*Navoi State University of Mining and Technologies, Navoiy, Uzbekistan*

[a)] *Corresponding author:feruz.raximov.2017@mail.ru*

Abstract. This article presents a scientific analysis of the renewable (green) energy generation potential using the example of the Damkhoja drinking water main pipeline, built on a natural slope, that is, a closed pipeline system operating without pumps. The diameter of the pipeline is 1400 mm, and its length exceeds 100 km; water consumption is 2 m^3/s. The flow characteristics in the hydraulic system–velocity, pressure, and energy loss–were mathematically modeled based on the Navier-Stokes, Bernoulli, and Darcy-Weisbach equations. Based on these mathematical models, it is determined that the installation of a small hydro turbine can generate about 1 MWh of electricity. The results of the study confirm the applicability of the project in terms of efficient use of existing water infrastructure, improving energy efficiency and developing sustainable and environmentally friendly energy sources. This approach serves as an important scientific and practical basis for the development of agriculture, water resources management and strengthening regional energy security.

INTRODUCTION

Modern main pipeline systems designed for the transportation, storage and distribution of drinking water play a crucial role not only in meeting the needs of the population, but also as a stable source of energy. In particular, the continuous and regular flow of water in closed pipelines operating on natural slopes opens up alternative opportunities for the production of environmentally friendly energy. In this context, the search for methods of obtaining renewable energy by integrating a hydro turbine into the existing infrastructure of main water pipelines has become a critically important task [1]. When performing technical analysis and calculations, it is necessary to thoroughly investigate hydraulic parameters such as flow velocity, pressure distribution, energy loss, and laminar or turbulent flow conditions. Especially when converting an existing system into an energy source, analysis and evaluation based on the Navier-Stokes equations for fluid motion, the Bernoulli expression for energy balance, and the Darcy-Weisbach formulas that take into account friction coefficients are critically important. In addition, an accurate assessment of the pressure distribution, flow velocity, and total hydraulic losses along the pipeline is crucial for correctly modeling water flow characteristics and ensuring optimal turbine operating conditions. In this work, the main attention is paid to the scientific analysis of these processes, an indicator of the prospects for designing a small hydroelectric power plant using the Damkhoja main water pipeline as an example [2-5].

EXPERIMENTAL RESEARCH

Water supply to residential areas, industrial enterprises and household needs is usually carried out through pressure piping systems. In contrast, sewage systems operate primarily through pressure-free pipelines using natural gravity forces. Both systems have excess energy reserves, some of which are discharged through hydraulic valves and pressure reducing devices to maintain water pressure within normal limits [6].

These hydraulic devices, eliminating excessive pressure and ensuring the safety of the system, also lead to unproductive consumption of a certain part of the available energy resources. From a theoretical and practical point of view, it is possible to convert this excess pressure into useful electricity using microhydrogenerators installed inside the pipeline, which replace reduction devices. This approach is especially relevant for large-scale systems such as the Damkhoja main pipeline, where the flow rate and pressure of water are created due to natural slopes. This scientific and technical approach not only ensures effective pressure management, but also creates the potential for stable energy generation in the drinking water supply system, thereby increasing energy efficiency through the introduction of mini-hydroelectric power plants [7-10].

International experience testifies to the successful implementation of projects to convert excess energy in pressure pipelines of drinking and industrial water supply systems into electricity. In particular, in Italy, the Turin water supply network has replaced pressure reducing valves with microhydroelectric power plants that generate more than 1 GWh of electricity per year. In addition, small turbines are installed in the drinking water supply system in Kyoto (Japan), which not only generate electricity, but also maintain the hydraulic stability of the system. In addition, in Colorado (USA), the Denver Water Utility used pressure drops in the drinking water supply to launch a 30 kW power plant using microhydrogenerators in 2013 [11-15].

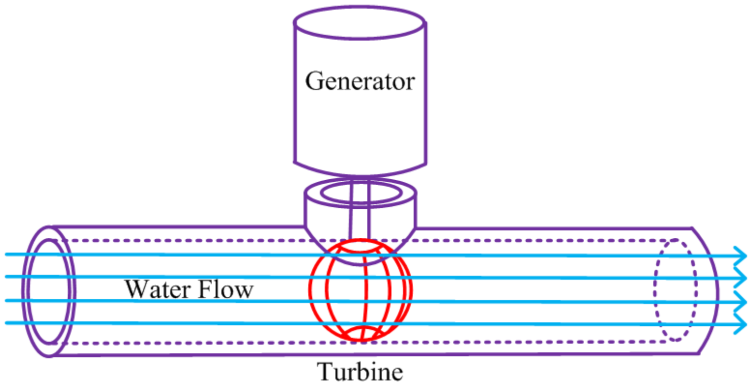

Figure 1. A schematic model of a small hydraulic unit integrated into the pipeline of a water supply system.

These projects demonstrate the efficient use of overpressure in pressure pipeline networks, without the need to use additional fuel in the energy production process, making them waste-free and environmentally friendly technologies. The hydrostatic pressure and dynamic flow velocity resulting from the natural slope in the Damkhoja main water basin create favorable and energy-efficient conditions for small hydropower systems. The continuous movement of water in the pipeline ensures the uninterrupted use of hydropower resources. Thus, the optimal placement of turbines and generator sets, taking into account pressure and speed changes, allows for maximum energy efficiency through in-depth analysis. This approach not only improves the drinking water supply system, but also turns it into a sustainable energy source [16].

The first image shows a schematic model of a small hydropower plant integrated into the pipeline of a water supply system. In drinking water supply systems and industrial systems, water flows under pressure through pipes, which often leads to mechanical dissipation of excess pressure. However, this hydropower system allows efficient conversion of pressurized water flow into electrical energy. The diagram shows a hydro turbine generator system located inside an internal pipeline. The water flow moves through the pipe and rotates the turbine. This rotation is then converted into electrical energy by means of a generator [17-20].

Classical and modern methods of hydraulic modeling were comprehensively applied in the analysis of the system. The hydraulic processes in the study were modeled based on the following theoretical principles and formulas [21]:

The Navier-Stokes equations are fundamental differential equations that describe the motion of liquids in three-dimensional coordinates as a function of time. They allow you to determine the velocity field and pressure distribution in the flow;

The Bernoulli equation, based on the principles of conservation of energy in closed pipeline systems, makes it possible to analyze changes in pressure, kinetic and potential energy in the flow;

The Darcy-Weisbach equation, used to determine friction losses in pipelines, allows you to calculate the pressure drop depending on the length of the pipe, diameter, flow velocity and coefficient of friction;

The Reynolds number plays a crucial role in determining the flow regime (laminar, transient, or turbulent) and is used to characterize flow behavior in hydraulic calculations;

Thanks to the application of these theoretical foundations, hydraulic phenomena in the pipeline were comprehensively investigated and the technical and economic feasibility of implementing small-scale hydropower solutions into the existing water infrastructure was determined.

The Navier-Stokes equations are fundamental partial differential equations that describe the motion of a fluid in three-dimensional coordinates as a function of time. These equations allow us to determine the velocity field and pressure distribution in the flow. The equations are presented as a system of partial differential equations. For incompressible liquids, they take the following form [22]:

$$\frac{\partial u}{\partial t} + (u \cdot \nabla) \cdot u = -\frac{1}{\rho} \nabla \cdot p + \nu \cdot \nabla^2 \cdot u + f \quad (1)$$

where: u - the fluid velocity vector (three-dimensional: u_x, u_y, u_z), t - time, ρ - fluid density, p - pressure, ν - kinematic viscosity, f - external forces.

$$\frac{\partial u_x}{\partial t} + u_x \cdot \frac{\partial u_x}{\partial x} + u_y \cdot \frac{\partial u_x}{\partial y} + u_z \cdot \frac{\partial u_x}{\partial z} = -\frac{1}{\rho} \cdot \frac{\partial p}{\partial x} + \nu \cdot (\frac{\partial^2 u_x}{\partial x^2} + \frac{\partial^2 u_x}{\partial y^2} + \frac{\partial^2 u_x}{\partial z^2}) + f_x \quad (2)$$

$$\frac{\partial u_y}{\partial t} + u_x \cdot \frac{\partial u_y}{\partial x} + u_y \cdot \frac{\partial u_y}{\partial y} + u_z \cdot \frac{\partial u_y}{\partial z} = -\frac{1}{\rho} \cdot \frac{\partial p}{\partial y} + \nu \cdot (\frac{\partial^2 u_y}{\partial x^2} + \frac{\partial^2 u_y}{\partial y^2} + \frac{\partial^2 u_y}{\partial z^2}) + f_y \quad (3)$$

$$\frac{\partial u_z}{\partial t} + u_x \cdot \frac{\partial u_z}{\partial x} + u_y \cdot \frac{\partial u_z}{\partial y} + u_z \cdot \frac{\partial u_z}{\partial z} = -\frac{1}{\rho} \cdot \frac{\partial p}{\partial z} + \nu \cdot (\frac{\partial^2 u_z}{\partial x^2} + \frac{\partial^2 u_z}{\partial y^2} + \frac{\partial^2 uz}{\partial z^2}) + f_z \quad (4)$$

where: u_x, u_y, u_z - component of the velocity in the directions x, y, z (m/s), respectively, $\partial u_x/\partial t, \partial u_y/\partial t, \partial u_z/\partial t$ is the rate of change of velocity with time (acceleration), $\partial u_x/\partial x, \partial u_z/\partial z,$ etc - changes in space (velocity gradients), $(u\cdot\nabla)\cdot u$ - convective acceleration, Zamoskvorechie flow $(1/\rho)(\partial p/\partial x)$ the force created by the pressure change in x, $\nu\cdot\nabla^2\cdot u_x$ - limit dispersion viscosity forces arising due to the internal friction of a fluid, f_x, f_y, f_z - components of external forces in the directions x, y, z.

The application of the Bernoulli equation is crucial in the production of electricity by installing hydroelectric generators on main pipelines. This method is based on converting the energy of a fluid flow into electrical energy. Below we will analyze this process using the Bernoulli equation [23]:

$$P_1 + \frac{1}{2} p \cdot v_1^2 + \rho \cdot g \cdot h_1 = P_2 + \frac{1}{2} p \cdot v_2^2 + \rho \cdot g \cdot h_2 \quad (5)$$

where: P_1 and P_2 - pressures at two points along the pipeline, v_1 and v_2 - fluid velocities at those points, h_1 and h_2 - elevations (heights) at the corresponding points.

The Bernoulli equation, presented in equation (5), expresses the law of conservation of the total mechanical energy of the water flow between two points along the pressure pipeline. This total energy consists of three main components: pressure energy, kinetic energy, and gravitational potential energy. The balance of these forms of energy determines the change in hydraulic pressure along the pipeline at steady flow. In the context of microhydroelectric power integration, this ratio is important because it allows us to estimate the available hydraulic head that can be used by the turbine without violating the operating pressure requirements of the water supply system. Thus, equation (5) serves as the main analytical tool for determining places where there is an excess of hydraulic energy that can be safely converted into electrical energy [24,25].

The energy difference is calculated using Bernoulli's equation as follows:

$$\Delta E = \left(P_1 + \frac{1}{2} \rho \cdot v_1^2 + \rho \cdot g \cdot h_1 \right) - \left(P_2 + \frac{1}{2} \rho \cdot v_2^2 + \rho \cdot g \cdot h_2 \right) \quad (6)$$

The expression in equation (6) is the difference in total mechanical energy between two points of the pressure pipeline. This energy consists of pressure energy, kinetic energy, and potential (gravitational) energy, which together determine the ability of flowing water to perform useful work when passing through a hydro turbine. A positive value of ΔE indicates the presence of sufficient excess hydraulic pressure to convert into electrical energy without compromising the hydraulic stability of the pipeline. Therefore, an accurate estimate of ΔE is necessary to determine the effective operating range of microhydrogenerators and to ensure that energy extraction does not lead to a decrease in the required operating pressure for downstream consumers [26].

RESEARCH RESULTS

This difference is converted into electrical energy by the hydrogenator. The Darcy–Weisbach equation is one of the main formulas used to calculate pressure losses during fluid flow in pipelines. This formula is widely used in hydromechanics and is crucial for analyzing and optimizing fluid flow efficiency [27].

$$\Delta P = f \cdot \frac{D}{L} \cdot \frac{p \cdot v^2}{2} \tag{7}$$

where: *ΔP* - pressure loss (*Pa*), *f* - Darcy friction factor (dimensionless), *L* - length of the ipeline (*m*), *D* - diameter of the pipeline (*m*), *ρ* - fluid density (*kg/m³*), *v* - average velocity of the fluid (*m/s*).

Equation (7) is a Darcy-Weisbach model for hydraulic friction losses in a closed duct. The value *ΔP* depends both on the geometric properties of the pipeline and on the dynamic characteristics of the water flow *(p, v).* Since the dissipation of friction directly reduces the available hydraulic pressure, this equation is fundamental for estimating the actual amount of energy recovered in pressurized water supply systems. An accurate DP assessment ensures that microhydroelectric water extraction does not adversely affect the required pressure levels for downstream consumers [28-31].

The Darcy coefficient of friction f depends on the Reynolds number. The Reynolds number is calculated as follows:

$$\mathrm{Re} = \frac{\rho \cdot \upsilon \cdot D}{\mu} \tag{8}$$

where: μ - dynamic viscosity of the fluid (*Pa·s*).

If Re < 2000, the flow is laminar, and the formula f = Re/64 is applied. If Re > 4000, the flow is turbulent, and f is determined using the Moody diagram.

The Reynolds number in equation (8) determines whether the flow inside the pipeline is laminar, transient, or turbulent. This classification is important because the coefficient of friction f in equation (7) strongly depends on the number Re. The turbulent flow that usually occurs in large diameter water pipes leads to increased friction losses and directly affects the net amount of hydraulic energy available for conversion by the turbine. Therefore, accurate determination of the Reynolds number is a critical preliminary step in assessing the feasibility of using hydroelectric power.

The mathematical model of electricity generation using the Damkhoja drinking water pipeline, standing on a natural slope, is summarized in the form of a general equation, including the Bernoulli equation, the Darcy–Weisbach formula and the efficiency of energy conversion by a hydrogenerator [29-30].

$$P = \eta \cdot Q \cdot (\rho \cdot g \cdot h - f \cdot \frac{L}{D} \cdot \frac{\rho v^2}{2}) \tag{9}$$

where: η - efficiency of the hydrogenerator, *Q* - water flow rate (*m³/s*), ρ - water density (*kg/m³*), *g* - gravitational acceleration (9.81 *m/s²*), *h* - elevation of the slope (m), *f* - Darcy friction factor, *L* - length of the pipeline (m), *D* - diameter of the pipeline (mm), *v* - fluid velocity (m/s).

This expression defines the useful electrical power that can be obtained from the water flowing through the pressure pipeline. The available hydraulic energy is determined by the natural height difference along the pipeline, and friction losses reduce the useful head. The remaining hydraulic energy multiplied by the flow rate and efficiency of the turbine generator system provides the actual power output. This ratio is crucial for assessing the technical and economic feasibility of installing a microhydroelectric power plant in a pipeline.

Experimental calculations were carried out in the Damkhoja drinking water supply system operated by Zievuddin Suvsoz *LLC*. The main hydraulic parameters of the Damhoji water supply system are as follows:

– Pipeline diameter *(D)* -1400 mm;
– Flow rate *(Q)* - 2 m^3/s;
– Pipeline length *(L)* - more than 100 km;
– The kinematic viscosity of water (v) is 1.004×10^{-6} m^2/s (at 20 °C);
– The pipeline material is stainless steel.

Figure 2 shows a graph of the distribution of pressure and velocity of liquid through the pipeline depending on the distance.

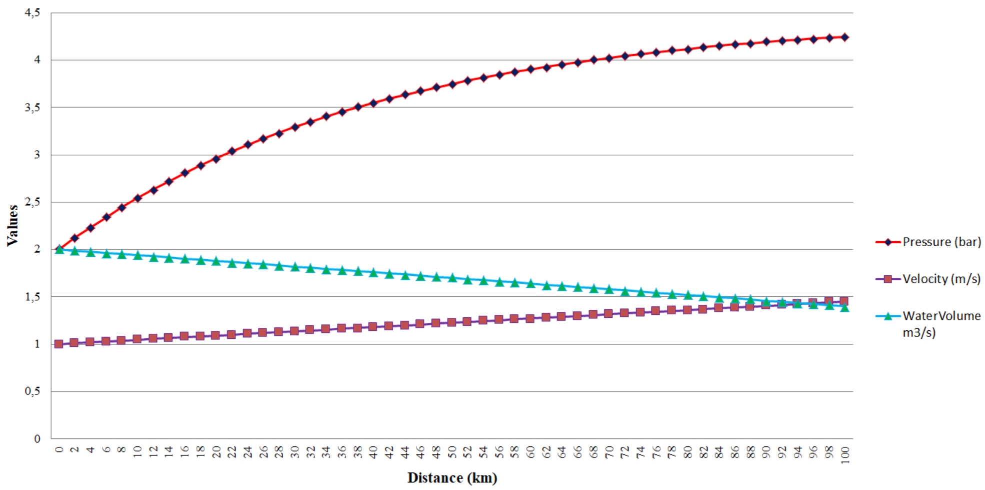

Figure 2. Variation of pressure, fluid velocity, and water volume along the Damkhoja main pipeline.

Based on this graph, the course of changes in three important hydraulic parameters was analyzed: pressure, fluid velocity, and water volume along the Damkhoja main pipeline with a slope (i.e., with increasing distance).

Pressure - the pressure near the pipeline inlet is relatively low, and as the distance increases, it increases steadily. This change is explained by the increase in hydrostatic pressure caused by the natural slope [32-61]. Vertical sections of the pipeline, compared with closed and horizontal sections, significantly increase the pressure.

Velocity - at the initial point, the flow rate is low, and as the flow progresses through the pipeline, there is an increase in water velocity with increasing slope and pressure. This reflects the conversion of the potential energy of the liquid into kinetic energy, as described by the Bernoulli equation. This trend plays a crucial role in ensuring the stability of the flow dynamics and creating optimal conditions for the operation of the turbine.

Water volume - as the distance through the pipeline increases, the volume of water gradually decreases. This is due to the division of water into branches, consumption at points of consumption, or the use of water through maintenance points. Reducing the flow rate, in turn, can directly affect the speed and pressure parameters.

This graph clearly shows the complex hydraulic changes in the main pipeline system. Each of these conditions has a significant impact on the process of generating electricity and plays an important role in choosing the type of hydro turbine, determining its location and increasing its efficiency.

All cities are served by pressurized pipeline systems for supplying water for drinking, domestic, or industrial use, while sewage and wastewater systems typically operate by gravity. Theoretically, systems equipped with reduction devices can replace them with in-tube generators, thereby generating useful electricity while maintaining control over water flow and pressure.

CONCLUSIONS

The article discusses in detail the current hydraulic characteristics of the main drinking water pipeline, as well as an assessment of the pipeline's potential for energy production. Calculations show that factors such as pipeline diameter, water flow, slope and flow stability can serve as a sufficient basis for creating a small hydroelectric power plant using natural water flow. Modeling based on the Navier-Stokes, Bernoulli, and Darcy-Weisbach equations made it possible to determine the flow rate, pressure loss, and power generation capacity. According to the results obtained, an average of 1 MWh of electricity can be obtained from the water flow in the pipeline. This opens up the opportunity to rethink the existing drinking water supply infrastructure as an additional source of electricity. In addition, graphical analysis showed that as the slope of the pipeline increases, pressure and velocity increase, and the volume of water decreases. This indicates that the energy generation potential is higher in the upper sections, but the power is reduced to the lower ones. These aspects are crucial when choosing the location and design of a hydro turbine. In general, the Damkhoja main water supply system not only performs the function of supplying drinking water, but also has the potential to become a stable and environmentally friendly energy source in modern conditions. This approach can be considered as a promising solution for improving energy efficiency, reducing environmental impact and increasing the energy independence of the region.

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