Environmental Aspects and Operation Mode of Small Hydropower

Josifs Survilo, *Riga Technical University*

Abstract **– The use of renewable sources must be balanced with environmental aspects. Especially it relates to the use of river water flow. Environmental requirements are hard to achieve on large hydropower. Much hydro is built and yet can be built on small rivers, usually building the dams which create small lakes and prevent movement of fauna along the river. In places of large inclination of river channel the dam can be substituted by water ducts, such as pipes. The flow of water in the pipe meets resistance to its movement and some part of water pressure is lost. There is little resistance to movement of water by laminar flow but this flow exists by small velocities. So it can be counted on turbulent flow. By a given diameter of pipe the maximum power can be get when 1/3 of the water pressure is used on water movement in the pipe. The cost of pipe by a given flow is proportional to the pipe length multiplied by the root of fifth degree of the pipe length. Artificial rapids can be made which reduce pipe length. Such a hydro must be connected to a grid. It operates in the rhythm of the river.**

Keywords **– Dam, efficiency, environment, small hydro.**

1. INTRODUCTION

The fuel shortage and its high prices become everyday topic. Developed countries not only speak about it but much do in this direction as well. However we must think not only about energy but about our surroundings as well. Wind farms create noise, pose a threat to birds, occupy land. Solar energy can be best used in arid arias. Geothermal energy is tied to specific regions of the earth. The same applies to the energy of water but rivers are more evenly distributed over the globe.

The disadvantage of hydroelectric power is a negative impact on the environment. This is mainly in the fact that, firstly, large territory is occupied by reservoirs, which continuously are filled with silt, secondly, the fauna cannot move along the river because the river is blocked by dams. Dams are also a danger to the surrounding area if they are not reliable [1]. To limit the area of the reservoir, the dam are built not only across the river but around the perimeter of reservoir as well. And here the question of cost should not be on the last place. But what to do? How to handle without dam? There is no alternative when the hydro plant must operate only in certain periods of time without losing energy of water. When generators are working, the reservoir is emptying, the rest of the time it is being filled. And we have two features: 1) the power plant operates at the right time, 2) all the water is used to produce electricity. If at least one property is not required to use, we shall try to do without the dam.

Most large rivers in the world are used to generate electricity. In Latvia, here remained only small rivers and the lot of them already harnessed. Some rivers flow through the national park and are not usable the useable way.

So here small hydro plants are to build which is friendly to the environment. Such a small rivulets as yet are enough and they can be more conveniently utilized at the east of the country where a hilly landscape is.

It is hard to determine how much energy can be used of small rivers from a given territory. Many factors affect the result. One can undertake construction only by weighing all the factors with the help of a qualified consultant.

II. THE WAYS OF UTILIZING THE WATER ENERGY

In order to turn a turbine, you need to pile up the water. This can be done in two ways: with help of the dam or through the penstock (pipe) (Fig. 1). Some water wheels do not require piling up water [2]. They draw power P from flowing water (Fig. 2) but their efficiency is small.

Recall the basic coherences of hydropower.

The pressure p of piled up water (N/m^2):

$$p = \gamma h\,, \tag{1}$$

where γ is specific weight of water (N/m^3), h is a head of water (m).

Generated by hydro plant power (W):

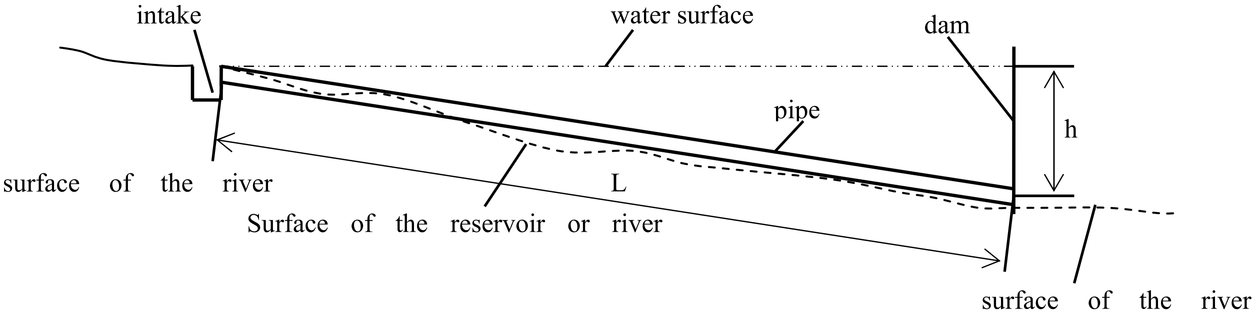

Fig. 1. Two versions of water heap up:1) building dam; 2) using tube

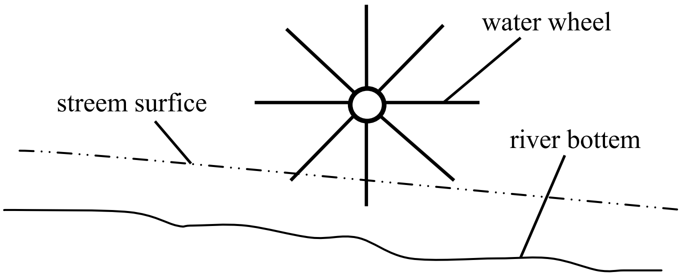

Fig. 2. Streem power utilized by water wheel

$$P = \eta \Delta p_e \Phi , \qquad (2)$$

where η is an efficiency factor, Δp_e is pressure drop for generation of electricity (N/m^2); Φ is rate of water flow through a turbine (m^3/s).

Here you can see an analogy with electrical circuit: Δp_e stands for voltage drop across a load, Φ stands for current in the load. Efficiency factor η describes the losses on the path from turbine entrance to the generator output. The difference between dam and pipe is that, when water is piled up in reservoir, p stands for Δp_e in (2), i.e. entire head is used for electricity production; in case of pipe only part of water head Δp_e can be used; the other part of the head Δp_p is necessary to push water through the pipe:

$$p = \Delta p_e + \Delta p_p . \qquad (3)$$

If we assign useful factor k to part Δp_e of entire pressure p

$$\Delta p_e = kp , \qquad (4)$$

then

$$\Delta p_p = (1-k)p . \qquad (5)$$

And overall efficiency factor, observing (2) and (4), is:

$$\eta_{oa} = k\eta . \qquad (6)$$

The pressure used to push water through the pipe, by analogy with electrical circuit, is:

$$\Delta p_p = R_h \Phi , \qquad (7)$$

where R_h is resistance to water flow through the pipe (kg/(m^4·s).

Δp_p; R_h and Φ are analogous to ΔU; R and I (voltage drop, electrical resistance and current respectively).

The power drawn from the water stream by water wheel (Fig. 2) is [2]:

$$P = (1/2)\kappa_{ww} \Phi v^2 , \qquad (8)$$

where v is the speed of water (m/s); κ_{ww} is coefficient including density of water and efficiency of water wheel (kg/m^3). The efficiency of water wheel is low and this version further is not considered.

3. PENSTOCK INSTEAD OF DAM

To eliminate the shortcoming of dam, it should be tried to use the penstock (pipe). The water flowing in the pipe is subjected to resistance R_h against its flow. The water flow in completely filled pipe can be of two ways: laminar and turbulent [3]. In larger velocities it is turbulent, in small ones it is laminar. The Reynolds's number Re [4] (non-dimensional quantity) determines what type of flow we have:

$$\mathrm{Re} = \frac{vD_p}{\nu} , \qquad (9)$$

where v is speed of water (m/s); D_p is internal diameter of a pipe (m); and ν is water kinematic viscosity (m^2/s), for water at 10° C $\nu = 1.307 \cdot 10^{-6}$.

At Re < 2300 flow of liquid in pipe is laminar, otherwise it is turbulent.

Laminar flow

The laminar flow is described by Poisuille's law [5]:

$$\Phi = \frac{\Delta p_p \pi D_p{}^4}{128 \mu L} . \qquad (10)$$

where μ stands for dynamic viscosity (Pa·s i.e. N·s/m^2), for water at 10° C μ is $1.307 \cdot 10^{-3}$, L is pipe length (m).

Resistance to laminar water flow, observing (7), is:

$$R_h = \frac{128 \mu L}{\pi D_p{}^4} . \qquad (11)$$

From (2), observing (4), (5) and (7) generated power (W) is:

$$P = \eta \frac{p^2 (k - k^2)}{R_h} . \qquad (12)$$

Optimizing generated power, we find that it is maximum by

$$k = 0.5 ; \ \Delta p_e = \Delta p_p \qquad (13)$$

and maximum power is:

$$P_{\max} = \eta \frac{p^2}{4R_h} . \qquad (14)$$

It means that, by given flow resistance R_h, maximum power is generated when half of the water pressure is spent on water pushing through the pipe and other half – on electricity generation.

Here we again have analogy with electrical circuit: the maximum power can be drawn from the emf source when internal resistance of the source is equal to load resistance [6].

To know what movement of water can be practically reckoned with, we shall consider the diameter of pipe which is necessary to push water flow rate Φ through in laminar flow. Water mean velocity at a given flow rate Φ can be expressed as:

$$v = \frac{4\Phi}{\pi D_p{}^2} . \qquad (15)$$

Based on (9) and (15) we obtain an expression for the pipe diameter by which laminar flow still exists:

$$D_p \geq \frac{4\Phi}{\pi \nu \,\mathrm{Re}} . \qquad (16)$$

At flow rate, for example, 1 m^3/s the pipe diameter should be $D_p \geq 424$ m. This figure excludes laminar flow from consideration and further only turbulent flow is considered.

Turbulent flow

Turbulent flow is described by Darcy – Weisbach [7] equation:

$$h_p = f\frac{Lv^2}{2gD_p}, \quad (17)$$

where h_p is head loss to push water through pipe; f is Darcy – Weisbach friction factor called also Moody friction factor (non-dimensional quantity); g is free fall acceleration (m/s^2); v is average velocity of water flow (m/s).

The Darcy – Weisbach friction factor f can be calculated in several ways but for actual purpose, it is more convenient to use Moody Diagram (Fig. 3) [8] which shows factor f plotted against Reynolds number Re for various relative internal roughness ε/D_p (ε is roughness of pipe internal surface).

Pipe water head h_p in accordance with (1) is:

$$h_p = \Delta p_p / \gamma . \quad (18)$$

Water specific weight γ can be expressed through water density ρ:

$$\gamma = \rho g , \quad (19)$$

where ρ is water density (kg/m^3), ρ=1000.

Then, observing (15), water flow rate can be determined so:

$$\Phi = \pi\sqrt{\frac{D_p^5\Delta p_p}{8f\rho L}} = \pi\sqrt{\frac{D_p^5}{8f\rho L\Delta p_p}}\Delta p_p \quad (20)$$

and resistance to turbulent water flow is:

$$R_h = \frac{1}{\pi}\sqrt{\frac{8f\rho L\Delta p_p}{D_p^5}} = \frac{2f\rho Lv}{\pi D_p^3}. \quad (21)$$

By turbulent water flow resistance grows with pressure drop Δp_p. This complicates the matter.

If we want to have given water flow in a pipe by some pressure Δp_p than, observing (5), internal pipe diameter should be:

$$D_p = \sqrt[5]{\frac{8f\rho L\Phi^2}{\pi^2(1-k)p}} . \quad (22)$$

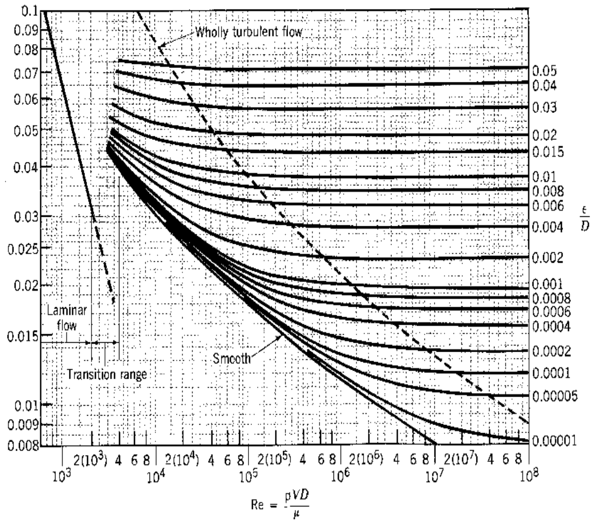

Fig. 3. The Moody Diagram

Generated power can be defined based on (2), (4); (5) and (20):

$$P = \eta\pi kp\sqrt{\frac{D_p^5(1-k)p}{8f\rho L}} = \eta\pi\sqrt{\frac{D_p^5p^3}{8f\rho L}}\sqrt{k^2-k^3} . \quad (23)$$

Optimizing, we find that maximum power, using pipe of diameter D_p and sufficient river flow, is by

$$k = 2/3 . \quad (24)$$

Maximum power and optimum water flow are:

$$P_{\max} = 0.4275\eta\sqrt{\frac{D_p^5}{f\rho L}}\sqrt{p^3} ; \quad (25)$$

$$\Phi_{opt} = 0,6413\sqrt{\frac{D_p^5 p}{f\rho L}} . \quad (26)$$

The overall efficiency factor according to (6) and (24) is:

$$\eta_{oa} = (2/3)\eta . \quad (27)$$

If maximum power P_{max} is given, the diameter must be:

$$D_p = 1,40485\sqrt[5]{\frac{f\rho LP_{\max}^2}{\eta^2 p^3}} . \quad (28)$$

But to increase the overall efficiency factor, it is necessary to increase useful factor k which entails pipe diameter D_p increase (see (22)).

Pipe diameter is proportional to the root of fifth degree of pipe length.

At a given flow rate Φ and other input data from (22) we can find necessary pipe diameter. Friction factor f complicates the task. It is necessary to know internal roughness ε of the pipe. Pipe diameter can be found in several rounds. Before calculations, the first more or less suitable value of the friction factor must be assumed. With each subsequent round the result is more accurate.

Calculation procedure is explained by following example. The necessary data for small river and 100 kW hydro are given: optimum (maximum) power P_{max} 100 kW; water density ρ=1000 kg/m^3; pipe length L=30 m; efficiency factor η=0,8; water head 3 m; pipe made of concrete, internal roughness ε=0.3 mm. The first value of friction factor is assumed f=0.02. By (1) and (19) water pressure p=29430 N/m^2; by (28) pipe internal diameter D_p=1,15 m; by (26) optimum flow rate Φ_{opt}=6.371 m^3/s; by (15) water mean velocity v=6,132 m/s; by (9) Reynolds's number Re=5.4·10^6; calculated ε/D_p=2.61·10^{-4}; from Moody diagram friction factor f=0.0145. With this value of friction factor we make the second calculation round an find that D_p=1.078 m; ε/D_p=2.78·10^{-4}; Re=5,75·10^6. The data are almost the same as the first ones and further calculations are unnecessary.

It is tempting idea of design tricks to reduce the resistance to water movement in the pipe as it does the dolphins to increase the speed of movement in water.

The water flow in a river is unstable [9]. In small rivers it is even more volatile. On what flow to calculate the pipe, decides the person concerned. In any case, you must reckon with the fact that sometimes the stream will be maximum and then to get the maximum power at this flow, formulas (22); (24) should be used. When water flow decreases the useful factor k increases. The pipe must be permanently filled with water and by smaller water flow rate h_p decreases and useful factor k grows. The pipe flow is maintained so that portion of river stream goes on its natural course.

Such an operation algorithm involves the use of appropriate turbine. It would be more economical if the plant would work with the same turbine efficiency at constant pressure (the pipe is filled fully all the time) but with varying flow rate.

The longer the pipe the more expensive it is and the greater the pressure loss. By unchanging pressure loss, pipe diameter is proportional to the root of fifth degree of pipe length L (see (22)). It means that the cost of pipe is approximately proportional to $L\sqrt[5]{L}$.

It is possible to decrease pipe length creating the artificial rapids on the river throwing in the river channel various heavy pieces at hand.

By comparison of dam cost and pipe cost taking into account the generated power at both versions (dam and pipe), one can see whether it is necessary to compensate environmental expenses.

It is time to pay attention to the special feature of the use of pipe. The dam is missing and there is no accumulation of water. The electricity generation is tied to river flow. And it means that **such a hydro must be connected to a grid** and operation mode is that of **generation in the rhythm of the river**.

In return, river isn't blocked by the dam.

4. CONCLUSIONS

1. Building the small hydro using the pipe instead of dam satisfies environmental aspects.
2. Theoretically such hydropower using the pipe instead of dam is possible on other rivers, however practically the expenses on pipe should be taken into account.
3. Efficiency of pipe hydro is smaller than the dam hydro since part of water pressure is lost in the pipe.
4. Hydraulic resistance of laminar flow is constant but that of turbulent flow grows with water flow mean velocity.
5. By turbulent flow generated power does not grow so fast with pressure of water as it would be by laminar flow.
6. Pipe hydropower must be connected to a grid and its operation is in the rhythm of river flow.

7. REFERENCES

[1] N. Sparw, J. Sällfors, *Cracks in hydropower concrete structures – a study at the Uri Hydroelectric Power Project*. Jammu & Kashmir state, India, Chalmers Tekniska Högskola Institutionen för Byggnadsmaterial, 1995, pp.9 – 13.

[2] Calculating the amount of available power, http:en.wikipedia.org/wiki/Hydropower.

[3] Laminar and turbulent flow of fluids, http://www.scribd.com/doc/27113441/Laminar-Flow-and-Turbulent - Flow-of-Fluids.

[4] Reynolds number, http://en.wikipedia.org/wiki/Reynolds_number.

[5] Hagen – Poiseuille equation, http://en.wikipedia.org/wiki/Hagen%E2%80%93Poiseuille_Equation.

[6] K.Tabaks, "Elektrotehnikas teorētiskie pamati. Stacionārie procesi lineārās ķēdēs", Rīga, "Zvaigzne", 1985, lp.51.

[7] Darcy – Weisbach equation, http://en.wikipedia.org/wiki/Darcy - Weisbach_equation.

[8] The Moody Diagram, http://biosystems.okstate.edu/darcy/DarcyWeisbach/MoodyDiagram.ht.

[9] J. Barkans, I. Zicmane, *Peculiarities of annual flows of world's rivers*. World Energy Council, 2005, pp.12 – 15; 67 – 210.

Josifs Survilo. Born in Kraslava, Latvia in 1936 March 26. PhD, defended in 1980 at the Urals Polytechnic Institute in the field "Power systems and the control of them ". Dr. sc. ing. earned in Riga Technical University, Latvia in 2001. After graduating from Riga Polytechnic Institute in 1960, 40 years worked as an engineer at the Riga works "Energoautomatika". Since 2000 working in Riga Technical University as a researcher.

Previous publications: J.Survilo. Specifics of electricity supply in loop network (Part1). Latvian Journal of Physics and Technical Sciences, No 2, pp. 34 – 44; 2012. J.Survilo. Nominal voltages of the networks (Part 2). Latvian Journal of Physics and Technical Sciences, No 5, pp. 3 – 15; 2011. J.Survilo, D.Antonovs, E.Bieļa. Non-uniformity impact of power losses in Kurzeme Ring project case. PQ 2012 8th International Conference 2012 Electricity Power Quality and Supply Reliability, Tartu, Estonia, June 16 – 18.

Address: Kronvalda 1, LV-1010, Riga.
Phone:+371 67089939,
E-mail:jahzeps@eef.rtu.lv.

Josifs Survilo. Mazo hidrostaciju vides aspekti un darba režīms

Atjaunojamo avotu izmantošanā jāievēro apkārtējās vides prasības. Sevišķi tas attiecas pie spēkstaciju būvēs uz upēm. Ūdens enerģija var būt izmantota ar lielāku lietderību, kad tas uz turbīnu tiek padots zem hidrauliskā spiediena, kas parasti tiek panākts ar dambja būvi. Būvējot lielas hidrostacijas, gandrīz nav iespējams ievērot vides prasības. Ietekme uz apkārtējo vidi notiek divējādi: 1) upju augšpusē pirms dambja tiek veidota liela ūdenskrātuve, kas pastāvīgi piesārņojas ar dūņām; 2) upe ir šķērsota ar dambi kas ietekmē ūdens faunu; pie tam dambja pārrāvuma gadījumā cietīs zemāk esošas teritorijas. Mazās upēs no dambja var atteikties, izmantojot tā vietā cauruli. Ja ir dambis, tad viss ūdens spiediens tiek izmantots elektrības ražošanai. Pie caurules izmantošanas daļa no ūdens spiediena ir vajadzīga ūdens plūsmai caurulē, kas samazina kopējo lietderības koeficientu. Laminārā ūdens plūsma caurulē nodrošina lielāko lietderību, pretestība ūdens plūsmai ir mazāka un nav atkarīgā no plūsmas ātruma caurulē. Pie noteiktā caurules iekšējā diametra (turpmāk – diametrs) maksimālo jaudu var iegūt kad ūdens spiediena puse tiek izlietota ūdens plūsmai caurulē un paliekošais spiediens elektrības ģenerācijai. Bet uz lamināro plūsmu nevar cerēt, jo tā iestājas pie ļoti mazām ūdens ātrumiem, kad Reinoldsa koeficients mazāks par 2300. Pie turbulentas plūsmas caurule izrāda lielāko pretestību, kura aug ar plūsmas ātruma palielinājumu. Caurules diametrs ir proporcionāls piektās pakāpes saknei no ģenerētas jaudas kvadrāta. Rēķinot caurules diametru, ir nepieciešams ievērot caurules iekšējas virsmas raupjumu; to var darīt izmantojot Mūdi diagrammu. Ģenerēta jauda ir proporcionāla kvadrātsaknei no ūdens spiediena trešajā pakāpē. Pie uzdotā caurules diametra maksimālo jaudu var ģenerēt, kad ūdens plūsmas radīšanai ir izmantota 1/3 no ūdens spiediena un pārējais uz elektrības ģenerēšanu. Maksimālā kopēja lietderība ir 2/3 no tās, kad ir dambis. Turbīnai jāstrādā ar labu lietderību pie pastāvīga spiediena, bet pie mainīgās ūdens plūsmas. Caurules cena ir proporcionālā mazliet vairāk nekā tās garums. Dabiskās vai mākslīgas krāces saīsina cauruli. Elektrības ģenerēšana ir piesieta pie upes plūsmas un spēkstacijai jābūt pieslēgtai pie tīkla; tās darba režīms saskan ar upes ritmu.

Иосифс Сурвило. Режим работы малых гидростанций в свете сохранения окружающей среды

Использование возобновляемых источников энергии должно учитывать требования окружающей среды. Особенно это относится к использованию рек для генерирования электроэнергии. Энергия воды может быть эффективнее использована, когда вода подается в турбину под напором. При строительстве больших электростанций почти невозможно соблюсти требования окружающей среды. На малых ГЭС дело обстоит иначе. Вред

окружающей среде наносится двумя путями: 1) большое водохранилище образуется с верхней стороны дамбы, которое постоянно засоряется илом; 2) река перегораживается дамбой, что воздействует на фауну реки и существует угроза нижележащей территории в случае прорыва дамбы. На малых реках от дамбы можно отказаться, вместо них применяя трубу. В обычных ГЭС (с дамбой) весь напор воды используется для генерирования электроэнергии. Труба же требует определенного напора для проталкивания воды в ней, тем самым уменьшая общий кпд. Ламинарный поток воды в трубе обеспечивает больший кпд, сопротивление движению воды меньше и не зависит от скорости воды. При данном внутреннем диаметре в дальнейшем – диаметр) трубы максимальная мощность может быть достигнута, когда половина напора воды затрачивается на движение воды в трубе, а вторая половина на генерирование. Но на ламинарный поток нельзя рассчитывать, так как он существует при очень малых скоростях воды, когда коэффициент Рейнольдса менее 2300. Турбулентному потоку труба оказывает большее сопрротивление, которое возрастает с увеличением средней скорости воды в трубе. Диаметр трубы пропорционален корню пятой степени из квадрата мощности. При расчете диаметра трубы необходимо учитывать шероховатость внутренней поверхности трубы, для этого можно использовать диаграмму Муди. Генерируемая мощность пропорциональна квадратному корню из напора в третьей степени. При данном диаметре трубы максималная генерируемая мощность наступает, когда на движение воды расходуется 1/3 напора, а остальное на генерирование. Максимальный общий кпд равен 2/3 от кпд электростанции с дамбой. Турбина должна работать с хорошим кпд при постоянном давлении воды, но при переменном потоке. Цена трубы пропорциональна немного более, чем ее длине. При естественных и искуственных порогах на реке длина трубы уменьшается. Генерирование электричества связано с количеством воды в реке, станция должна быть присоединена к сети, а режим работы – это генерация в ритме реки.