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Feasibility of the sizes of water-conveyance system in run-of-river power plants

Mikhail Balzannikov[1,*]

[1]Samara State Technical University, Institute of Architecture and Civil Engineering,
194, Molodogvardeyskaya St., 443001, Samara, Russia

Abstract. The paper deals with run-of-river power stations. The author notes the importance of the implementation of the technical-economic calculations in large-sized elements of the water-conveyance system in run-of-river power plant: turbine pits and intake pipes. The article shows that the volume of construction and the total cost of power plants construction depend on the size of water-conveyance system elements. The task of the research is the economic feasibility analysis of intake pipes sizes in run-of-river power plants, built in the European part of Russia. The author presents the methodology of economic analysis for justification of the length of the intake pipe, based on the method of the total cumulative effect. The methodology is used for calculations of low-pressure run-of-river power plants. The paper gives the results of feasibility of the optimal sizes of intake pipe. The article analyses the influence of operating conditions of power plants on the choice the optimal length of an intake pipe. The analysis showed that it is economically feasible to use intake pipes with a greater length. The length of the intake pipe will increase the efficiency of power plants at the expense of pressure losses of the output stream. The results are important for a correct choice of the main geometrical dimensions of the designed power plants.

1 Introduction

Hydroelectric power plants (HPP) play an important role in electricity supply of various consumers during the stress periods of the daily production schedule of power supply systems as they have very high maneuverable qualities [1, 2]. At the same time, stations of this type demand considerable costs of construction, especially construction of run-of-river power plants on the low-land rivers [3-7], besides, these stations produce significant negative impact on the environment [8, 9].

It is very important to conduct careful research and technical and economic calculations for reasonable feasibility of the geometrical sizes of large-size parts of the building of hydroelectric power plant, including, elements of the water-conveyance system for reduction of unfairly big expenses on construction of hydroelectric power plants [10-12].

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[*] Corresponding author: balzannikov@samgasu. ru

At the same time, among different types of research, pilot studies play important role for such feasibility, as they allow choosing favorable forms and outlines of walls of elements providing the minor losses of a stream pressure [13-16].

The basic large-size elements of the water-conveyance system in run-of-river power plants are the turbine pits and intake pipe [17, 18]. Their turbine pits, as a rule, are spiral, produce defining impact on the overall construction dimensions in the plan. Intake pipes have the greatest value for formation of the general height of a power plant object.

Intake pipes of the run-of-river constructions of power plants with vertical hydraulic aggregates are most often built in the form of elbow devices (Fig. 1). It enables reduction of foundation embedding of an object, lowering work amounts of works and financial costs of its constructing. However, overall dimensions of an intake pipe influence not only the cost of construction works for all power water-conducting elements, but also losses of a pressure of water flow in them. Therefore, they define the general performance coefficient of the hydraulic turbine and overall performance of hydroelectric power plant in general.

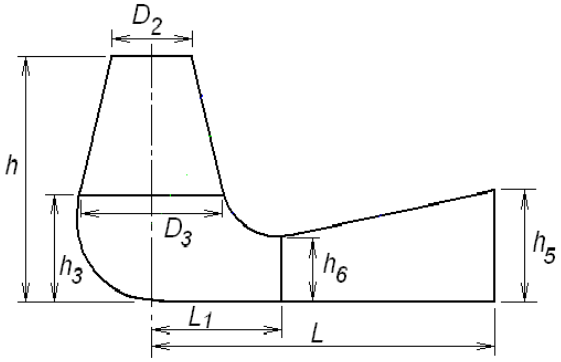

Fig. 1. Forms and parameters of an intake pipe in the cross-section of run-of-river power plant construction.

The task of this research was the feasibility of the optimal main sizes of the intake pipes in the run-of-river hydroelectric power plant and identification of influence of conditions in which the hydroelectric power plant operates on the choice of their key geometrical parameters.

2 Materials and Methods

The research was conducted, using the method of the total cumulative effect. The following equation was chosen as a criterion [6]:

$$\sum_{t=1}^{T}\left(\sum_{n=1}^{m}\Delta D_n\right)_t (1+i)^{\tau-t} - \sum_{t=1}^{T}\left(\sum_{n=1}^{m}\Delta P_n\right)_t (1+i)^{\tau-t} \geq 0 \ , \tag{1}$$

where: ΔD_n – additional revenue amount, , ΔP_n – amount of additional expenses (costs), T – considered time interval, t – current annual period, τ – the year of expenses, i – discount rate.

The length of intake pipe L greatly influences the general loss of water flow pressure in it. On the one hand, increase in length of the intake ΔL will cause expenses growth on construction works because of volume increase of the ground excavation and volume of the poured concrete:

$$\Delta P = c_1 W_1 + c_2 W_2 , \tag{2}$$

where c_1 and c_2 – the cost of unit volume of ground and concrete works, , W_1 and W_2 – are additional volumes of ground and concrete works.

Length increase of the intake pipe can also lead to growth of other expenses, for example, costs of the valves established at the stream exit or the cost of the lifting equipment.

On the other hand, the area of output section will increase with the length increase of a diffuser part of the intake pipe on ΔL. At the same time the average speed of a water stream in output section will decrease that will cause reduction of losses of a high-speed pressure in output section at Δh:

$$\Delta h = \left(\frac{\alpha V^2}{2g} - \frac{\alpha V_1^2}{2g} \right), \tag{3}$$

where V and V_1 – average speed of water flow in output section according to initial option and option with the extended diffuser area, α – irregularity coefficient of water stream speed in the output section.

Loss enhancement of a pressure will cause the generation of additional power ΔN, additional power ΔE and the additional income ΔD:

$$\Delta N = 9{,}81 \eta Q \Delta h , \tag{4}$$

$$\Delta E = \Delta N T_N . \tag{5}$$

$$\Delta D = \Delta Э b , \tag{6}$$

where η – efficiency factor of hydraulic unit, Q – water flow, T_N – conditional annual quantity of hours of power usage of power plants, b – charge rate per 1 kWh of electric power.

The analysis of constructive solutions of intake pipes in the run-of-river power plants constructed in Russia on the Volga Rivers and Kama – Lower Kama, Cheboksary, Zhigulyovsk, Saratov and Volgograd hydroelectric power plants. The analysis has shown that the size characterizing the length of intake pipe – its relative length $L'=L/d$ where d – diameter of the turbine wheel, is close in the size equal to 3,5. This size has also been accepted as initial parameter during further research. The intake pipe of the Zhigulyovsk hydroelectric power plant has served as a compatible of technical and economic calculations. The length varied from initial size towards its increase during the calculation process. For different values of L the quantities were counted as (2) – (6) and used for criterion (1).

Change of geometrical parameter L towards its increase ΔL was considered as economically justified decision if the condition (1) was satisfied, i.e. if the sum of the provided additional income connected with increase in the sizes of the intake pipe for the considered period of time was not less than the sum of the year of additional expenses caused by change of this geometrical parameter, or: $R \geq 0$.

3 Results

The use of the mentioned method helps to calculate the optimal main sizes of the intake pipes of run-of-river hydroelectric power plant and identification of influence of service conditions of hydroelectric power station on the choice of the best parameters of the intake pipes in hydraulic units. Calculations are executed for the conditions close to parameters and service conditions of the Zhigulyovsk hydroelectric power station on the Volga River. Ranges of the varied parameters are specified in tab. 1.

Table 1. Range of varied parameters of power plants.

№	Parameter	Value
1	Hydro turbine pressure, m	24
2	Turbine parameter, m	9,0
3	Water discharge trough turbine, m^3/s	620
4	Original relative length of intake pipe	3,5
5	Charge rate for the electric energy in the first year, rub/kWt	2,4
6	The use of installed capacity per year, hour.	from 1000 up to 7000
7	Length increase of the intake pipe, m	from 0,5 up to 8,0
8	Additional expenses on the construction works, thousands of rubles/m^3	from 10 up to 15
9	Period of calculations, years	From 5 up to 20
10	Discount rate, %	from 2 up to 10
11	Dynamics of charge rate of electric energy, % per hour	from 0 up to 20

Results of calculations were presented for descriptive reasons in the graphic form. In Fig. 2 the generalized results of these technical and economic calculations at T_N = 3000 hours are presented for the ten year period T.

All constructed curve dependences $E = f(\Delta L, b)$ have a maximum. They demonstrate the presence of optimal size of the varied parameter – length of the intake pipe.

The initial size of the intake pipe with a relative length of 3,5 corresponded to the absolute value of 31,5 m. According to the obtained data the optimal size of increase in relative length of the intake pipe was 0,25-0,33 (absolute – 2,5-3,0 m). Data demonstrates that the maximum economic effect for the considered conditions can be reached in case the application of the intake pipe having the total relative length equal 3,75-3,83 (absolute – 34,0-34,5 m). At the same time all range of sizes ΔL for which R is a positive value, are related to economically justified decisions.

Results of calculations for identification of influence of external service conditions of run-of-river power station on the greatest possible increase in length of the intake pipe at which this increase will be economically justified i.e. at which the condition (1) will be satisfied are given in Fig. 3.

The calculations show that the greatest lengthening of the intake pipe: the relative size $\Delta L'$ = 0,90-1,01 (absolute – 8,1-9,1 m)if the number of hours of use of rated power T_N = 3000 and the discount rate equal to 2% , and the relative size $\Delta L'$ = 0,72-0,80 (absolute – 6,5-7,2 m) is gained in case the discount rate is 10%. At the same time the total length of the intake pipe will be the following: relative size – 4,40-4,51 and 4,22-4,30; an absolute value – 39,6-40,6 m and 38,0-38,7 m.

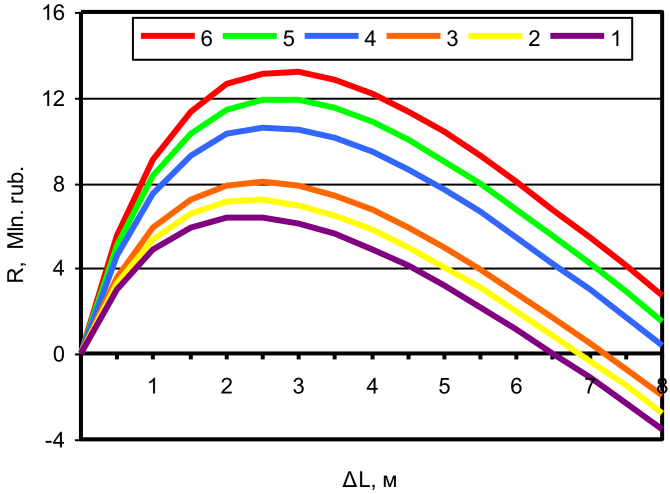

Fig. 2. Dependence diagram $R = f(\Delta L, b)$ where b = 2,4 rub/kWh and T = 10 years (bottom upwards): 1 – where i = 10% and non-change rate for electric power, 2 – where i = 10% and annual rate increase by 10 %, 3 – where i = 10% and annual rate increase by 20 %, 4 – where i = 2% and non-change rate for electric power, 5 – where i = 2% and annual rate increase by 10 %, 6 – where i = 2% and annual rate increase by 20 %.

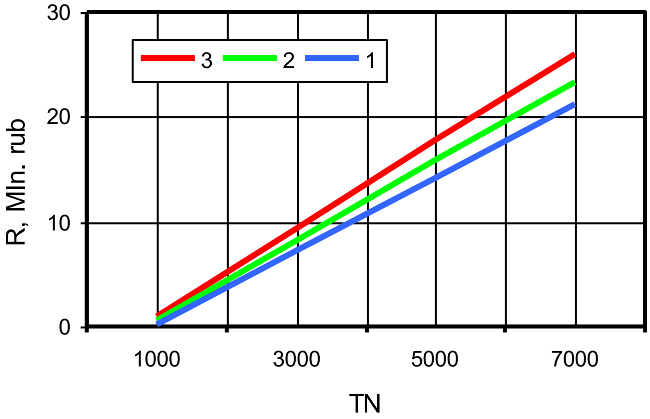

Fig. 3. Dependence diagram $\Delta L_{MAX} = f(i, b)$ where T = 10 years (bottom upwards): 1 – non-change rat e for electric power, 2 – annual rate increase by 10 %, 3 – annual rate increase by 20 %.

The authors conducted research about the influence of an important indicator of regime service conditions of hydroelectric power station – number of hours installed capacity use T_N on integrated economic effect. Fig. 4 shows dependence diagram of integrated economic effect on this parameter.

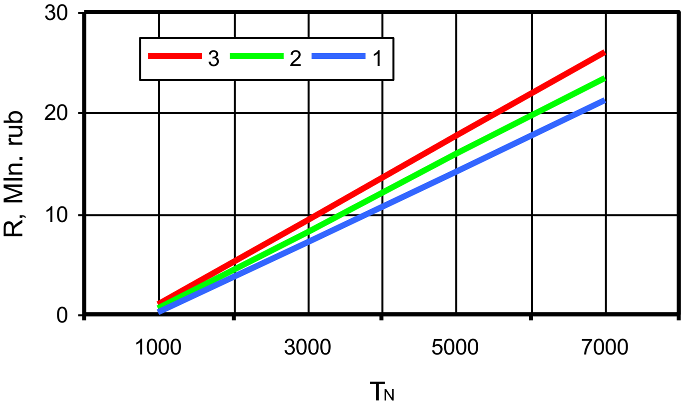

Fig. 4. Dependence diagram $R = f(T_N, i)$ for ΔL=2,5 where T = 10 years and non-change rate for electric power (bottom upwards): 1 – when the discount rate is equal to 4%, 2 – 6%, 3 – 8%.

The diagrams show that economic effect will considerably improve if number of hours of integrated capacity use increase for run-of-river power plants in case the optimal sizes of the intake pipe are identified. In the process of calculations the measure of an integrated economic effect where T_N = 7000 hours was defined as the sum of 21-26 million of rubbles.

4 Discussion

The received results have allowed defining optimal geometric parameters of the most important element of the water-conveyance system of run-of-river hydroelectric power plant – the intake pipe under modern economic conditions. The general view of the set of the constructed curves of dependence shows that initial increase of the intake pipe length causes firstly economic effect increase for the considered ranges of conditions change of hydro units operation. However, in case of further increase in dimensions of pipe costs of construction works begin to increase more intensively and economic effect decreases. Existence of an optimum of the varied parameter – length of the intake pipe proves the necessity of amending recommendations for the determination of the intake pipe length that tend to increase. The reason for dimensional underrating of water-conveyance system of run-of-river power plant is the determination to reduce the initial costs for power plant construction.

The results given in Fig. 4 mean that special attention should be paid to justification of dimensions of the intake pipes for the run-of-river hydroelectric power plants working in a semi-peak and peak zone of the diurnal behavior of energy load. A considerable economic effect of the intake pipe length increase can be gained under these conditions

It is also necessary to note that the calculated data is provided for quite short base period – 10 years. It takes significantly long time to operate power plants. It is obvious that the amount of economic effect significantly depends on the duration of the considered base period. So, increase during the base period from 10 to 20 years will lead to increase in economic integrated effect by 45-60%.

The obtained results will be of great importance for the correct choice of the basic geometric parameters of the elements of the water-conveyance system and can be used for the determination of the sizes of the intake pipes at the designed power plants.

5 Conclusions

The main conclusions of the research can be formulated as follows:

1. Feasibility of the main sizes of elements of water-conveyance system, including the elbow intake pipe in hydroelectric run-of-river power plant, and the choice of their optimal parameters is of great importance for ensuring high overall performance of hydroelectric power station.
2. Length of the intake pipe regarded as recommended for the hydroelectric power stations which have been earlier constructed in Russian run-of-river power plant, can be considered as minimum admissible under the terms of normal operation of the hydraulic turbine now. Nowadays it is necessary to carry out technical and economic calculations for detection of viability of increase of this parameter and feasibility of its optimal value in each case in the design process of hydroelectric power station.

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