MACHINE BUILDING AND MACHINE SCIENCE

UDC 621.224
https://doi.org/10.23947/2687-1653-2022-22-2-142-149

Original article

Converting Hydraulic Resistance Energy of the System into Electricity

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Abstract

Introduction. A gravity conduit with a control valve and a pressure regulator in the gravity water-supply pipe is considered under conditions when the hydraulic regime of the water-supply system is not disturbed. In relation to such a system, the problems of converting the energy of local artificial hydraulic resistance into electricity are investigated.

Materials and Methods. Literature that highlights the possibility of using microturbines for power generation in water systems was studied. The actual values noted by the continuous pressure recorder (logger) for 12 hours were presented, as well as the water consumption by the turbine at a given unit section (the average for a year), and the pressure differential. It was noted that the use of small hydroelectric power plants in water supply systems significantly reduced the cost of their operation. The indicators of water consumption in the hydroturbine unit during the year, broken down by months, were given. The maximum power at the turbine inlet was calculated. The principles of selecting the type of hydraulic turbine were described. The average efficiency values for different elements of the hydroturbine plant, the average parameters of the power of the small hydro and the corresponding indicators of the average monthly electricity generation were indicated.

Results. Equipping the units under study with specially designed turbines can enable to obtain electrical energy through converting artificially created by local resistance and extinguished mechanical energy. It is possible to apply the approaches described in this article when replacing many of the pressure control units of the Yerevan City Network system. The productivity of a small hydro power plant was predicted, as well as the terms of its construction and operation — for 2 years and 30 years, respectively. The construction and maintenance costs were calculated in advance. The expected data on income, expenses, and net profit are given. It is indicated that it will potentially be close to 6 million drams per year. The analysis of the data allowed us to conclude that the internal rate of return will be at the level of 10.4%, and the payback period is 9 years.

Discussion and Conclusions. We recommend replacing the regulator with a hydroturbine having the same hydraulic resistance and automatic flow control in the system. The conclusions were confirmed by the energy and economic indicators of the hydroturbine plant located on the section of the Arzakan — Yerevan main water pipeline.

Keywords: hydraulic resistance, energy, hydroturbine, adjuster, water supply, energy efficiency indicator, renewable energy sources, pressure control, expert systems.

Acknowledgements: the authors would like to thank the reviewers, whose critical evaluation of the submissions and suggestions for improvement contributed significantly to the quality of this article.

For citation: A. A. Sahakyan, D. A. Butko. Converting Hydraulic Resistance Energy of the System into Electricity. Advanced Engineering Research, 2022, vol. 22, no. 2, pp. 142–149. https://doi.org/10.23947/2687-1653-2022-22-2-142-149

Introduction. Traditional non-renewable primary energy sources, which are very limited in resources, continue to play a dominant role in the Armenian economy. The active use of fossil energy sources has caused environmental problems such as air and soil pollution, water scarcity, and ecosystem degradation. Population growth, continuous household and industrial energy consumption should be taken into account. All this suggests that further quantitative (extensive) development of the energy industry is inexpedient. The use of renewable energy sources to replenish the overall energy balance of the country is an imperative of the time. This approach makes it possible to provide sustainable development while preserving the environment. Water and energy resources are essential for human life and are subject to regular economic, technological, demographic, and social impacts [1]. According to some estimates, 2–3 % of the world's electricity consumption comes from water systems (WS) [2], and pumping units are used in 80–90 % of cases. The costs of their maintenance are among the main operating costs of WS [2]. The concept of rational and efficient use of water resources and electricity is of strategic importance for sustainable development and climate change mitigation. Rational use of water and electricity is hampered by weak infrastructure and outdated operating procedures. This is especially true for developing countries. Moreover, in line with the Millennium Development Goals[1], there is a need for alternative solutions: the goal is to halve the number of people without sustainable access to clean water and basic sanitation. As renewable energy sources, it is proposed to put into operation small hydroelectric power plants (SHPP) in sections of the water supply network with local hydraulic resistance, subject to semi-open valves or pressure regulators. This is cost-efficient for the production of electricity and water supply, and illustrates perfectly the rational use of water resources. In the past decades, hydroelectric power was one of the main sources of energy from water. Today, the water sector is considered a direct consumer of electricity, and this affects the distribution of water resources[2]. Active energy consumption directly affects the state of water resources in the world, which in turn is the cause of climate change. Rational use of energy should contribute to sustainable development through the competent distribution of energy resources at all stages of transformation. For a comprehensive assessment of the problem, an example of the construction of the SHPP on the Arzakan —Yerevan water pipeline is given.

Materials and Methods. The Arzakan-Yerevan water pipeline supplies water to the administrative districts of Yerevan (Arabkir, Malatia-Sebastia, Achapnyak, Erebuni) and adjacent settlements (Zovuni, Kanakeravan, Nor-Achin, Nor-Gekhi, Yeghvard, etc.). The water pipeline originates from the Arzakan spring, and on the territory of the Getamej administrative community, it is divided into two water pipelines with different pressure conditions. The construction of the SHPP on one of the branches of this water pipeline feeding the north-western and western districts of Yerevan is being considered. The company operating on the dividing branch of the water pipeline installed a semi-open valve to

[1] Millennium Development Goals. United Nations URL: https://www.un.org/development/desa/ru/millennium-development-goals.html (accessed: 05.06.2022) (in Russ.)

[2] Mao Yushi, Sheng Hong, Yang Fuqiang. The true cost of coal. Understanding China's Energy Landscape. 2008. URL: https://www.understandchinaenergy.org/greenpeace-chinathe-china-sustainable-energy-programwwf-china-main-authors-mao-yushi-sheng-hong-yang-fuqiang-2010-the-true-cost-of-coal-full-report/ (accessed: 05.06.2022).

adjust the water flow in the system. This provides the pressure in the water supply for settlements located above the main highway (adjacent to the city of Nor-Achin). When the valve is semi-open, a local hydraulic resistance of about 13 m of water column (w.c.) is created (before that, the pressure in the water pipe was about 33 m w.c.).

We propose to install a SHPP instead of a semi-open valve, without disturbing the normal hydraulic mode of operation of the water supply system. Figure 1 shows a plan of the area in the Google Earth program, and Table 1 summarizes the actual values recorded by the continuous pressure recording device (logger) for 12 hours.

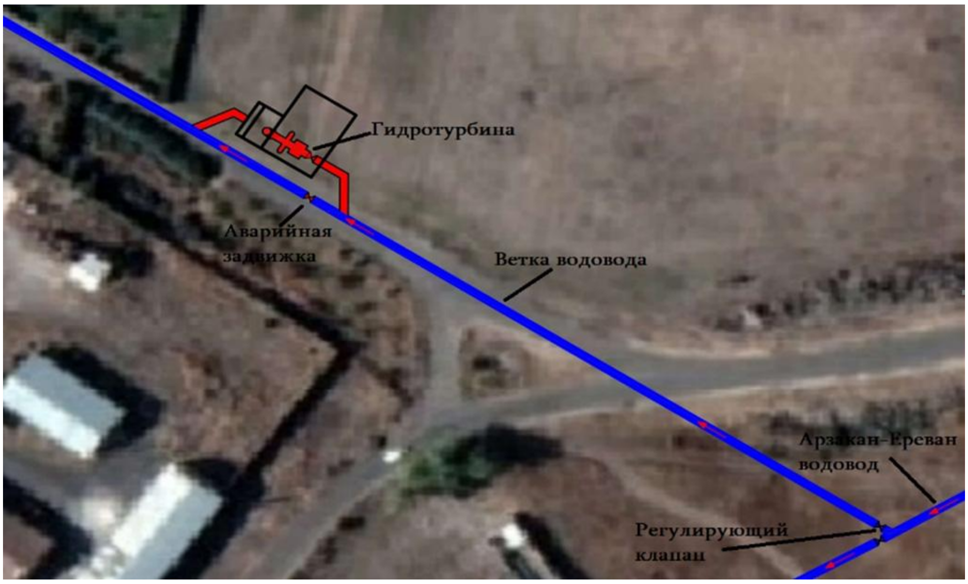

Fig. 1. Map of the area in Google Earth

Table 1

Data from pressure recorders installed in the study area

Research Date	Time	Registered pressure (m H2O)	
		Before semi-open valve	After semi-open valve
15.09.2020	20:00	32.8	13.0
15.09.2020	21:00	33.2	12.6
15.09.2020	22:00	33.3	13.0
15.09.2020	23:00	33.3	13.0
16.09.2020	00:00	33.5	12.8
16.09.2020	01:00	33.8	12.4
16.09.2020	02:00	33.9	13.2
16.09.2020	03:00	33.9	13.1
16.09.2020	04:00	33.9	13.6
16.09.2020	05:00	33.8	13.3
16.09.2020	06:00	33.8	13.2
16.09.2020	07:00	33.7	12.6
16.09.2020	08:00	33.4	13.0

The proposal aims at providing the transformation of hydraulic energy artificially created in the local resistance unit into electrical energy. Favorable conditions are created at the construction site of a small hydroelectric power plant (on a branch of the Arzakan-Yerevan main water pipeline) for the integrated use of water and energy potential. The flow rate of the turbine in this section of the assembly is 1.15 m^3/s (average during the year). The control device on the pipe provides a given flow rate. As a result, pressure drops from 20.3 m w.c. to 21.4 m w.c. (Table 1). The expediency of the practical use of the so-called “hidden” energy generated in the sections of main water pipelines in the Republic of Armenia should be noted. The hydropower potential of water supply systems has long been known, but not properly explored. The literature describes in detail the possibilities of using microturbines to generate electricity in water supply systems [3−5]. Gravity systems in areas with high slopes form significant pressures in water supply and distribution networks, creating the prerequisites for generating hydroelectric power. Turbines installed in water distribution networks can also be used as pressure control systems. To do this, pressure relief valves (PRV), which control water losses and leaks, are used [6]. They dissipate energy, thus reducing the pressure in the system. As for water turbines, they can convert excess pressure into electricity[3]. Major advantages of hydraulic energy recovery in water pipes, according to F. Vieira and J. S. Ramos [3, 7], are improving the energy efficiency of the system through the use of local sources, and reducing dependence on external (grid) energy. In addition, hydraulic energy recovery contributes to an overall reduction in operating costs. F. Vieira and J. S. Ramos [3, 7] emphasize in their research that the use of small hydroelectric power plants in water supply systems reduces significantly the cost of their operation. This is due to the fact that the proposed solution enables to replace the control valve with a hydraulic turbine equal in hydraulic resistance. Table 2 shows the water consumption in the system (monthly averages are indicated).

Table 2

Water consumption in the hydroturbine unit

Month	Consumption, m^3/s		
January	1.20	July	1.30
February	1.10	August	1.30
March	1.10	September	1.05
April	1.00	October	1.05
May	1.10	November	1.10
June	1.30	December	1.20

Note that the maximum head is Hmax = 21.4 m, the minimum — Hmin = 20.3 m.

Average annual consumption, according to Table 2: Q = 1.15 m^3/s.

With a design head equal to H = 20 m, the flow power at the turbine inlet [12]:

$$N = \rho q Q H = 1000 \cdot 9.81 \cdot 1.15 \cdot 20 = 225632 \text{ Вт} \approx 225 \text{ kW}.$$

Principles for selecting a hydro turbine. With a low head and a higher flow rate (for SHPP), a turbine with a high specific speed should be selected. Of the reaction turbines, an axial jet turbine will do. Of the low-power active turbines, Banki turbine should be chosen to pass a relatively large flow rate. However, in this case, it is unacceptable to use an active turbine, since when it is filled, excess pressure is formed at the outlet, and Banki turbine operates as a very poor jet turbine with very low energy performance.

[3] The Millennium Development Goals Report 2011. United Nations. New York, 2011. URL: https://www.un.org/millenniumgoals/pdf/(2011_E)%20MDG%20Report%202011_Book%20LR.pdf (accessed: 05.06.2022).

It is recommended to install the hydro turbine unit at the valve on the bypass line. Inlet and outlet valves will provide uninterrupted operation of the line even in the event of a station shutdown. The operation of the SHPP will be monitored by pressure sensors installed at the inlet and outlet of the turbine. This maintains the required pressure on the line[4]. When installing equipment on drinking water mains, special requirements should be taken into account [8-10]. Specifically, contamination of the water with lubricating oils and other materials[5, 6] must be avoided. In general, the distributed water should meet the quantitative and qualitative standards of drinking, domestic, and industrial consumption [11].

Energy indicators of SHPP. The following average efficiency values are applied for different elements of the hydro turbine installation: $\eta_т = 0.86$, $\eta_{ген} = 0.94$.

Turbine shaft power: $N_z = \eta_z N = 0.86 \cdot 225 = 193.5$ kW, and at the generator output: $N_{ген} = \eta_{ген} N_z = 0.94 \cdot 193.5 = 184$ kW.

Table 3 presents the averaged parameters of the power of the SHPP and the corresponding indicators of the average monthly electricity generation.

Table 3

Average monthly capacity and output of SHPP

Month	Power, kW	Output, kWh
January	190	141,360
February	174	116,930
March	174	129,456
April	158	113,760
May	174	113,456
June	206	148,320
July	206	153,264
August	206	153,264
September	166	119,520
October	166	123,504
November	174	125,280
December	190	141,360
	Total	1,573,474

It should be noted that the use of a SHPP jet turbine at a large negative suction height ($h_S = -13$ m), in our opinion, is proposed for the first time in world practice. In this case, on the one hand, the occurrence of cavitation is

4 Markaryan AYa, Tokmadzhyan VO. Regulirovanie proizvoditel'nosti nasosov s tsel'yu predotvrashcheniya kavitatsionnykh yavlenii. In: Proc. 7th Int. Congress “Water: Ecology and Technology”. Moscow: EHKVATEHK-2006. Part 1. P. 566. (In Russ.)

5 Sanitarakan Kanonner yev Normer N2-III-A2-1, Khmelu jur: Jramatakararman kentronats’vats hamakargeri jri vorakin nerkayats’vogh higiyenik pahanjner, Voraki hskoghut’yun, Yerevan, 2002t, ej 11. (In Armenian)

6 Barry JA. Watergy: Energy and Water Efficiency in Municipal Water Supply and Wastewater Treatment Cost-Effective Savings of Water and Energy. The Alliance to Save Energy. Washington, 2007. 44 p.

excluded [9, 12], which, undoubtedly, is regarded positively. On the other hand, it is not known how the high pressure at the outlet of the turbine affects the efficiency, therefore, in our calculations, a slightly underestimated indicator is used.

Research Results. The electricity produced by the SHPP (Table 3) is planned to supply to the general energy system of the Republic of Armenia on the terms of guaranteed purchase at prices approved by the Commission on Regulation of Public Services of Armenia (currently, the tariff is 10.579 drams per kWh).

According to Table 3, during the year, the SHPP will produce at least 1.5 million kWh. According to preliminary calculations, the construction period of the SHPP is 24 months, and the service life is 30 years. The cost of construction and design of the SHPP will amount to 60.4 million drams (Table 4).

Table 4

SHPP construction costs

Works	Cost, AMD mln
Pipeline construction / maintenance	2.2
Construction of the HPP building	14.5
Cost of installing hydraulic units (hydro turbines, generators)	18.0
Transformer substation	10.7
Construction of high voltage power lines	3.0
Design and calculation work	7.0
Other costs	5.0
Total	60.4

Anticipated revenues, operating costs, and profit are shown in Table 5.

Table 5

Forecast of annual financial indicators

Indicator	Amount, AMD mln
Gross income	15.9
Salary, operating expenses, current repairs, and elimination of accidents	7.0
Duties and other obligatory payments	0.2
Depreciation costs (taking into account 30 years of operation)	2.0
Other costs	0.2
Profit before income tax	7.4
Income tax	1.5
Net profit	5.9

The data on annual expenses presented in Table 5 are based on the current regulatory legal acts of the Republic of Armenia. According to these documents, the value added tax and income tax is 20 %[7], and the property tax is 0.6 % (of the residual value). Based on the data on the construction and current operating expenses of the SHPP, Table 6 shows the key indicators of financial productivity.

[7] Hayastani Hanrapetut'yan Harkayin orensgirk', HO-165-N, yndunvats 2016 t'vakani hoktemberi 4-in (In Armenian).

Table 6

Financial performance indicators

Indicator	Unit rev.	Value
Internal rate of return	%	10.4
Payback period	years	9.0

Discussion and Conclusions. Due to the mountainous terrain in the greater territory of the Republic of Armenia, local resistance is often created to adjust the pressure in the water supply network. As a rule, we are talking about semi-open valves and the installation of pressure control equipment. Equipping the network nodes with specially designed turbines will enable converting artificially created local resistance and extinguished mechanical energy into electrical energy. It should be noted that more than 300 semi-open valves and pressure control equipment were installed in the Yerevan water supply system alone. Many of them require replacement. The solutions proposed in this article can be applied to the areas under repair.

References

1. Karl-Ulrich Rudolph. The German Water Sector. Policies and Experiences. Berlin – Bonn – Witten: Federal Ministry for the Environment, Nature Conservation and Nuclear Safety. Federal Environmental Agency; 2001. P. 151.

2. Cabrera E, Pardo MA, Cobacho R, et al. Energy audit of water networks. Journal of Water Resources Planning and Management. 2010;136:669–677. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000077

3. Ramos JS, Ramos HM. Sustainable application of renewable sources in water pumping systems: Optimized energy system configuration. Energy Policy. 2009;37:633–643. https://doi.org/10.1016/j.enpol.2008.10.006

4. Galperin EM, Poluyan VI, Chuvilin VN. Reliability of water supply and water disposal systems. VST. 2006;9:38−42.

5. Davidov AB, Buligin VI, Radetskiy MYu. Guarantee of water supply system reliability. VST. 2004;3:6−8.

6. Fontana N, Giugni M, Portolano D. Losses reduction and energy production in water-distribution networks. Journal of Water Resources Planning and Management. 2012;138:237–244.

7. Vieira F, Ramos HM. Hybrid solution and pump-storage optimization in water supply system efficiency: A case study. Energy Policy. 2008;36:4142–4148. https://doi.org/10.1016/j.enpol.2008.07.040

8. Bogomolov AI, Mikhailov KA. Gidravlika. Moscow: Stroiizdat; 1972. 648 p. (In Russ.)

9. Lovkis ZV. Gidravlika. Minsk: Belarusskaya navuka; 2012. 439 p. (In Russ.)

10. Landau L, SirenkoYu. (eds.) Gidroehnergetika i okruzhayushchaya sreda. Kiev: Libra; 2004. 484 p. (In Russ.)

11. Frijns J, Middleton R, Uijterlinde C, et al. Energy efficiency in the European water industry: learning from best practices. Journal of Water and Climate Change. 2012;3:11–17. https://doi.org/10.2166/wcc.2012.068

12. Vikulin PD, Vikulina VB. Gidravlika sistem vodosnabzheniya i vodootvedeniya. Moscow: MGSU; 2014. 248 p. (In Russ.)

Received 04.05.2022

Revised 28.05.2022

Accepted 07.06.2022

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Claimed contributorship:

A. A. Sahakyan: basic concept formulation; research objectives and tasks; computational analysis; text preparation; formulation of conclusions. D. A. Butko: analysis of the research results; the text revision; correction of the conclusions.

Conflict of interest statement

The authors do not have any conflict of interest.

All authors have read and approved the final manuscript.