Overshot water wheel efficiency measurements for low heads and low flowrates

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Abstract. Utilizing of low renewable energy sources is an actual topic nowadays. This paper is focused on the locations with the low hydro-energy potential. It means locations with a head about 1m and flow rates about tens of litres per second. Hydro turbines for such parameters belong to the pico-turbines. It is not easy to design the hydro-turbine for such parameters with an acceptable efficiency. One of the possibilities is to use a water wheel. It is possible to find in a literature that the efficiency of overshot water wheels achieves 85%. This is the very good efficiency. It is not so easy to find some experimental data which proves this statement. Aims of this work are to design a simple manufactured overshot water wheel, measure the hydraulic efficiency of this wheel for wide range of parameters, finding an effect of the leading edge adjusting and the effect of the channel outflow edge position on the water wheel efficiency.

1 Motivation

A big effort has been expend to utilize renewable energy sources nowadays. The attention is not focussed only on big energy sources but also on a small one. It means the sources with the power of hundreds or tens of watts. These small sources can be very useful in case of remote residences without an electric grid. Moreover, the prices for the electric energy will grow more and more.

This paper is focussed on the water renewably energy. It is not so easy to design a water turbine for very small hydro energy potential with the high efficiency. There are number of different interesting solutions how to transfer the water energy to the electrical energy. One of the very interesting solutions is the bladeless water turbine SETUR [1]. This turbine utilizes very interesting flow phenomena Coanda effect to transfer water energy to mechanical energy but efficiency is very low for low hydro energy potential [2, 3].

Another possibility to utilize this low hydro potential is using a water wheel. Water wheels were used to transfer the water energy into the mechanical energy for many years. Many water wheel types, for different flow conditions, were developed and tuned to obtain maximal efficiency. These wheels have rather complex shape of blades and its production is not easy. But the efficiency is rather high. Well designed water wheels can reach efficiencies 75% (undershot) to 85% (overshot) [4].

The water wheels are processing mainly potential energy of water (Overshot), but some of them are designed to process a kinetic energy (Undershot) [5].

The only problem, to produce electric energy, is low speed of the water wheels. It is necessary to use a gearbox.

Many do-it-yourself men made different constructions of simple water wheels but no one measure its efficiency.

The water wheel, which can be produced easily, was designed in our department. Many parameters, which affect the efficiency, got into the experiment preparation. There was build the tests ring in our laboratory for basic characteristics water wheel measuring.

2 Water wheel design

The basic design idea was to make buckets of the water wheel from the pipe. The quarter of pipe was cut off. These buckets are then squeezed between two plastic circular discs. This construction allows an adjustment of the bucket leading edge positions against the inlet stream. Water wheel and shape of the bucket is in the figure 1.

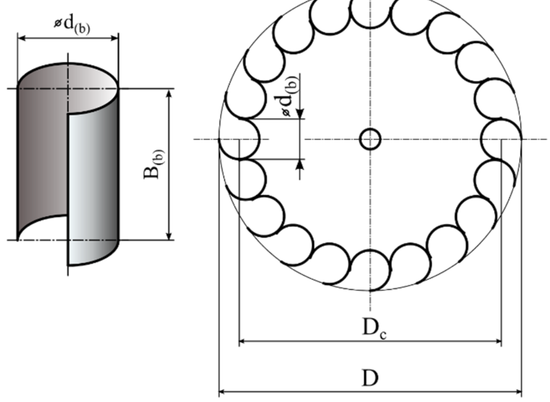

Fig. 1. Bucket and water wheel shape.

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Beside the easy bucket design, the idea was that this bucket shape allows processing not only potential energy but also the kinetic energy of the water stream. Basic wheel dimensions are in the next table

Table 1. Basic wheel dimensions.

Description	Label	Units	Value
Maximal wheel diameter	D	[mm]	900
Bucket centres diameter	$D_{(c)}$	[mm]	760
Bucket diameter	$d_{(b)}$	[mm]	140
Bucket width	$B_{(b)}$	[mm]	290

3 Experiment layout

Water wheel location and experiment layout is depicted in the figure 2. Water is flowing from a large container through rectangular channel. The end of the channel can be elongated. Than the water stream impacts water wheel buckets.

Some parameters are mentioned in the picture. Total head ($H_{(t)}$) is measured from the wheel bottom up to the water level in the container. If this total head is used for efficiency evaluation then the hydraulic losses in the channel are included into this value. The head H has to be taken for evaluation of the hydraulic water wheel efficiency.

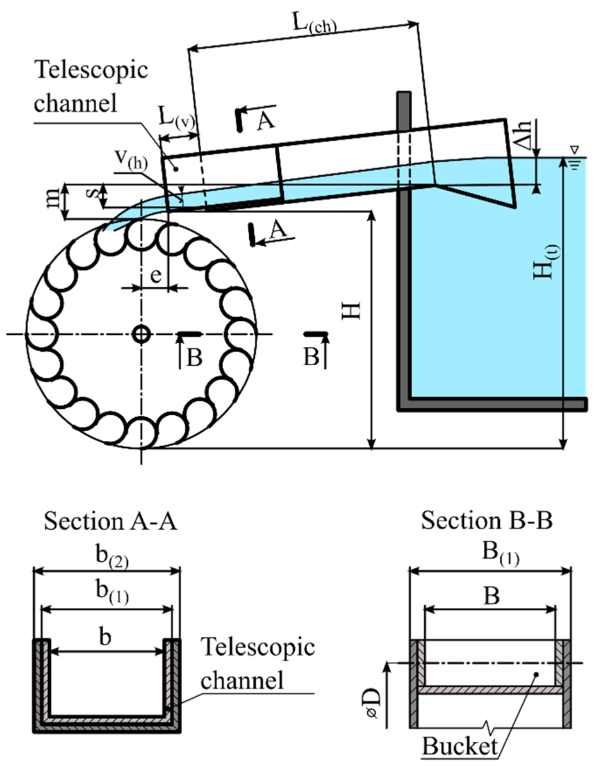

Fig. 2. Experiment layout.

A few words is necessary to say about the channel. The channel consists of two parts. One part is fixed and another part is movable. It allows the total channel length elongation. The length of the channel, it is better to say the location of the channel outflow edge, plays significant role in the water wheel efficiency. Length of the fixed channel part is signed as $L_{(ch)}$ and the channel elongation is signed as $L_{(v)}$. The difference of the inlet and outlet fixed channel edge altitudes is signed as *s*. The slope of the channel bed can be expressed as $s/L_{(ch)}$.

The difference of the water wheel top altitude and the inlet channel edge altitude is signed as *m*. The horizontal distance between water wheel axes and outlet channel edge is signed as *e*. The water depth near the channel outlet is signed as $v_{(h)}$. This is an important parameter for kinetic energy determining. The vertical distance of the water level in the tank from the inlet channel edge is singed as Δh.

4 Basic parameters measuring

Testing circuit has been built in the laboratory of Department of Fluid Engineering. The schema of this circuit is outlined in the Figure 3

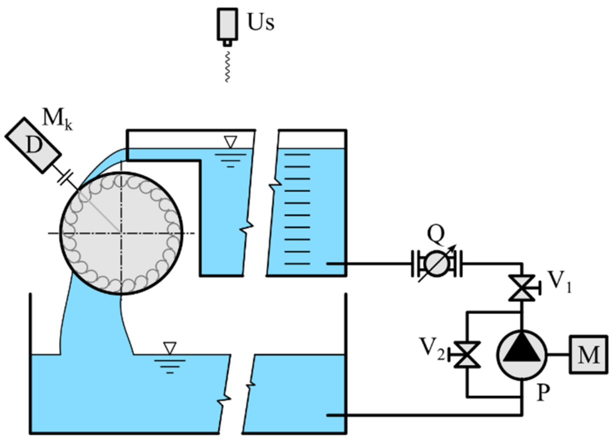

Fig. 3. Testing circle schema.

Feeding pump (P) delivers water from the suction tank to the upper tank. Then the water flows through a slates grid to calm the flow disturbances down. The channel, directing the water on the water wheel, is placed on the opposite side of the upper tank. The water falls down to the suction tank after it leaves the wheel. The fluid flow rate is controlled by the bypass equipped with two valves ($V_{(1)}$, $V_{(2)}$). The flow rate was measured by the magnetic flow meter (Q) DN 80 type MQI series 99 SMART (precision ±0.2% from the measured value). The horizontal water level position was measured by an ultrasonic water level sensor (Us) type 2HMU series 99 Smart (sensor capacity is 2m, precision is 0.8% from the capacity) . The speed of rotation and the torque on the wheel shaft was measured by the dynamometer (D). Torque was measured by torque measuring flange typeT10F HBM. Torque capacity is 50 Nm. Precision is 0.2% of this capacity. Wheel speed is measured by optical incremental sensor which is a part of the torque measuring flange. Precision is 0.1% of the setting capacity (3000 rpm).

All measured data were collected in the computer. All data were measured within 30 s time interval with the frequency 10 Hz. After that the average values were calculated.

Bolt with sharp end above water level was used for water depth measuring in the channel. The measurement was rather rough because of the water level waves. This measurement was done in two locations of the channel span and average value was then calculated.

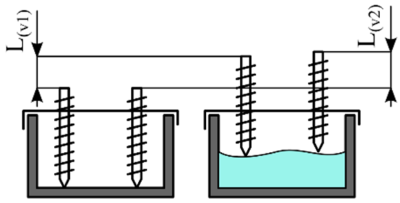

Fig. 4. Measuring of the water depth in the channel.

5 Measuring procedure

There are two adjustable parameters in this water wheel arrangement. First of them is bucket adjusting and second is horizontal position of the outflow channel edge. Bucket position labelling is outlined in the figure. 5. The value means the angel from the vertical axis.

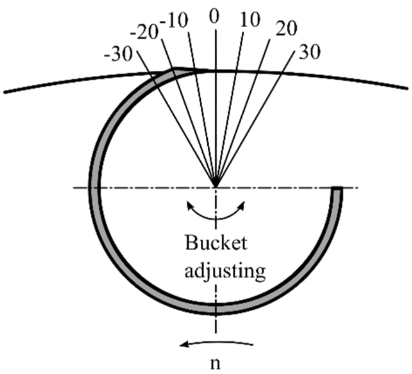

Fig. 5. Labelling of the bucket adjusting.

Two-bucket positions were tested 0 and -20. Labelling of the horizontal position of the outflow channel edge is outlined in the Fig. 6. Position value 0 means that the outflow channel edge is exactly in the water wheel axis. It means that the value of the channel edge position corresponds with the dimension *e* in the figure 2. All six-outflow channel edge positions were tested. Twelve configurations of bucket and outflow channel edge positions were tested. About ten different flow rates, in a range from 5 $l.s^{-1}$ to 25 $l.s^{-1}$, were tested for each configuration. Lower limit is set due to the flow meter precision and upper limit is set due to the safety overflow edge placed in the upper tank. The upper limit of flow rate was lower for some outflow channel edge positions because the water stream flowed behind water wheel. It means that part of the flow rate was not utilized. About eight different wheel speeds was set for each flowrate setting.

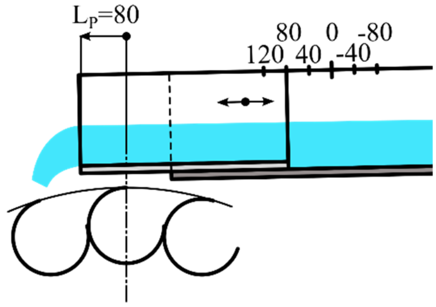

Fig. 6. Labelling of outflow channel edge position.

The wheel speed was set within the range 15 rpm to 65 rpm approximately. Lower limit was about 35 rpm for some high flowrates because the dynamometer torque limit was reached in these cases.

6 Basic expressions

The aim of these tests were to gather all data to be able calculate hydraulic water wheel efficiency and power on the wheel shaft and then find influence of bucket and outflow channel edge positions on them. Available input power can be calculated in two ways. The easiest one is to express it from the total head $H_{(t)}$.

$$P_{(int)} = \rho.Q.g.H_{(t)} \tag{1}$$

The efficiency value is slightly lower than in the next expression because including of channel hydraulic losses in the value. The different head value is taken into consideration in the next input power expression. The head (H) is measured as vertical difference between outflow channel edge position and the wheel bottom in this case. I is necessary to take into account kinetic energy of the stream into the input specific energy. Another expression for input power then is

$$P_{(in)} = \rho.Q.\left(\frac{v^2}{2} + H\right) \tag{2}$$

The kinetic energy of the stream is calculated from the average velocity (v) in the channel outflow. The hydraulic losses in the channel are excluded in this approach. The average velocity can be expressed this way.

$$v = \frac{Q}{b.v_{(h)}} \tag{3}$$

The only problem is in height of water in the channel as it is explained at the end of the chapter 4.

The expression (1) will be taken as the input power in this case.

The power on the wheel shaft can be calculated from the expression (4).

$$P_{(out)} = M_{(k)}.2.\pi.n \quad (4)$$

Speed of wheel is signed as n [s^{-1}]. Hydraulic efficiency ($\eta_{(h)}$) can be then calculated this way

$$\eta_{(h)} = \frac{P_{(out)}}{P_{(in)}} = \frac{M_{(k)}.2.\pi.n}{\rho.Q.\left(\frac{v^2}{2}+H\right)} \quad (5)$$

Another, maybe interesting, result is calculation of unit speed ($n_{(11)}$) – unit flow rate ($Q_{(11)}$) diagram. Unit speed can be expressed this way.

$$n_{(11)} = \frac{n.D}{\sqrt{H}} \quad (6)$$

It is a speed of imaginary wheel with diameter 1 m and operating under head 1 m.

Unit flow rate can be expressed similar way like in case of Banki turbine

$$Q_{(11)} = \frac{Q}{D.b.\sqrt{H}} \quad (7)$$

7 Results and discussion

It is impossible to show all obtained results, due to a huge number of measurements, here in this paper. Only some of them will be chosen to show them.

The results of efficiency will be discussed first. The input power was calculated from expression (1). If the expression (2) is taken into consideration then the efficiency is slightly higher.

The efficiency diagram for configuration bucket -20 and channel edge position is in the figure 7. The dots represent values obtained from the measurements. The lines represent polynomial approximation of the function between efficiency and wheel speed.

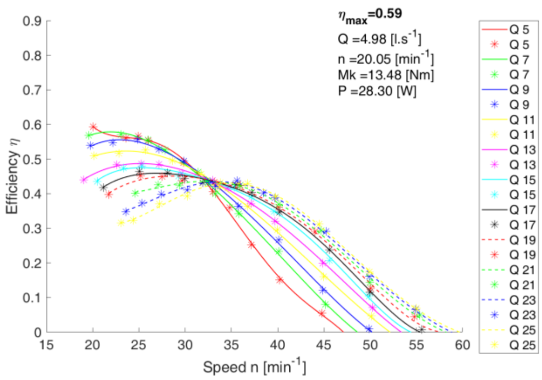

Fig. 7. Efficiency for configuration, bucket -20 and channel edge position -80 for different flow rates.

The number beside the Q (flow rate), in the diagram, means the rounded value of flowrate. Maximal efficiencies are reached for low flow rates and low speeds. The efficiency will be probably higher for lower wheel speeds. But it was difficult to do measuring below wheel speed 15 rpm due to high torque pulsations. And also low wheel speeds are not convenient for electricity production.

The efficiency diagram for configuration with total maximum efficiency of these tests is in the Figure 8. Total maximum efficiency was reached for configuration of the bucket 00 and channel position -40.

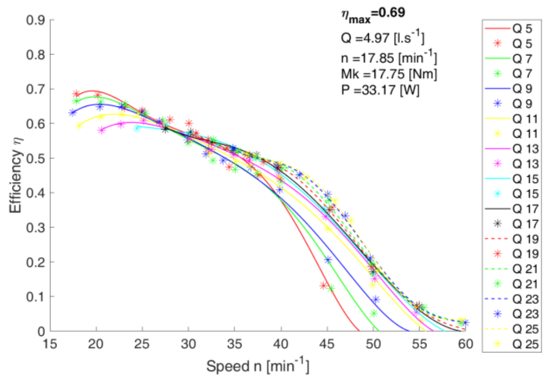

Fig. 8. Efficiency for configuration, bucket 00 and channel edge position -40 for different flow rates.

Basic parameters for maximal efficiency at each configuration are listed in the Table 2. Maximal efficiency for bucket configuration is signed by the grey background. It is apparent that the efficiency is higher for bucket configuration 00 in all cases of channel edge position.

Table 2. Basic parameters for maximal efficiency obtained at each configuration.

Configuration		η_{max}	Q	N	P
Buck	Chan	[-]	[$l.s^{-1}$]	[min^{-1}]	[W]
-20	**-80**	**0.59**	**4.98**	**20.05**	**28.30**
	-40	0.58	5.02	21.31	28.29
	0	0.55	6.84	23.66	36.92
	40	0.53	12.95	35.37	69.47
	80	0.53	9.00	40.03	47.18
	120	0.56	6.96	35.56	38.33
00	-80	0.66	7.00	20.63	45.29
	-40	**0.69**	**4.97**	**17.85**	**33.17**
	0	0.66	4.98	25.15	31.82
	40	0.65	5.02	25.78	31.86
	80	0.66	6.91	24.36	45.25
	120	0.66	6.98	34.76	45.18

The explanation is that the bucket in configuration -20 is more open and water is leaving the wheel prematurely. It is interesting that in the case of bucket configuration -00 the maximal efficiencies are reached under almost the same flow rates for each channel position and the efficiency does not variate so much too.

Different situation is in case of bucket configuration -20. The maximal efficiencies are reached under different flow rates and the difference between them is bigger.

The only problem with this measurements and results is with the dynamometer torque limit for the high flowrates. It is apparent from torque diagram for the total maximum efficiency configuration (bucket 00, channel position -40) in the Figure 9. It was not possible to decrease wheel speed due to torque limit. Probably the efficiency would not be higher but the power could be bigger. It will be discussed later.

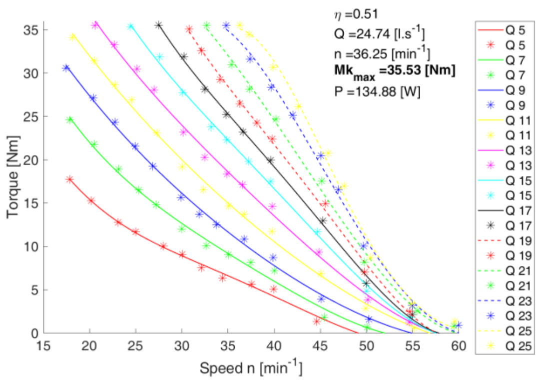

Fig. 9. Torque for configuration, bucket 00 and channel edge position -40 for different flow rates.

Now it will be useful to say a few words about efficiency. Maximum efficiency and maximum power do not correspond for given configuration. From the owner point of view is probably more important the output power then the high efficiency. Output power diagram for configuration bucket -20 and channel edge -40 is in the Figure 10. This is the case of maximal power for bucket configuration -20. The output power grows with the flow rate. Maximum output power is for flow rate 25 l.s^{-1}.

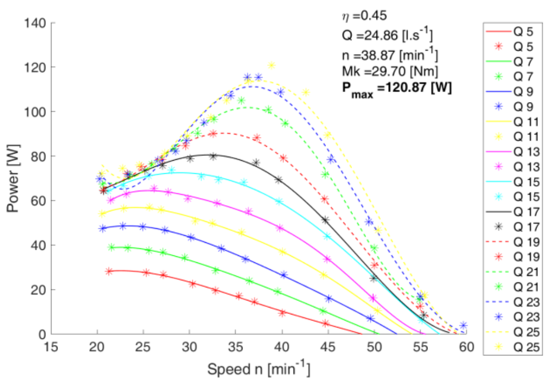

Fig. 10. Output power for configuration, bucket -20 and channel edge position -40 for different flow rates.

The wheel speed related to the maximal output power is higher than the wheel speed related to the maximal efficiency. The wheel speed related to the maximal power is about half of run away speed.

The power diagram for the maximal power for bucket configuration 00 is in the Figure 11. There is apparent influence of torque limit. If it is possible to measure with lower wheel speed then the maximum power will be probable higher. In this case the wheel speed related to the maximum output power will be shifted to the lower values than the half of run-away speed. In this case the wheel speed related to the maximum efficiency and the wheel sped related to the maximum power will be closer than in the case of bucket configuration -20.

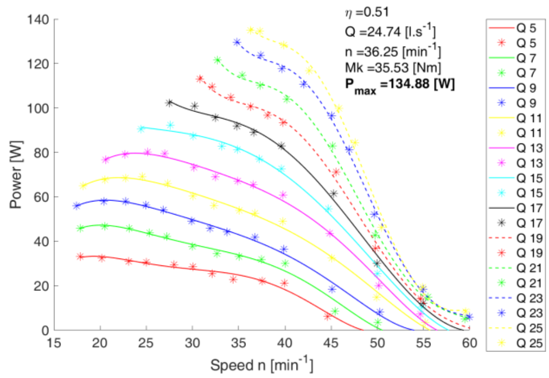

Fig. 11. Output power for configuration, bucket 00 and channel edge position -40 for different flow rates.

Table 3. Basic parameters for maximal output power obtained at each configuration.

Configuration		η	Q	N	P_{max}
Buck	Chan	[-]	[l.s^{-1}]	[min^{-1}]	[W]
-20	-80	0,43	24.89	33.79	114.47
	-40	**0,45**	**24.86**	**38.87**	**120.87**
	0	0,49	18,95	39.87	96.95
	40	0,48	14.94	34.85	73.56
	80	0,47	10.96	34.32	52.00
	120	0,56	6.96	35.56	38.33
00	-80	0.50	24.70	35.58	132.33
	-40	**0.51**	**24.74**	**36.25**	**134.88**
	0	0.58	18.93	34.91	113.78
	40	0.62	14.98	34.64	94.43
	80	0.65	11.08	35.18	71.59
	120	0.56	9.01	35.33	49.74

The basic parameters for maximum output power at each bucket and channel edge configuration are written in the Table 3. It is similar like in case of maximum efficiency. One can see that flow rate related to the maximal output power is strongly decreasing from the channel edge configuration 0, in both cases of bucket configuration.

Explanation is that the water stream is partially falling behind the wheel for these channel edge configurations (0, 40, 80, 120). It means that part of the flowrate is not utilized in the wheel. These channel edge configurations cannot be used for higher flow rates.

It is also necessary to say one note to the efficiency and output power. There was one problem with the water wheel and the channel design. The inner channel width is 235 mm and the inner wheel width is 271 mm. It is good that channel width is smaller than the wheel width but this difference is not sufficient. The water stream width is slightly bigger than the wheel width for high flow rates. It means that part of the flow rate is missing in case of high flow rates. If all water fall on the wheel then the power and efficiency could be slightly higher. 0

It is also interesting to draw the diagrams of unit speed (n_{11}) and unit flow rate (Q_{11}). The diagrams for three configurations are shown here. Two of them are for bucket configuration -20 with channel edge configuration -80 (Figure 12) and -40 (Figure 13) and one is for bucket configuration 00 and channel edge configuration -40 (Figure 14). These are chosen because the efficiency diagram or power diagram were aforementioned.

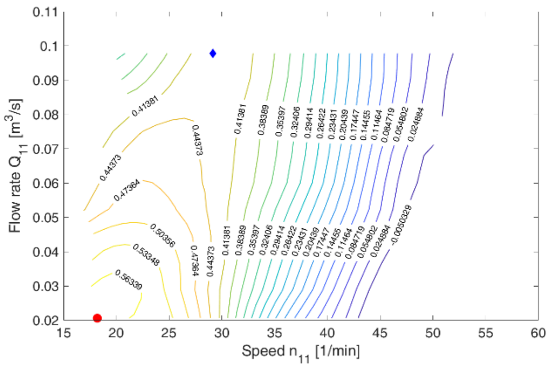

Fig. 12. Q_{11} n_{11} diagram for configuration, bucket -20 and channel edge position -80 for different flow rates.

The lines in the diagrams are the lines of constant efficiency. One can see that shapes of constant efficiency lines are oval. If this diagram is modelled in 3D then it is possible to see a ridge where efficiencies are rather high. The ridge sides are rather steep. It seems to be another local optimum of the efficiency in the diagrams Q_{11}–n_{11}. It rely happens in some other configurations.

It is apparent that some data due to torque limit are missing in the Figure 15. If one look carefully on this diagram then he can see that probably this is the case when the second local efficiency optimum will be there.

There are two dots in these three diagrams. Red circle dot shows point with the maximal efficiency and the blue diamond represents point with the highest output power.

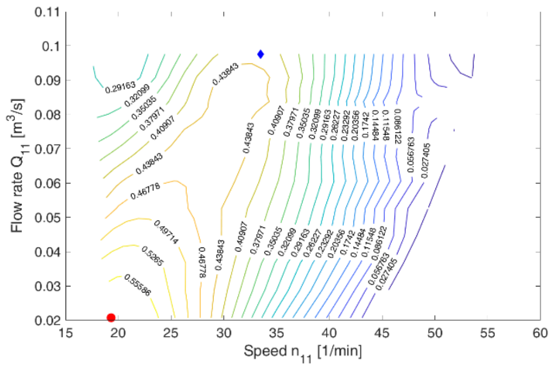

Fig. 13. Q_{11} n_{11} diagram for configuration, bucket -20 and channel edge position -40 for different flow rates.

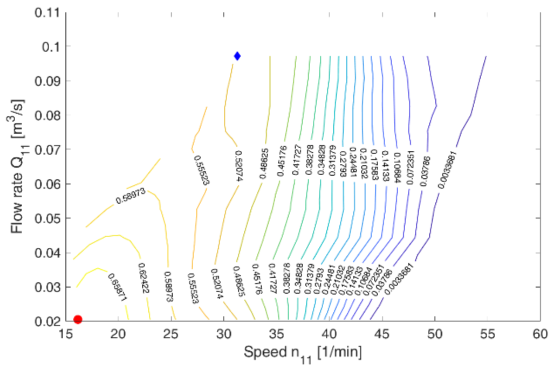

Fig. 14. Q_{11} n_{11} diagram for configuration, bucket 00 and channel edge position -40 for different flow rates.

As it is possible to see and as it was already mentioned the highest efficiencies are obtained for low flowrates and low wheel speeds. This is really interesting information in case of utilizing of hydro power sources with low potential.

8 Conclusion

The overshot water wheel with cylindrical buckets was tested and some results were presented in this paper. Advantages of this wheel type are in its easy production and possibility of bucket adjusting. Tested water wheel is in the figure 15.

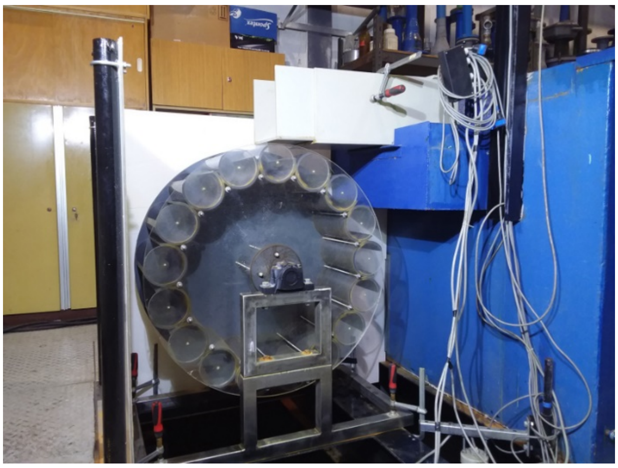

Fig. 15. Tested water wheel.

Measurement results for two bucked configurations (-20, 00) and for six horizontal channel edge configurations (-80, -40, 0, 40, 80, 120) were presented here. Basic water wheel parameters were measured for about ten different flow rates, within the range 5-25 $l.s^{-1}$, and for about eight different wheel speeds, within the range 15rmp-run away speed, for each water wheel configuration. It was found that the hydraulic efficiency maximum and the output power maximum were obtained for the bucket configuration 00 and the channel edge configuration -40. The efficiency was calculated as the total efficiency it means that the head was measured as a distance between the wheel bottom and the water level in the upper container. The maximal efficiency value was 0.69, which is not bad for such small water wheel. The maximal output power was 135 W. The output power maximum was influenced by the dynamometer torque limit so it means that it would be probably higher.

There are some reserves in the efficiency maximum and output power maximum due to some volumetric losses. Part of the flow rate flowed beside water wheel. It is shown in the Figure 16.

Fig. 16. Volumetric losses for high flow rates.

Possible improvements are as follows

- minimize losses in the channel
- minimize volumetric losses

How to decrease hydraulic losses in the channel? The flow in the channel is supercritical, it is apparent from the Figure 17. Supercritical flow means that there are high velocities and the self-induced waves are generated. The hydraulic losses in this flow case are rather high. If the subcritical flow will be reached then the losses will be lower.

The subcritical flow can be reached by placing a sluice gate at the channel end, which drives the flow on the water wheel.

What about the volumetric losses decreasing? These losses can be decreased by the channel outflow adjusting or by the wheel width increasing.

What about the future research? The ways of future research are as follows

- Performance of tests with more bucket configuration, mainly positive bucket positions (10, 20 …)
- Channel with the sluice gate at its end testing.
- Testing water wheel with different bucket diameters, higher and lower diameter.
- Testing the water wheel for bigger vertical distance of the channel outflow edge.

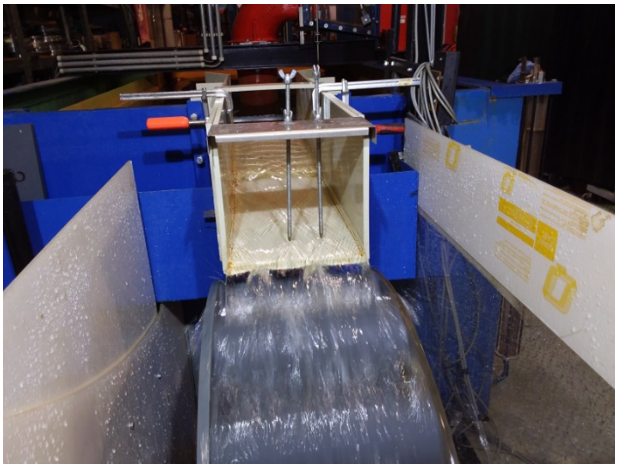

Fig. 17. Supercritical flow in the channel.

It is necessary to continue with the experiments to understand how all configuration parameters affect efficiency and output power. It was found that the bucket position 00 is better than the position -20 generally. Now more closed buckets will be tested, it means position 10 or 20. The water will not be poured out of the buckets easily but it is possible that some water stays in the bucket behind the lowest position and it means that this water will acts against the wheel rotation.

Next way will be testing modified channel with the sluice gate at the channel end. This will bring two advantages first, the hydraulic losses decreasing in the channel and second, the better flow stream regulating. There is one more parameter to be tested at the end. This is a diameter of the buckets under the constant wheel diameter. It is expected that it influences the flow rate which will be related to the maximal efficiency. It means that the wheel with the smaller bucket diameter will have maximal efficiency under lower flow rates. The wheel with bigger bucket diameter will probably have maximal efficiency under higher flow rates. This is only assumption and it is necessary to prove it.

The tests with the vertical channel outflow edge position could be interesting to carry out. In this case the channel outflow edge was placed as close as possible to the water wheel. It means that main energy transfer was from the potential water energy to the mechanical energy. When the channel outflow edge will be placed with bigger vertical distance then the transfer of kinetic energy to mechanical energy will play more dominant role.

Final summary of this work is that the water wheel of this construction is easy to make and the efficiency is rather big for the low heads and low flow rates. It is suitable for the remote residences due to its simplicity and high efficiency.

This research was financially supported under the project “Multiphysical problems of fluid mechanics “, number: FSI-S-17-4615.

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