**TECHNICAL TRANSACTIONS** | **CZASOPISMO TECHNICZNE**
ENVIRONMENT ENGINEERING | ŚRODOWISKO

1-Ś/2015

BERNARD TWARÓG*

# AN ANALYSIS OF THE APPLICATION OF THE ALDEN TURBINE – A CASE STUDY OF THE DOBCZYCE HYDROELECTRIC POWER PLANT

# ANALIZA ZASTOSOWANIA TURBINY ALDENA NA PRZYKŁADZIE HYDROELEKTROWNI DOBCZYCE

A b s t r a c t

This study contains an analysis of the Alden turbine with a power level of 5.0 MW in the Dobczyce power plant. Taking into account results of annalysis, it may be concluded that the contemplated use of the Alden turbine in the Dobczyce power plant is close to the limits of practical applicability and economic viability of this solution. The average annual energy output value achieved using the Kaplan turbines oscillates around 9 GWh, and if the turbines are replaced with an Alden turbine, the estimated average annual output may reach a maximum of 10.6 GWh which represents an increase in power output of about 17%.

*Keywords: Alden turbine, Kaplan turbine, power plant modelling*

S t r e s z c z e n i e

W pracy zaprezentowano analizę możliwości wykorzystania turbiny Aldena o mocy 5 MW w elektrowni Dobczyce. Uwzględniając uzyskane wyniki analizy, należy zauważyć, że zastosowanie turbiny Aldena jest na granicy technicznej możliwości oraz ekonomicznej efektywności. W dotychczasowej konfiguracji z turbinami Kaplana elektrownia średniorocznie produkuje 9 GWh. Przy zastosowaniu turbin Aldena produkcja mogłaby wzrosnąć do kilkunastu procent.

*Słowa kluczowe: turbina Aldena, turbina Kaplana, modelowanie pracy elektrowni wodnej*

**DOI: 10.4467/2353737XCT.15.193.4398**

* Ph.D. Eng. Bernard Twaróg, Institute of Hydraulic Engineering and Water Management, Department of Hydraulic Engineering and Water Management, Cracow University of Technology.

## 1. Introduction

The EU directive on energy from renewable sources (2009/28/EC) defines a target of a 20% share of energy from renewable sources to be achieved by the year 2020. Hydropower represents 70% of the total energy generated using renewable sources in Europe. Despite certain limitations to the growth of the hydropower industry in our region, there are development possibilities and potential in constructing new facilities and upgrading the existing ones. Taking into account the forecast increase in energy consumption, the proportion of energy from renewable sources must be more than double in comparison to that used in the nineteen-nineties. The targets set will be achieved among others developing the Alpine hydropower industry, as provided for in plans adopted for the next 2 years, including the construction of 60 new pumped storage power plants (about 27 GW). The indicated targets may also be achieved by upgrading the existing hydropower facilities, with more efficient, more advanced and pro-environmental solutions.

## 2. A short description of the Alden turbine

The concept of a fish-friendly turbine was first proposed at a meeting held in Denver, Colorado, in 1993. The objective was defined simply: to improve the efficiency of a turbine and reduce its impact on the environment, thus reducing the costs of its operation. The National Hydropower Association (NHA) formed a non-profit organisation with an initial contribution amounting to USD 500,000 in order to support research on the topic, and it also attracted supporters from the industry. Thus, work on the Alden turbine commenced.

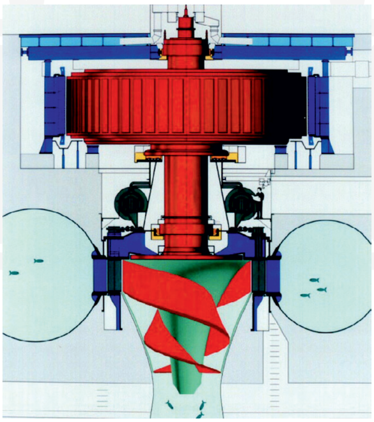

Fig. 1. An example of Alden turbine installation (Courtesy Alden Research Laboratory, Inc.) [8]

The Alden project focused on a completely new design of the turbine runner. The structure of the Alden runner was limited to three blades – thus, the pressure and velocity gradients were reduced, the clearance between the runner and the stay vanes was minimised while the flow passage width was maximised.

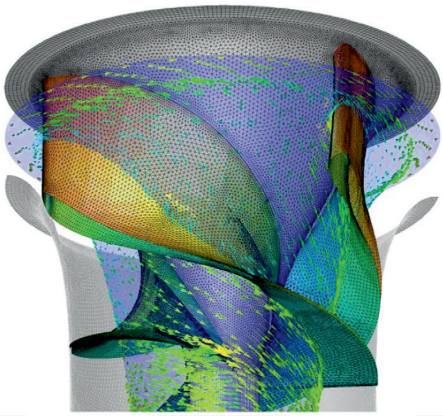

Fig. 2. The runner of the Alden turbine as used in CFD (Computational Fluid Dynamics) modelling [8]

Compared to traditional turbines, the Alden turbine is characterised by higher fish survival rates for similar flows, heads and fish species and by a higher level of efficiency; this is confirmed by prototype test results and data collected for traditional turbines.

Two basic parameters are used to determine the application potential of the Alden turbine: the head and the discharge. Based on biological and technical limitations, an appropriate head for the Alden turbine was determined within the range of 9.0 to 36.6 m. At smaller heads, starting from about 9 m, the fish survival rate is usually high, and consequently, the application of Alden turbines in such circumstances brings limited biological benefits. The turbine requires a minimum flow of about 17 $m^3/s$ to maintain a desirable fish survival rate and correct turbine operation. The upper limit is defined by the practical size of the machine rather than by operational or biological considerations. In practice, the head for the Alden turbine may vary between 7.6 and 43 m while minimum flow values start from 14 $m^3/s$. Taking into account experience gained by Voith Hydro Inc., it may be concluded that the contemplated use of the Alden turbine in the Dobczyce power plant is close to the limits of practical applicability and economic viability of this solution. This results from the nature of operation of the turbine at boundary flow values; nevertheless, an attempt to analyse the solution will be made.

Characteristic parameters include the head, flow, rotational speed and power values. Reasonable sizes of the runner diameter in the Alden turbine are contained within the range of 2.4 to 4.5 m. At diameters smaller than 2.4 m, clearances between turbine components (i.e. the spaces between vanes) are disadvantageously reduced and so is the fish survival rate. On the other hand, large diameters result in poor economic ratios being achieved by the system. The recommended rotational speed of the Alden turbine falls within the range of 90 to 140 rpm. At a speed below 90 rpm, the Alden turbine usually requires a large and expensive generator, and when the speed of 140 rpm is exceeded, the biological benefits offered by the turbine are reduced.

## 3. The Dobczyce hydroelectric power plant

Water for the power plant is delivered through an intake tower suitable for receiving water across the entire range of water level fluctuations in the reservoir. The power plant is supplied with water from a tunnel with a length of 131 m and a diameter of 2.20 m drilled in the Zamkowa Góra mountain massif. Two Kaplan turbines manufactured in the Czech Republic and two generators are installed in the power plant.

– installed power 2.5 MW,
– installed discharge 10.70 $m^3/s$,
– minimum head 14.8 m,
– maximum head 30.7 m,
– averaged annual output capacity amounts to 9.6 GWh,
– runner diameter 1.4 m
– rotational speed 350 $min^{-1}$.

Fig. 3. A view of the Dobczyce Dam from the tailwater side (Photo by B. Paluszkiewicz)

Fig. 4. A view of the hydroelectric power plant (Photo by B. Paluszkiewicz)

## 4. A simulation model

Basic equations:

$$V_{i+1} = V_i + \left(Q_i - \sum_{k=1}^{2} Q_{k,i}^{tur} - Q_i^{str} + Q_i^r - Q_i^j\right)\Delta t_i \tag{1}$$

$$\Delta H_i = H(V_{i+1})_{i+1} - H(V_i)_i \tag{2}$$

where:

- $\Delta t_i$ – s, time interval length (discretisation step), a constant value for the assumed horizon – a dynamically changing increase in time step may also be considered;
- $V_{i+1}$ – m$^3$, reservoir capacity at the end of interval $\Delta t_i$,
- $V_i$ – m$^3$, reservoir capacity at the beginning of interval $\Delta t_i$,
- $Q_i$ – m$^3$/s, natural inflow at the beginning of interval $\Delta t_i$,
- $Q_{k,i}^{tur}$ – m$^3$/s, outflow through generator turbine $k$ at the beginning of interval $\Delta t_i$,
- $Q_i^j$ – m$^3$/s, idle discharge at the beginning of interval $\Delta t_i$,
- $Q_i^r$ – m$^3$/s, forecast inflow from the differential catchment basin at the beginning of interval $\Delta t_i$,
- $Q_i^{str}$ – m$^3$/s, water volume losses converted into an average flow within interval $\Delta t_i$, including values of water intake.

Operating power of the generator turbine

$$N_{k,i} = \rho \cdot g \cdot \eta_i(Q_{k,i}^{tur}, \Delta H_i) \cdot Q_{k,i}^{tur} \cdot \Delta H_i \tag{3}$$

where:

- $N_{k,i}$ – W, averaged turbine power in time interval $\Delta t_i$,
- $\rho$ – 1000 kg/m$^3$, water density,
- $g = 9.01$ – m/s$^2$, gravitational acceleration,
- $\eta_i(Q_{k,i}^{tur}, \Delta H_i)$ – efficiency,
- $\Delta H_i$ – m, averaged head.

An equation describing the quantity of energy generated by turbine $k$ in time $\Delta t$

$$A_{k,i} = N_{k,i} \cdot \Delta t_i \tag{4}$$

$$A = \sum_{i=1}^{n} \sum_{k=1}^{2} A_{k,i} \tag{5}$$

where:

- $\Delta t_i$ – s, time interval length (discretisation step);
- $A_{k,i}$ – J, the quantity of energy generated by turbine $k$ in time $\Delta t_i$,
- $A$ – J, the quantity of energy generated in the analysed time period.

## 5. Data used and results of the modelling procedure

The model was developed and calibrated for average daily inflows to the Dobczyce reservoir in the period July 1993–January 2013. Data used in modelling was provided by the Regional Water Management Board in Kraków. Reservoir filling curves and the rating curve in the discharge channel represented key quantities used in the model. These characteristic values were used in the modelling procedure to calculate the average daily head at which the power plant turbines operate, and finally, to determine the values of turbine operating power and output.

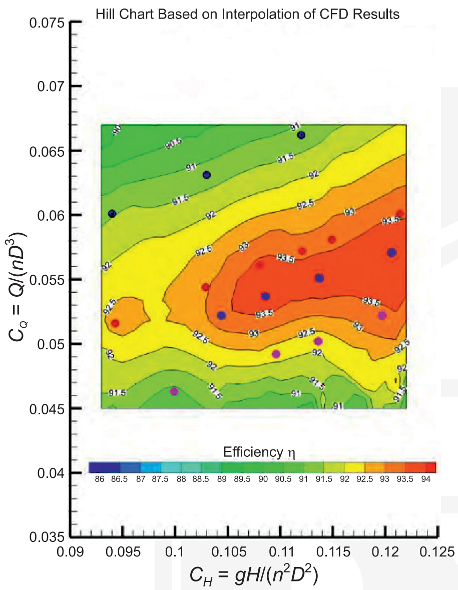


Fig. 5. Efficiency curve, % for the Alden turbine [8]

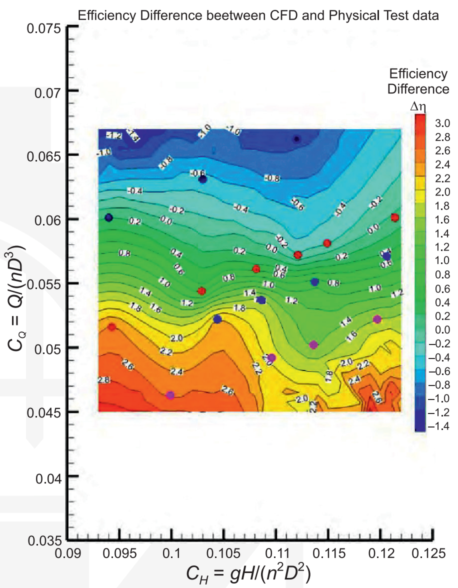


Fig. 6. Differences in efficiency,% between the CFD modelling results and a physical test [8]

Keeping in mind the principle of similarity of flow geometry and area, parameters of an Alden turbine adapted to the operating conditions of the Dobczyce power plant may be calculated using model turbines analysed by Voith Hydro Inc.:

- installed power 5.0 MW,
- installed discharge 10.70 $m^3/s$,
- minimum head 14.8 m,
- maximum head 30.7 m,
- runner diameter 2.06 m,
- rotational speed 175 $min^{-1}$.

The results of the model simulation enable us to determine the increase in energy generated by the Dobczyce power plant, should the Kaplan turbines be replaced with an Alden turbine. The average annual energy output value achieved using the Kaplan turbines oscillates around 9 GWh, and if the turbines are replaced with an Alden turbine, the estimated average annual output may reach a maximum of 10.6 GWh which represents an increase in power output of about 17%. Below, the reader will find the results of a simulation of power plant operation for the period January 2005 – January 2013.

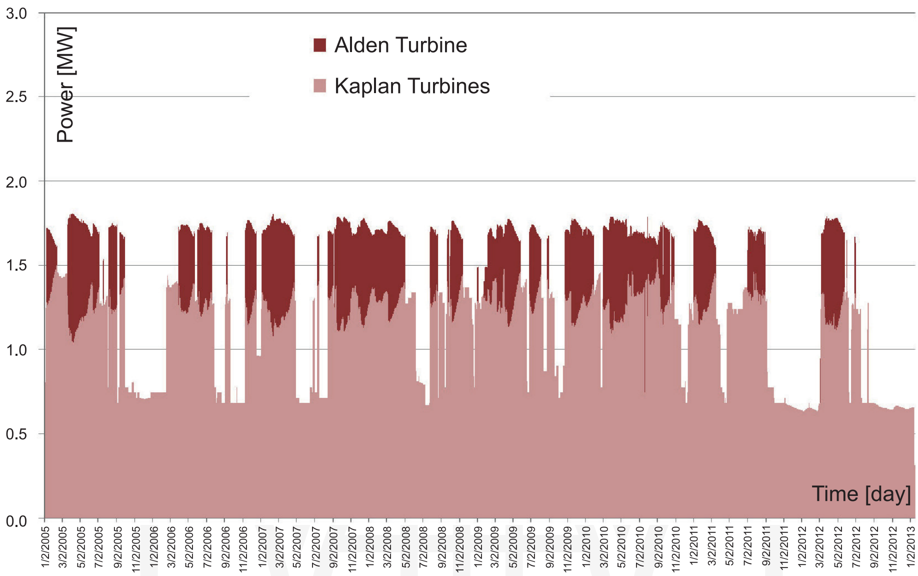


Fig. 7. A simulation of Kaplan and Alden turbine power

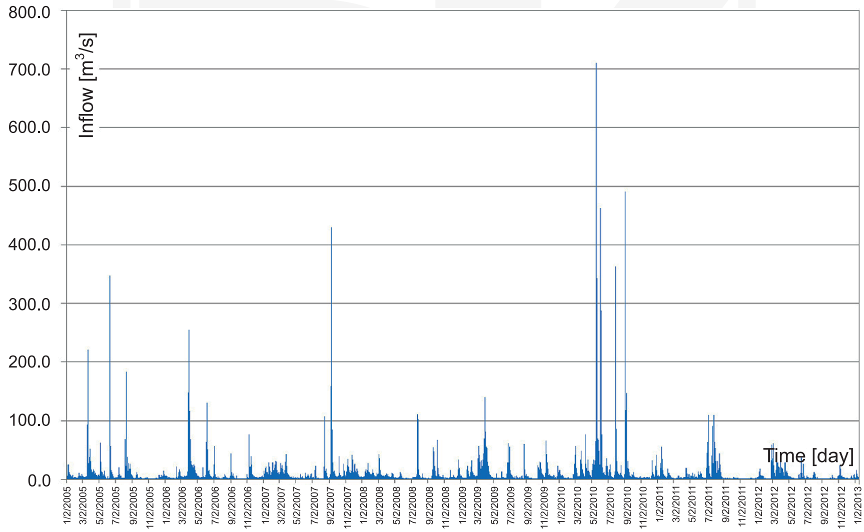


Fig. 8. Water inflow to the reservoir

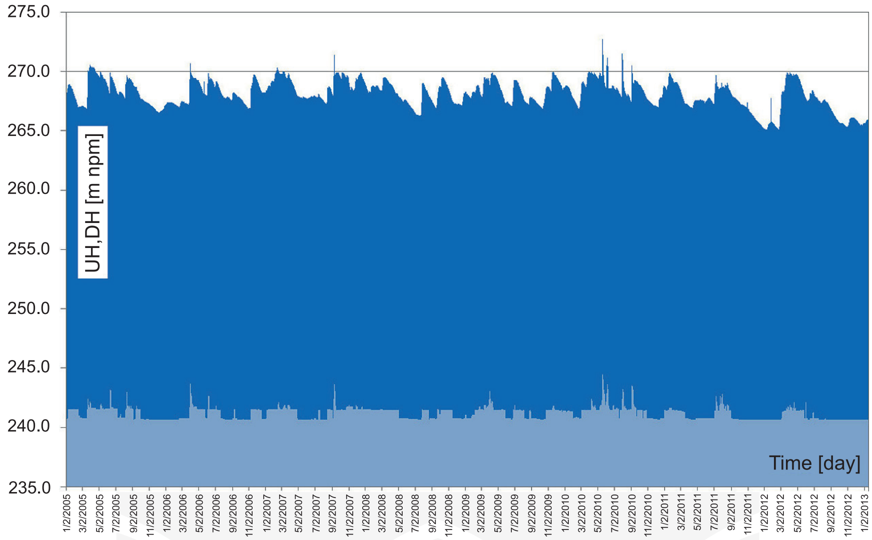


Fig. 9. Headwater level – HW, tailwater level TW

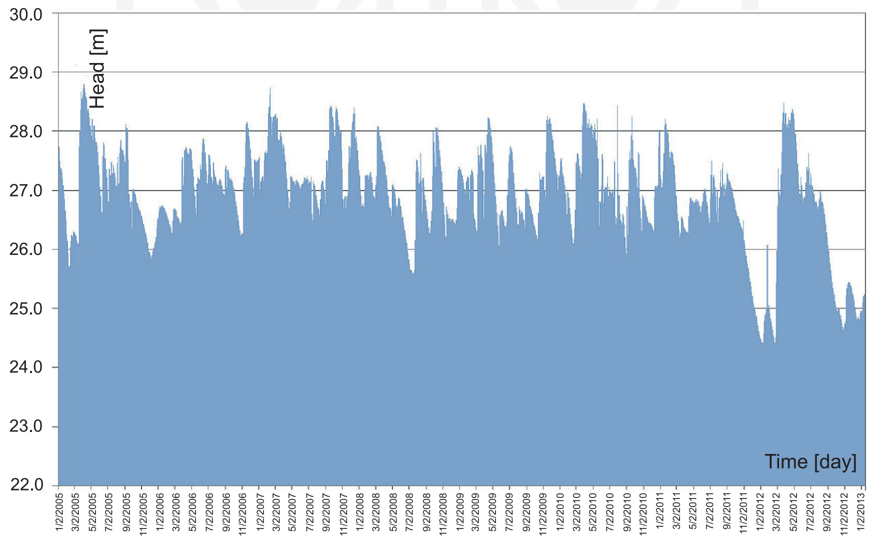


Fig. 10. Head

## 6. Conclusions

The patented Alden turbine advantageously differs from other turbine types in reduced fish mortality and injury caused by the pressure and impact of runner blades. Pilot analyses of biological conditions were completed as part of our project in 2002 and 2003 on a population of more than 40,000 fish. The analyses demonstrated a high fish survival rate exceeding 96%. The survival rates for smaller fish with a length below 8 cm are higher than 98%; the estimated survival rates for eel and sturgeon exceed 99%. Taking into account the high survival rates, Alden turbines may be used to generate electric power using (currently idle) water flows discharged by spillways or fish ladders, provided that the criterion of minimum flow is satisfied

Voith Hydro Inc., Pennsylvania, was selected as the sole manufacturer of the described turbines. The completion of comprehensive research on Alden turbines was scheduled for 2013. Additional work resulted in the efficiency of turbine operation being improved by up to 94%. An analysis of the installation costs of an Alden turbine, and those of conventional Francis and Kaplan turbines, leads to the conclusion that the costs are lower by around 35% to 40% for the conventional turbines (a Kaplan turbine is more affordable). However, an analysis made taking into account the environmental impact, a desirable reduction of energy losses and avoided fish ladder construction, shows that Alden turbine installation is less expensive, in view of the total balance of the aforementioned factors.

The parameters of the Alden turbine were calculated using the principle of similarity of flow geometry and the area for model turbines analysed by Voith Hydro Inc. This study contains an analysis of one turbine with a power level of 5.0 MW and a rotational speed of 175 $m^{-1}$, exceeding the allowable value recognised as fish-friendly by 25%. Taking into account experience gained by Voith Hydro Inc., it may be concluded that the contemplated use of the Alden turbine in the Dobczyce power plant is close to the limits of practical applicability and economic viability of this solution. This is due to the nature of the operation of the turbine at boundary flow values resulting in a low efficiency of turbine operation, falling within the range of 80% to 90%, from the existing fish ladder and a relatively high value of rotational speed.

## References


[1] Twaróg B., *Analizy lokalizacyjne pod małe inwestycje hydroenergetyczne na przykładzie zlewni rzeki Raby* (*An example of location analysis for small-scale hydropower projects*), Energetyka Wodna 02/2014, 42-44.

[2] Twaróg B., *Przykład analizy lokalizacyjnej pod hydroenergetyczne inwestycje małej skali – lokalizacja instalacji oraz optymalizacja parametrów hydroenergetycznych* (*An example of location analysis for small-scale hydropower projects: system location and optimization of hydropower parameters*), Energetyka Wodna 02/2014, 45-47.

[3] Hecker G.E., Amaral S., Allen G., Li S., Perkins N., Dixon A., Dixon D., EPRI, National Conference on Engineering and Ecohydrology for Fish Passage, U. Mass Amherst, June 5–7, 2012.

[4] Final Report – Pilot Scale Tests Alden/Concepts NREC Turbine. U.S. Department Of Energy, Advanced Hydropower Turbine Systems Program, 2003.

[5] Final Turbine and Test Facility Design Report Alden/NREC Fish Friendly Turbine, Prepared by Alden Research Laboratory, Inc. Northern Research and Engineering Corporation for the U.S. Department of Energy Idaho Operations Office, September 2000.

[6] Alden Fish-Friendly Hydropower Turbine Development & Deployment: Background and EPRI-U.S. Department of Energy Project Overview – Preliminary Engineering & Model Testing. U.S. Department of Energy, Funding Opportunity Announcement Number: DE-PS36-08GO98030 CFDA Number: 81.087, April 2010.

[7] A Summary of Environmentally Friendly Turbine Design Concepts, Mufeed Odeh,United States Geological Survey – BRD S.O. Conte Anadromous Fish Research Center Turners Falls, Massachusetts 01376, United States Department of Energy Idaho Operations Office Advanced Hydropower Turbine System Program, July 1999.

[8] Fish Friendly Hydropower Turbine Development and Deployment: Alden Turbine Preliminary Engineering and Model Testing. Final Report, October 2011. Electric Power Research Institute, October 2011.

[9] *Entwicklung von Kleinstwasserkraftanlagen für die spezifischen Landschafts- und Gewässerstrukturen in europäischen Mittelgebirgen am Beispiel des Thüringer Waldes*, eds. K. Thürmer, C. Kohout, M. Klich, M. Reuter, Institut für Wasserwirtschaft, Siedlungswasserbau und Ökologie, Das Projekt wurde unter der Nr TNA III-2/2012 aus Mitteln im Rahmen des EFRE gefördert, Schleusingen, Juni 2014.

[10] Twaróg B., *The Development of Small Hydropower-Plants in the Low Mountain Range*, Final Report, Cracow University of Technology, February 2014.