

MEASURING STAND TESTS OF A MICHELL-BANKI WATER TURBINE PROTOTYPE, PERFORMED UNDER NATURAL CONDITIONS

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Abstract

The article presents the result of tests of a single segment of a prototype water turbine, performed in order to determine its shaft power output as a function of rpm, and to verify the declared performance. The results have been compared with the outcomes of numerical calculations performed, for the same conditions, with the use of FLUENT software. The work presents information of crucial importance for presenting the process of testing the piece in question, such as: test environment, properties of the test piece, testing equipment used, as well as the methodology and the course of hydromechanical measurements, along with the characteristics of the results obtained. Then, the measurement results are discussed and analyzed. Conclusions are presented as well. Analysis of the results, taking into consideration the physical image of phenomena occurring in the case of flow-devices, such as water turbines, has made it possible to define other, important characteristics of the turbine, such as: output, shaft torque and efficiency, as a function of rpm and head of turbine. Test results have confirmed the expected mechanical and power-related properties of the turbine and have proved the numerical flow modeling model used effective.

A brief description of the prospects concerning new applications of the turbine discussed has been presented as well.

Keywords: turbine geometry, hydromechanical measurements, water head, shaft power output, flow rate, turbine efficiency.

1. INTRODUCTION

In September and October 2010, tests were performed at the dam in Białobrzegi Radomskie, on the river of Pierzchnianka, a tributary of Pilica, involving a 1:1 model of a single segment of the prototype Michell-Banki turbine [1].

The tests were aimed at both conducting a qualitative assessment of the turbine's behavior under natural water flow conditions, and at performing quantitative measurements of the turbine's energy-generating characteristics. The tests provided also the opportunity to verify the expected and declared properties of the turbine, and have allowed to once again (after tests of the 1:5 scale model performed in 2008 and discussed in [2,3,6]) to validate the CFD numerical method (FLUENT software), as presented in [4,5], and involving calculations for the 1:5 model of the turbine. The prototype turbine was made in cooperation with a project's partner – Darek&Co of Augustów. The test stand, in turn, along with the measurement and energy generation systems was designed and assembled at the Institute of Aviation. The tests were financed under a Specific Project of the ten Ministry of Science and Higher Education No. 6 ZR6 2006 C/06825, pursued between 2008 and 2010.

2. TEST PIECE AND MEASUREMENT CONDITIONS

2.1. Description of the turbine tested

A prototype turbine with the rotor (Fig. 2) positioned in a plywood housing (Fig. 5) has been tested. During the tests, the geometry of the housing, and especially of the intake and discharge portions, was modified compared to the model as the plywood design has to be simplified due to technical considerations, and due to the manner in which the turbine was positioned on the test stand.

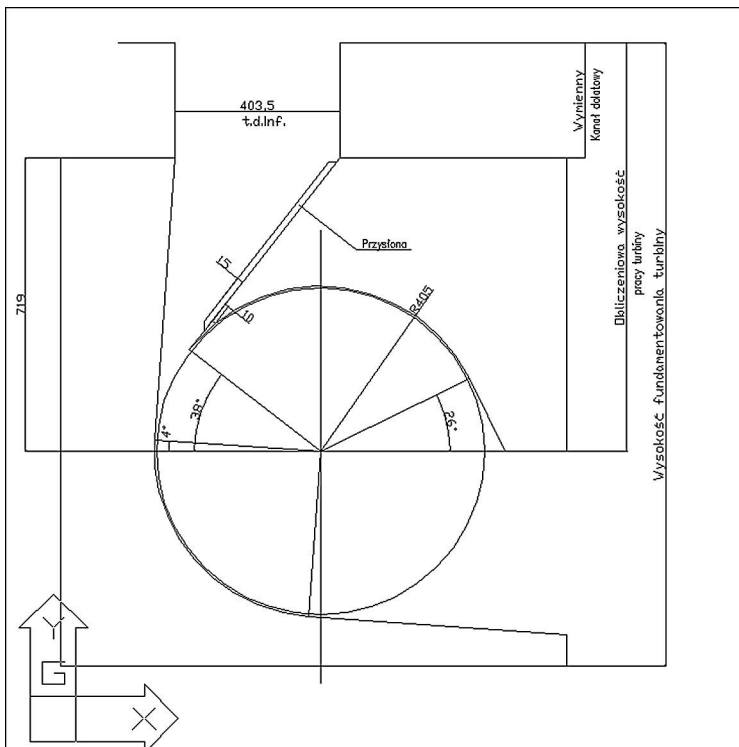


Fig. 1. Geometry of the prototype turbine tested [Grzegorz Nadłonek, 2010]

A simple (triangular) cross-section of the intake, and a horizontal discharge section were used in the prototype turbine. The geometry used is presented in Figure 1. Calculations pertaining to such a housing geometry, made with the use of FLUENT software and presented in [5] have failed to identify considerable differences in the turbine's characteristics, compared to the previous geometry



Fig. 2. Turbine rotor, installed [Włodzimierz Sawicki, 2010]

2.2. Test stand description

The test stand presented in Figures 3-5, of the bridge design, with the following elements installed: turbine, electricity generation system and measurement system, is made up of three parts: electricity generation and measurement section (upper), turbine section (middle) and base section (lower) mounted on the bottom, fully or partially submerged under the water level.

The main elements of the tests stand, with the generator system and a single turbine segment installed, include the following:

- 1 – power generation and measurement section
- 2 – turbine section
- 3 – base section
- 4 – power generator driven by a 1:13 gear
- 5 – rotational speed measurement point
- 6 – 1:1 chain drive connecting the turbine and the generator
- 7 – one turbine segment in a housing

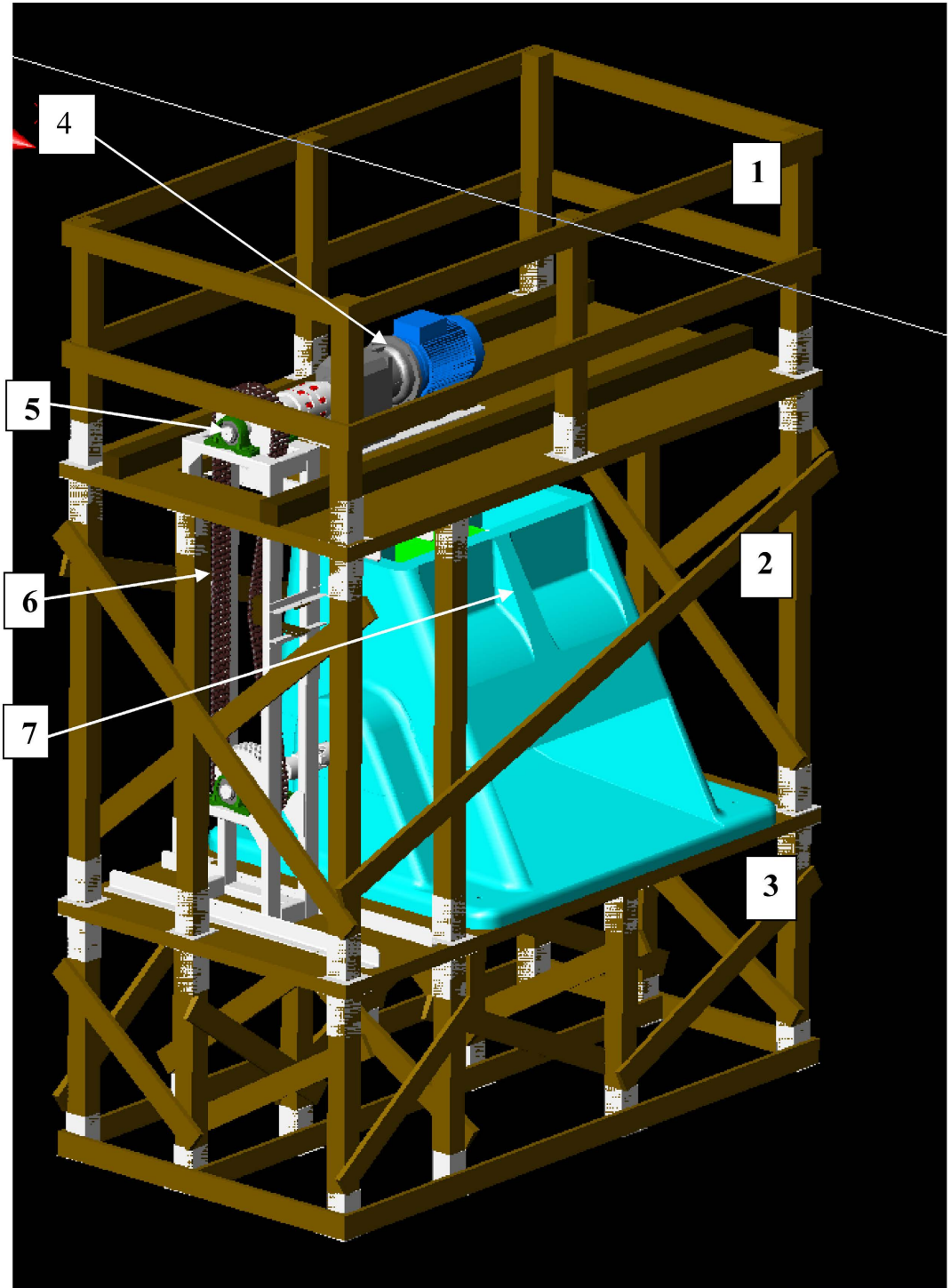


Fig. 3. Test stand diagram [Grzegorz Nadłonek, 2010]



Fig. 4. Electricity generation section with electrical system elements [Włodzimierz Sawicki, 2010]



Fig. 5. Complete test stand, with a turbine enclosed in plywood housing, installed at the dam [Włodzimierz Sawicki, 2010]

The tree-phase current measurement system installed at the test stand is presented in the diagram below:

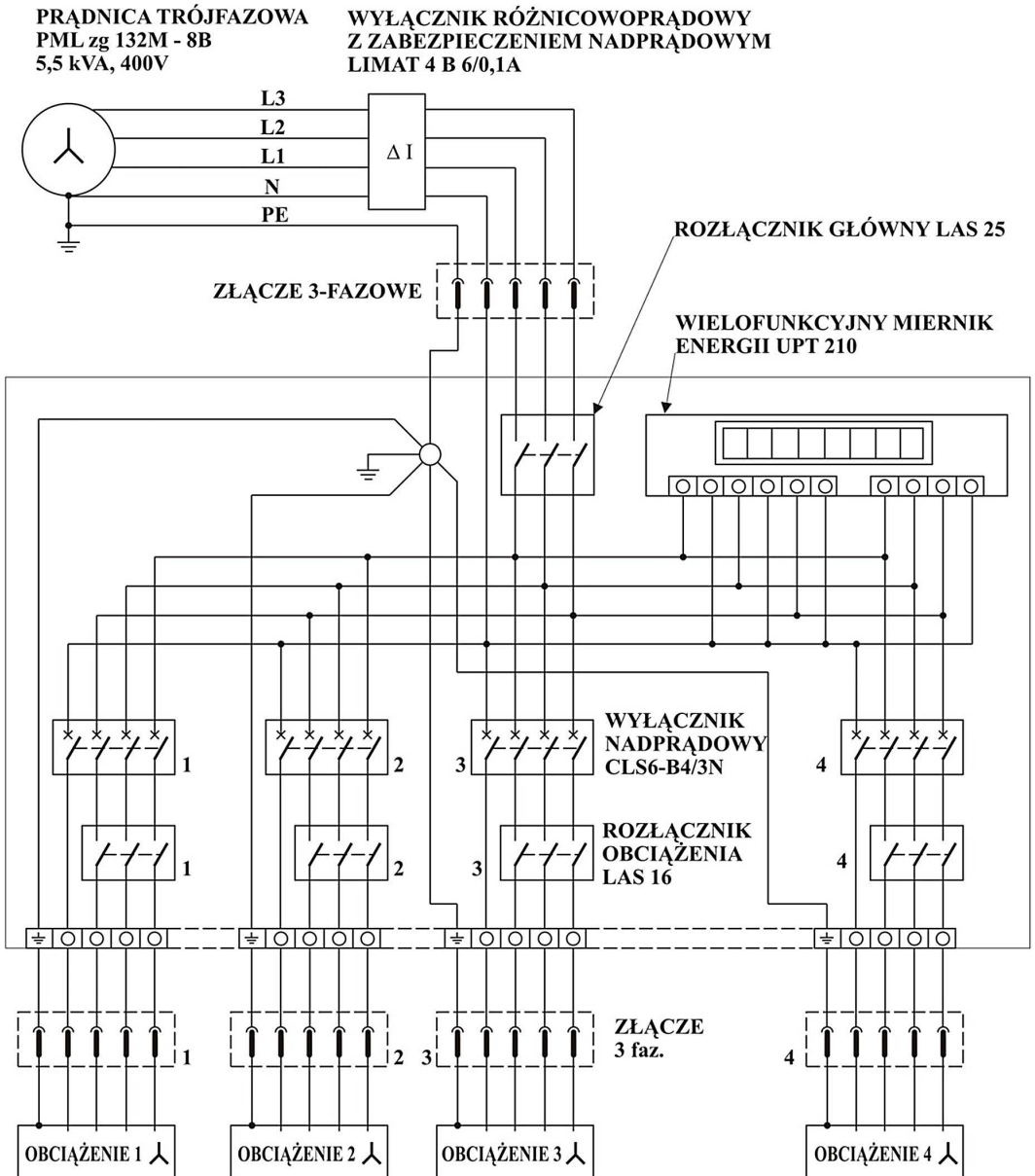


Fig. 6. Electrical measurement system diagram [Jan Dziupiński, 2010]

2.3. Measurements – conditions and procedure

The measurements aiming to determine the power characteristics of the turbine-powered generator, i.e. the electric power, have been conducted with fully opened water inlets, for two head values: 1.5 m and a head of between 1 and 1.5 m, hereinafter referred to as $1.0 < \mathbf{H} < 1.5$ m. Several measurement sequences have been performed, with two of them considered to be reliable (one for each head). The remaining sequences have been rejected due to difficulties encountered while attempting to ensure a sufficient water flow rate, or due to foreign objects stuck near the turbine's propeller and hampering its movement.

Specific electrical power characteristics have been determined by reading voltage \mathbf{U} and current \mathbf{I} values of one current phase at the generator's output, and by reading the turbine's rotational speed under different generator loads \mathbf{P}_{obc} induced by 750 W resistors any by the set of three light bulbs with the power rating of 150 W each. The maximum rotational speed of the turbine \mathbf{n}_{max} without any load has been read as well. Rotational speed readouts have been made with the use of the Lutron DT-2236 tachometer (Fig. 7).



Fig. 7. Rotational speed measurements [Włodzimierz Sawicki, 2010]

3. MEASUREMENT RESULTS

The measurement results for head values of 1.5 m and $1.0 < \mathbf{H} < 1.5$ m, qualified for further analysis, are presented in the table below:

The diagrams (Fig. 8 and 9) present the power \mathbf{P}_p readouts obtained at various rotational speed, expressed as:

$$\mathbf{P}_p = 3 \cdot \mathbf{U} \cdot \mathbf{I} \quad (1)$$

due to the fact that three-phase current was generated, where \mathbf{U} and \mathbf{I} are readouts pertaining to one phase (the numbers of individual readouts are presented in Table 1 above. Then, the electrical power characteristics has been defined for all three phases, as the envelope of maximum electrical power ratings from the individual readout sequences, which envelope has been interpolated between zero

power points (for rotational speeds of $n = 0$ and n_{max}) and local maximum power points identified based on the measurements. With the efficiency of the elements of the system transferring the power from the turbine to the generator’s output, the turbine shaft power characteristics P has been defined, where, for the individual points of the characteristics:

$$P = P_p / \eta_p \tag{2}$$

The total efficiency of the power transfer system η_p has been adopted based on the data provided manufacturers of the individual components of the power transfer system:

$$\eta_p = \eta_e \cdot \eta_z \cdot \eta_l \tag{3}$$

where:

$\eta_e = 0.9$ – electrical system efficiency,

$\eta_z = 0.9$ – 1:13 sprocket gear efficiency,

$\eta_l = 0.85$ – 1:1 chain gear efficiency.

The overall efficiency of the system transferring power from the turbine to the generator output equals:

$$\eta_p = 0.9 \cdot 0.9 \cdot 0.85 = 0.6885 \tag{4}$$

Table 1. Measurement results [Wojciech Zdrojewski, 2010]

Head [m]		1.5				Head [m]		1.0 < H < 1.5			
Parameter Readout	P_{obc} [kW]	n [o/min]	U [V]	I [A]	Parameter Readout	P_{obc} [kW]	n [o/min]	U [V]	I [A]		
12.	0	105	0	0	21.	3x0.75 +3x0.45	32.5	143	3.4		
13.	3x0.75 +3x0.45	39.5	175	4.0	22.	3x0.75 +2x0.45	37.0	158	3.7		
14.	3x0.75 +2x0.45	44.0	193	4.4	23.	3x0.75 +1x0.45	40.5	180	4.1		
15.	3x0.75 +1x0.45	49.0	215	4.8	24.	3x0.75	47.0	208	2.8		
16.	3x0.75	54.0	243	3.2	25.	2x0.75 +3x0.45	37.0	165	3.2		
17.	2x0.75 +3x0.45	46.0	207	3.7	26.	2x0.75 +2x0.45	43.0	190	3.5		
18.	2x0.75 +2x0.45	52.0	230	3.9	27.	3x0.75 +1x0.45	49.5	220	3.9		
19.	3x0.75 +1x0.45	59.0	260	4.2	28.	2x0.75	57.0	258	2.3		
20.	2x0.75	65.0	295	2.6	29.	3x0.45 +0.75	45.5	205	2.8		
					30.	2x0.45 +0.75	53.5	240	3.1		
					31.	1x0.45 +0.75	62.5	280	3.5		
					32.	0.75	72.0	330	1.5		
					33.	0	97.5	0	0		

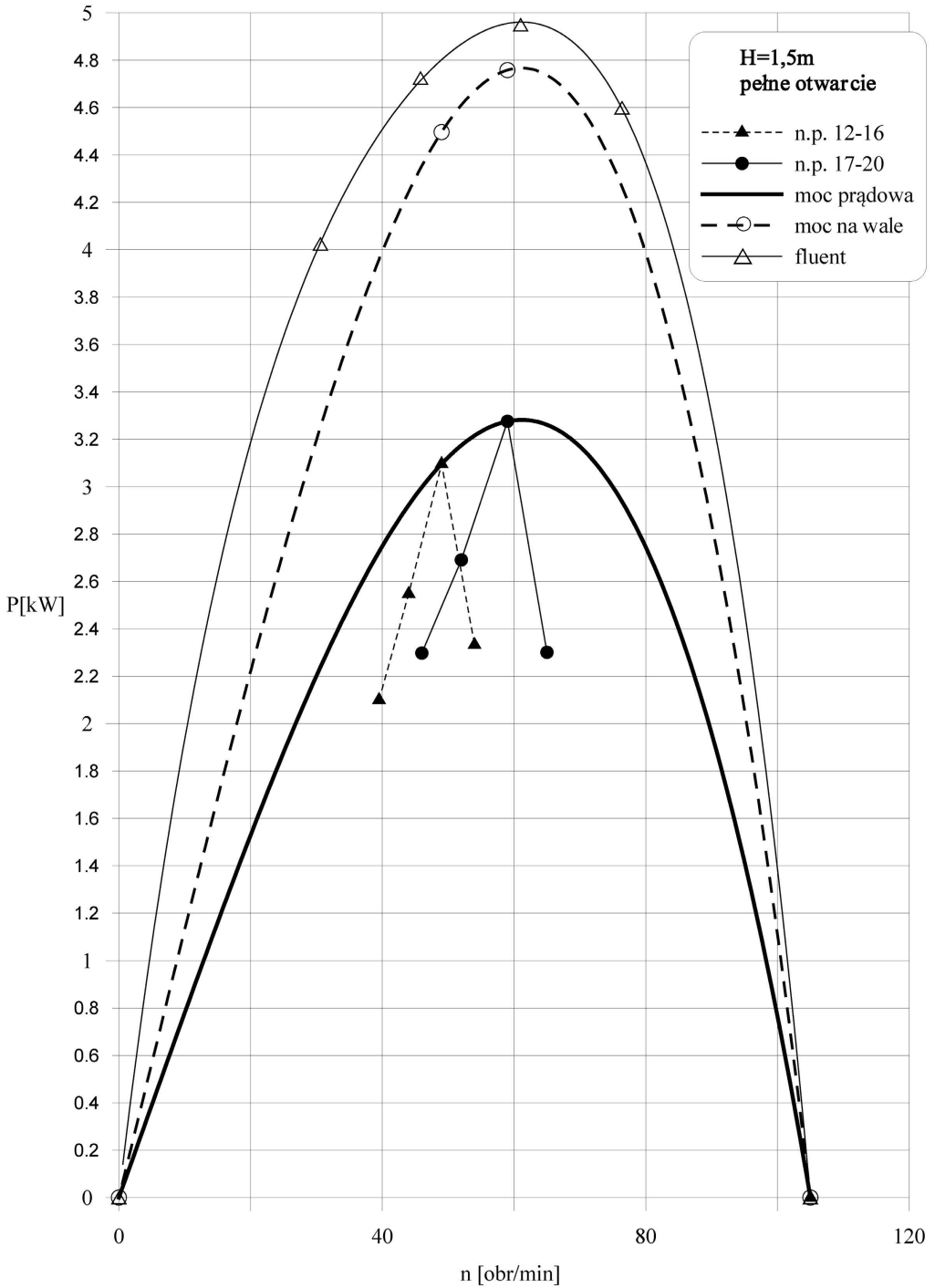


Fig. 8. Electrical power characteristics and turbine shaft power values for the head of 1.5 m.

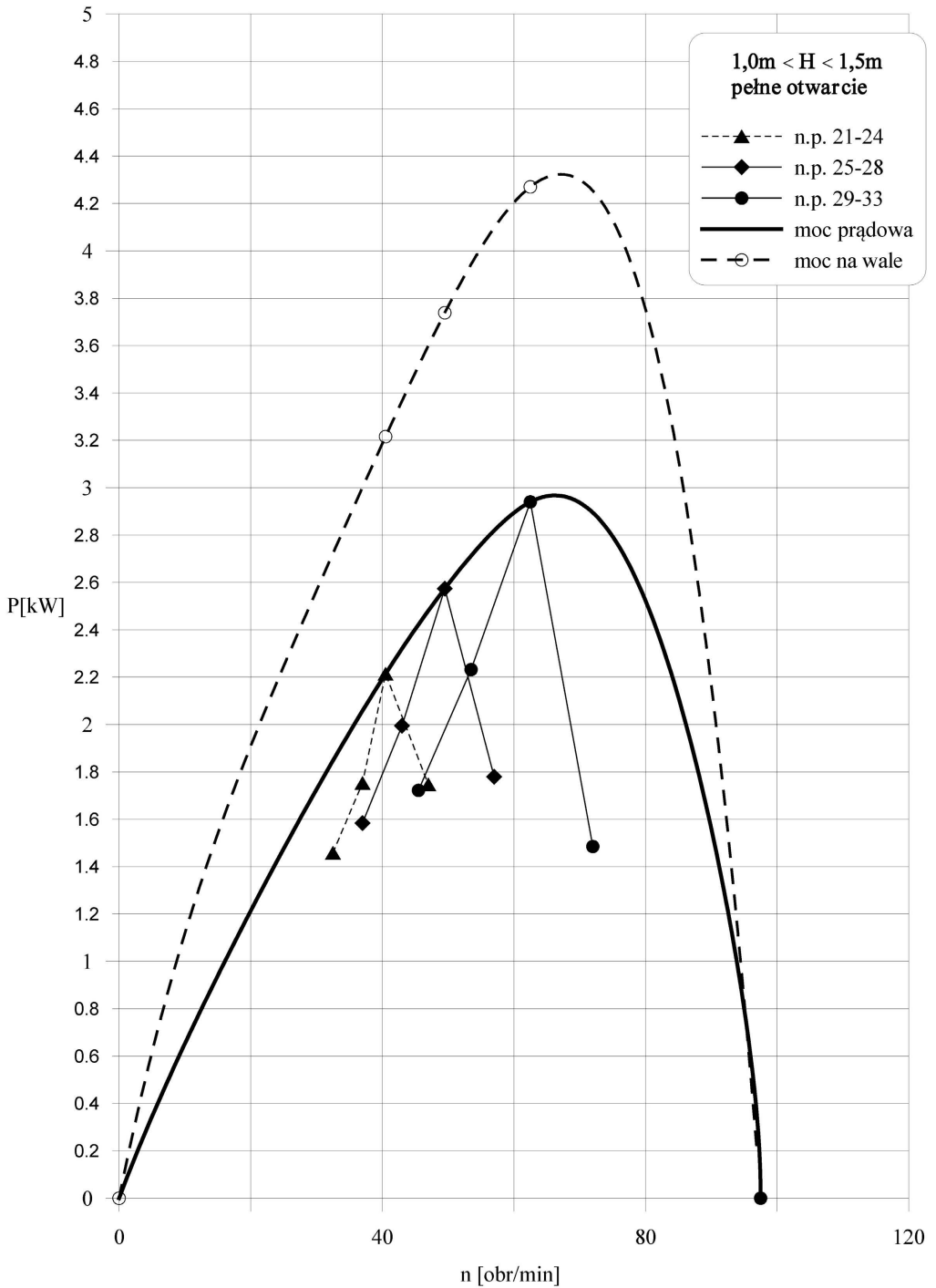


Fig. 9. Electrical power characteristics and turbine shaft power values for the head of $1.0 < H < 1.5$ m.

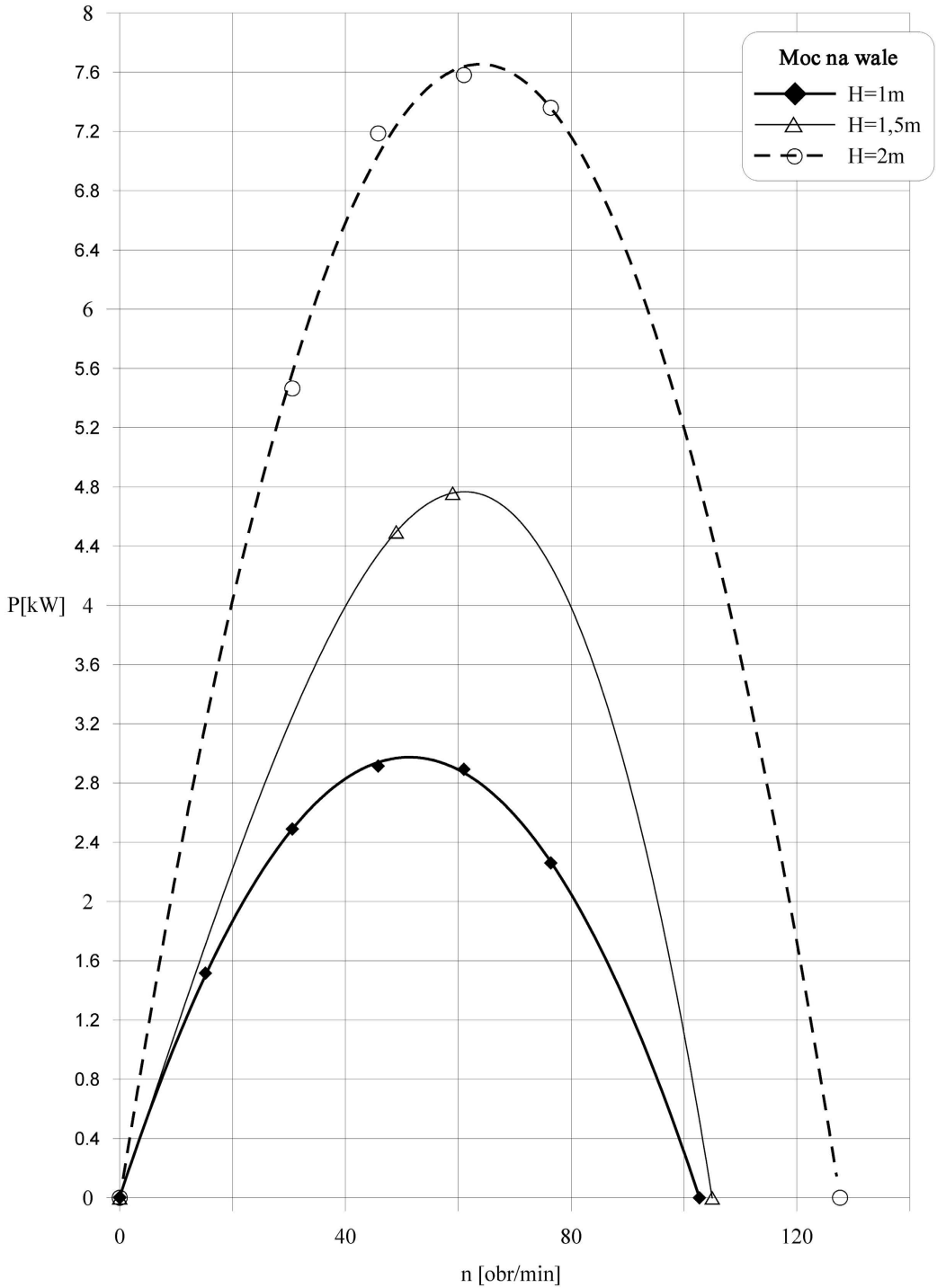


Fig. 10. Turbine shaft power as a function of rotational speed, for the head of 1, 1.5 and 2 m. Calculated characteristics.

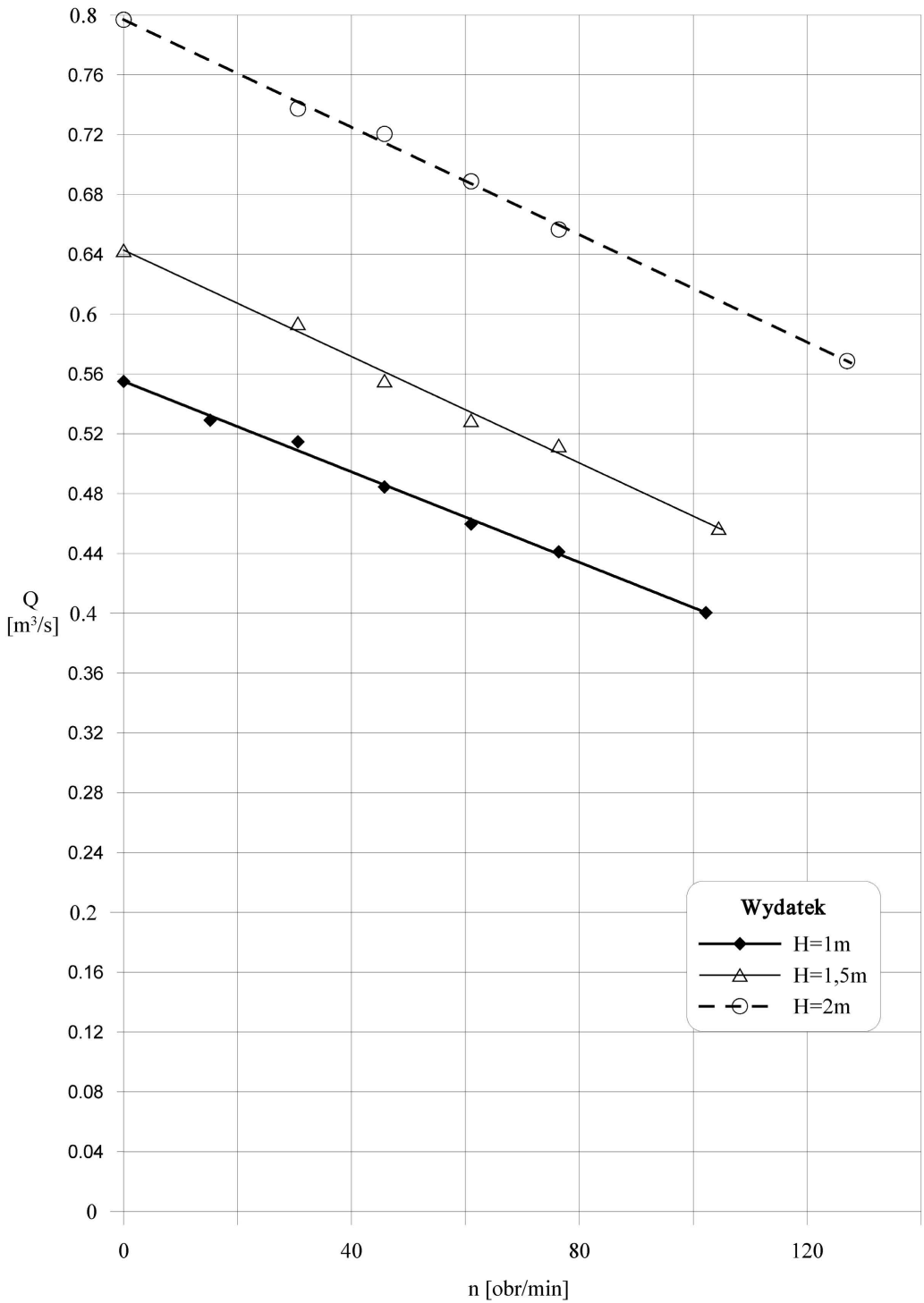


Fig. 11. Water flow rate as a function of rotational speed, for the head of 1, 1.5 and 2 m. Calculated characteristics.

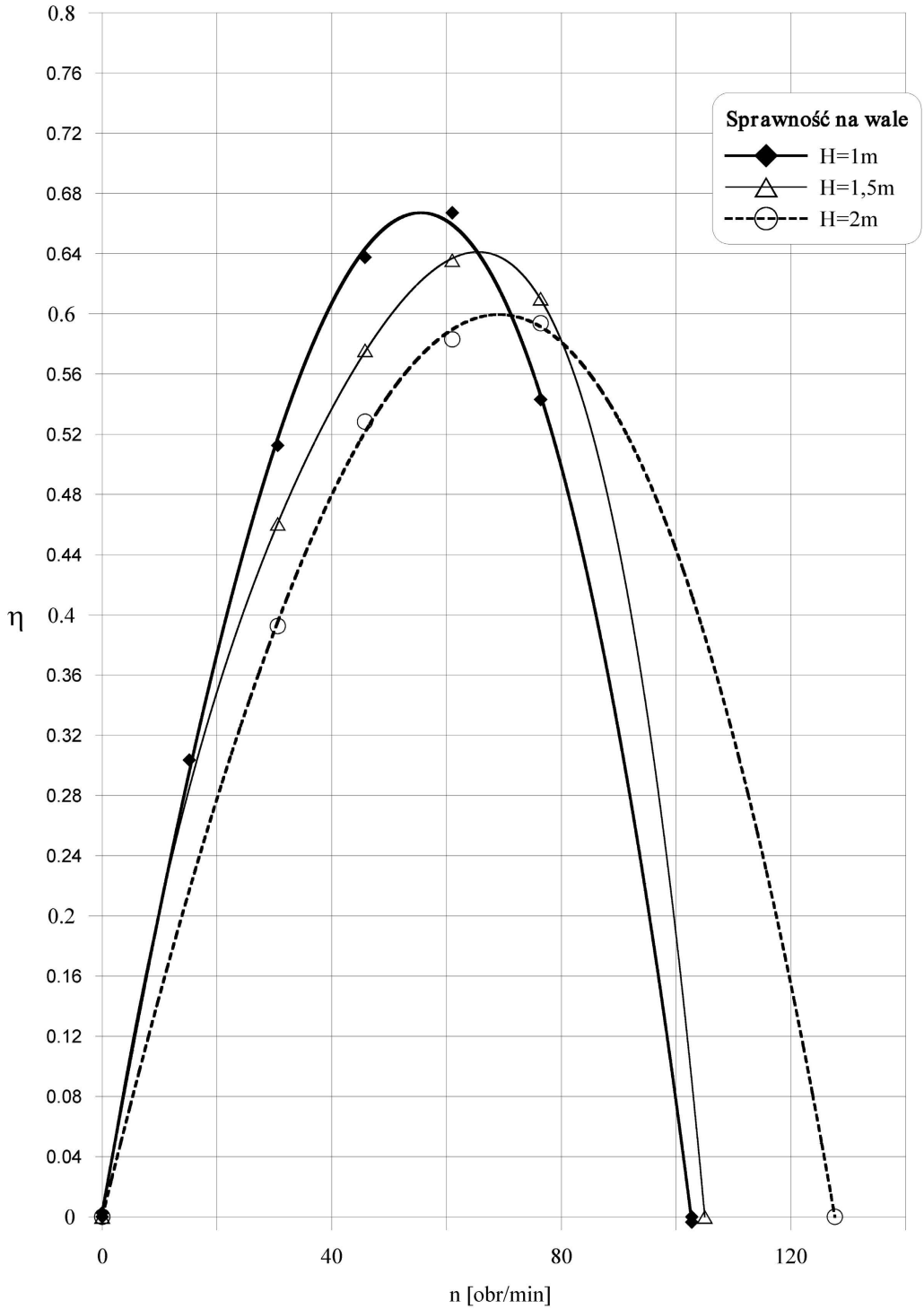


Fig. 12. Turbine shaft efficiency as a function of rotational speed, for the head of 1, 1.5 and 2 m. Calculated characteristics.

For the head of 1.5 m, in the diagram presented in Figure 8, the shaft power characteristics has been marked, as worked out during numerical calculations (FLUENT) in accordance with [5], with the similarity scale taken into consideration, for the same conditions as those experienced during the measurements. For the head of $1.0 < \mathbf{H} < 1.5$ m, due to the fact that its value was not determined precisely, no numerical characteristics is presented in Figure 9. While determining the turbine shaft power characteristics \mathbf{P} , the rate \mathbf{Q} and the shaft efficiency $\boldsymbol{\eta}$ for the heads of 1, 1.5 and 2 m the numerical calculations, as referred to in the INTRODUCTION, and referring to the turbine's 1:5 scale model from [5] have been used, with the similarity of conditions and the power correction factor (between the shaft power for the head of $\mathbf{H} = 1.5$ m, determined based on the aforementioned measurements, and the power obtained during the calculations) taken into consideration.

The correction factor, as the relation between the maximum shaft power measured and the calculated value, for the head of $\mathbf{H} = 1.5$ m, has been adopted as equaling **0.962**. The diagrams in Figures 10 – 12 present the turbine's characteristics determined based on the measurements (shaft power for $H = 1.5$ m) and calculations (other characteristics and heads) for the head values adopted. The points marked in the diagrams, obtained after recalculations, correspond to the calculation characteristics determined with the use of FLUENT software in [5].

4. DISCUSSION

4.1. Characteristics of the Michell-Banki turbine presented above, calculated based on the tests of a single turbine segment performed at a water, dam, as well as observations of the quality of operation of the turbine, lead to a conclusion that the properties of the turbine are satisfactory and they match the declared values – see Table from Chapter L of the “Final Report ...” [9], where the properties measured during the tests described herein (maximum power values for the head of $\mathbf{H} = 1.5$ m) have been compared with those declared prior to commencing the project, and with those expected based on numerical calculations for the two-segment turbine:

Table 2: Declared vs. tested values, according to [9]

	Parameter name	Planned value	Obtained value
1.	Nominal flow rate	1 m ³ /s	1.04 m ³ /s
2.	Head	1 ÷ 2 m	1.5 m
3.	Power output	7 ± 20% kW	Electrical 6.552 kW, shaft power 9.516 kW

and with the expected parameters of the final product, formulated after analyzing the results of tests of the 1:5 model (supplemented with the results of 1:1 prototype tests) – Table 3 in [3,6]:

Table 3. 1:5 model test parameters (averaged) and 1:1 scale turbine test parameters, according to [3] and [6]

TEST PIECE	1:5 MODEL			1:1 TURBINE			
Head [m]	1.0	1.5	2.145	1.0	1.5		2.145
					Expected	Measured	
P_{\max} [W]	94.5	189.0	322.5	2363	4725	4758	8063
M_{\max} [Nm]	10.1	15.1	23.0	1263	1888	1892	2875
$M_{P_{\max}}$ [Nm]	6.68	6.02	9.61	835	753	757	1201
$n_{P_{\max}}$ [rpm]	135	300	320	27	60	60	64
n_{\max} [rpm]	400	500	550	80	100	105	110
$Q_{P_{\max}}$ [kg/s]	16.6	23.7	32.0	415	593	520	800
η_{\max}	0.58	0.54	0.48	0.58	0.54	0.63	0.48

4.2. The test, involving both the 1:5 model and the prototype, have shown compliance with CFD numerical calculations performed with the use of FLUENT software. The above is confirmed by works [3,6] concerned with the model, and by the wording and the drawing from chapter 6 of the calculations pertaining to the 1:5 scale turbine model presented in [4]: “COMPARISON OF CALCULATION AND EXPERIMENTAL RESULTS. Tests of the turbine’s model and comparison of its results with the results of numerical calculations have shown an acceptable level of conformity between the calculation model and the actual test piece. In most cases, the calculation error did not exceed 14%. The largest error equaled 19%.

The diagrams presented in Fig. 13 above show a comparison of the results of numerical calculations (FLUENT) and of test stand measurements involving the 1:5 model (Experiment). Test measurement results presented in [2] and in figure 7-9 of [6], involve sequences of electrical power $U \cdot I$ with their values remaining within a narrow, repeatable range. The main factors resulting in discrepancies between the individual measurement sequences, as well as between the results of measurements and numerical calculations performed with the use of FLUENT, include leaks of the test stand, as well as inability to achieve fully air-free and absolutely repeatable flow of water through the duct (No. 6 in Fig. 4a in [2]), and, hence, at the turbine inlet. No leaks have been provided for in the calculations, and it was assumed that the medium entering the turbine would be made of 100% water.

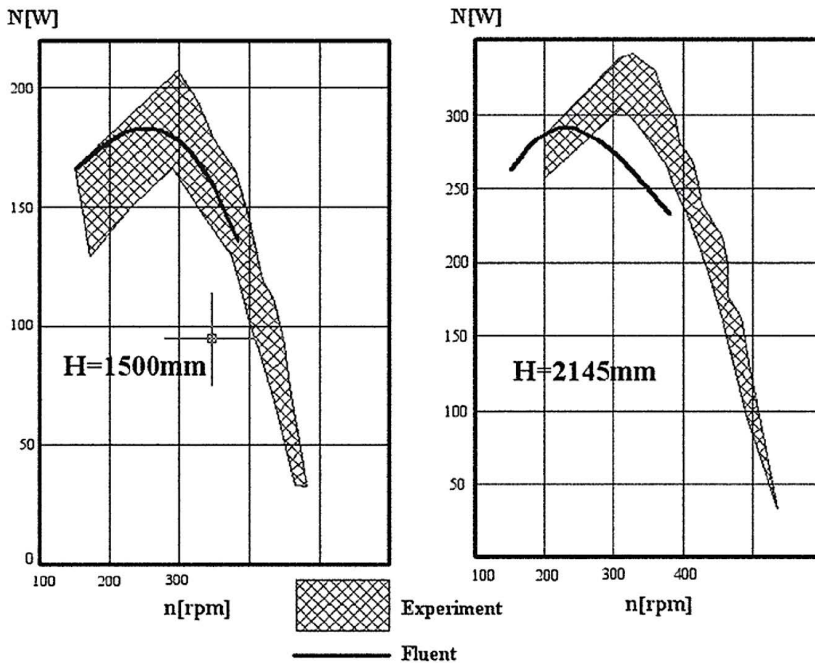


Fig. 13. Results of numerical calculations compared to experimental results – for the turbine operating at the head of 1500 mm and 2145 mm” (according to [4]).

The power output of the turbine’s model, in turn (on the shaft, with the measured efficiency of the power transfer system taken into consideration), as presented in Fig. 13 in [4], as well as in [2] and in Fig. 7-9 in [6], remains within a certain range resulting from the inaccuracy of determining the efficiency of the system transferring output power to electrical power, i.e. of the alternator and of the remaining elements of the electrical system. It needs to be borne in mind that information provided by the manufacturers of the individual components of the power transfer system was not absolutely certain. Therefore, it was assumed that the efficiency of the power transfer system equaled between 0.405 and 0.450. Hence, the measured shaft power of the turbine remained within the range presented above. A similar factor resulting in a difference between measurements and numerical calculations was observed while testing the prototype. Similar situations were dealt with in this case as well – the turbine inlet was partially filled with water, and even some solid particles were present in the water – unlike in the assumptions based on which FLUENT calculations were performed.

The scale of discrepancies is also proved by the correction factor, taken into consideration in the further analysis of tests results, describing the difference between prototype measurements and calculation results and equaling **0.962** (chapter 3, of this paper). The turbine tests performed under natural conditions, as discussed herein, have once again confirmed, after tests of the 1:5 scale model, that the numerical model was correct. They have also confirmed the correctness of the manner in which the flow of water through the turbine was simulated, and that the technical parameters selected were correct and useful as a future tool for modeling flows, especially those of two-phase and non-compressive character.

4.3. The specific speed, as analyzed in chapter 7 of [2] and in Table 1 of [6], defined in accordance with [10], for a turbine operating under natural conditions, at maximum power rpm $n_{P_{max}}$ and for the discussed heads of 1, 1.5 and 2 m, equals:

Table 4. Specific speed n_s depending on the head value [Wojciech Zdrojewski, 2008]

Parameter Head	H [m]		
	1.0	1.5	2.0
$n_{P_{max}}$ [rpm]	50	60	65
P_{max} [HP]	3.96	6.47	10.33
n_s [rpm]	99.50	91.94	87.84

The specific speed values presented above confirm the conclusion drawn after the tests of the model, in accordance with which the specific speed of the turbine discussed herein corresponds to that of low-speed Francis turbines.

4.4. A prototype turbine housing has been used in the tests, being of a simplified plywood design. Users of mass-produced turbines will be offered more advanced housing designs, as discussed in [8], characterized by varying costs of manufacture. The use of such more advanced technologies may improve the efficiency of the turbine, as the flow losses encountered while the water is passing through the turbine will be lower than those experienced in the plywood housing. The electrical efficiency of the turbine-generator system may also be improved (depending on the individual needs of the user) by the use of electrical and drive system components characterized by higher efficiency parameters, and also by varying cost levels.

4.5. The prototype water turbine with a plywood housing described in this paper was operating, after the tests had been completed, over the period of approx. 3 years, at a farm in Białobrzegi, producing electricity. After that time it was transported back to the Institute of Aviation. It was showing some signs of wear, but with the difficult operating environment considered, its conditioned was satisfactory to allow its continued use.

The prototype was overhauled in 2016 by replacing the blades and by installing a metal housing (instead of one made of plywood). The wooden stand was replaced with a metal one as well. Elements of the propeller and the drive transfer system supporting rack were refreshed by painting too. After the generator's drive chain has been replaced, the prototype will be available for presentation to potential customers. If any interest is expressed in the product, its modernization may continue, and lot production may be launched in cooperation with the prospective customer.

5. CONCLUSION

Characteristics of the Michell-Banki turbine presented in the paper, calculated based on the tests of a single turbine segment performed at a water, dam, as well as observations of the quality of operation of the turbine, lead to a conclusion that the properties of the turbine are satisfactory and they match the declared values.

The test, involving both the 1:5 model and the prototype, have shown compliance with CFD numerical calculations performed with the use of FLUENT software.

The specific speed values presented in the paper confirm the conclusion drawn after the tests of the model, in accordance with which the specific speed of the turbine discussed herein corresponds to that of low-speed Francis turbines.

The use of more advanced technologies for housing manufacturing may further improve the efficiency of the turbine.

The prototype water turbine with a plywood housing described in this paper was showing some signs of wear after 3 years of regular operations, but with the difficult operating environment considered, its condition was satisfactory to allow its continued use.

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BADANIA STOISKOWE PROTOTYPU TURBINY WODNEJ MICHELL-BANKI W WARUNKACH NATURALNYCH

Streszczenie

Praca przedstawia wyniki badań jednego segmentu prototypu turbiny wodnej przeprowadzone w celu określenia charakterystyk jej wyjściowej mocy na wale w funkcji obrotów i sprawdzenia deklarowanych parametrów użytkowych. Porównano je z wynikami obliczeń numerycznych z zastosowaniem oprogramowania FLUENT dla takich samych warunków. W pracy zawarto istotne informacje niezbędne dla prezentacji procesu badań omawianego obiektu takie jak: okoliczności tych badań, własności obiektu badań, zastosowaną aparaturę badawczą, a także metodę oraz przebieg pomiarów hydromechanicznych wraz z własnościami ich rezultatów. Następnie omówiono uzyskane wyniki pomiarów oraz ich analizę i wnioski z niej wynikające. Analiza wyników, z uwzględnieniem obrazu fizycznego zjawisk występujących w przypadku urządzeń przepływowych takich jak turbiny wodne, pozwoliła na określenie innych istotnych charakterystyk pracy turbiny czyli: wydatek, moment na wale oraz sprawność w funkcji prędkości obrotowej i spad. Wyniki badań potwierdziły przewidywane własności mechaniczne i energetyczne turbiny oraz wykazały skuteczność zastosowanego numerycznego modelowania przepływów.

Krótko nakreślono perspektywy rozwoju zastosowań omawianej turbiny wodnej.

Słowa kluczowe: geometria turbiny, pomiary hydromechaniczne, spad wody, moc na wale, wydatek wody, sprawność turbiny.