Design of a new Kaplan pico-turbine runner blades

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1. Introduction

When an infrastructure is remote from the grid and a low-flow water resource with a small head is available, installing a small-hydro power plant to produce electricity can be a solution. Nevertheless, the implementation of this technology in developing countries is not simple and requires adaptation of the manufacturing techniques used. Indeed, one of the major problems in implementing and realization of renewable energy projects in developing countries is the lack of qualified personnel and the lack of modern and adapted infrastructures \cite{1} for manufacturing in particular. Moreover, the investments costs (manufacturing and installation) of these power plants should be very low to guarantee a return on investment over a reasonable period. It is indeed essential to be able to manufacture locally and not to create a technological dependence. In this context, the Institute for Applied Research into Energy Systems (ENERGY) \cite{2} and
the Sustainable Engineering Systems Institute (SeSi) [3] of University of Applied Sciences of Fribourg in Switzerland have developed, in collaboration with the Albert Schweizer Ecological Center (CEAS) [4], a 1 kW low-cost hydropower plant. This paper presents the advantages of a 1 kW pico turbine with simplified design of the blades compared to a “standard one” with profiled blades, for developing countries, and designed in Fribourg. The comparison takes into account economic factors due to manufacture and operation (efficiency) but also to the design process.

2. Approach

Initially, pico-turbine with profiled blades is conceived and developed by numerical simulations (CFD) to produce 1 kW power output at 0.055 \( m^3/s \). In addition to a performance analysis, complete analyses of the design and manufacturing cycles are performed. Thus, this turbine is manufactured by a 5-axis CNC machine (Computer Numerical Control). The numerical results are validated by experimental tests.

Secondly, a complete analysis of the manufacturing techniques available and mastered in developing countries (project with the Centre Ecologique Albert Schweizer [4] in Madagascar) allowed to develop a second turbine of 1 kW with simplified blade geometry. The manufacturing techniques used are welding and sheet metal. Thus, the turbine has a cylindrical hub that can be turned on conventional machine and the blades are welded on the hub. The sheet metal blades with constant thickness are bent using a wooden die with the desired radius. Numerical simulations (CFD) are performed to find the optimum sheet thickness and bending radius to achieve the best performance for the same flow conditions previously set for the profiled blade turbine. Similar analyses are performed as for the turbine with profiled blades.

Finally an economic evaluation and comparison between the 2 developed turbines is carried out by taking into account the operation of the turbine. Indeed, the decrease in efficiency between the two types of turbines can be assimilated to a loss that can be compensated by cheaper manufacturing techniques.

2.1. Geometry of the turbine

Figure 1 represents the geometry of the turbine as studied. It is installed in a 175 mm diameter pipe. 6 fixed guide vanes and 4 runner blades are foreseen.

![Figure 1](image_url)  
**Figure 1.** Geometry of the studied turbine.

2.2. Hypotheses of the numerical analysis

To characterize the different turbines performances, the simulation boundary conditions are kept identical. The numerical model consists of four meshes corresponding to 4 domains as shown in figure 2. The first one is the upstream pipe with an annular cross-section corresponding to the shaft. The second mesh comprises six fixed guide vanes used to pre-rotate the fluid before it enters the runner. The third mesh includes the runner blades and finally the fourth mesh consists of the turbine nose and the downstream pipe. The meshes remain unchanged for all calculations.
except the third mesh, which adapts to the shape of the blades. Periodic flow hypothesis allows the use of symmetry to lighten the model. Each geometry is divided into symmetrical portions as shown in figure 2. Steady-state RANS simulations (Reynolds averaged Navier-Stokes) are performed at constant rotation speed of 1000 \( \text{rpm} \) by varying the volume flow rate from 0.035 to 0.070 \( \text{m}^3/\text{s} \). \( k-\epsilon \) turbulence model is used for all simulations.

**Figure 2.** Boundary conditions and domains used for CFD calculations.

### 2.3. Hypotheses of the economic analysis

The development, manufacturing and operating costs are based on the Switzerland tariffs to compare the two turbines and only the relative differences shall be considered. Thus, the hourly development cost is 60 CHF. The manufacturing costs depend on the used materials and the manufacturing techniques. They are based on the rates of the mechanical workshop of the University of Applied Sciences in Fribourg. The economical return on the investment is calculated according to the average electricity price in Fribourg in 2018, which is 17.86 cts/kWh [6]. The turbine’s operating time is estimated at 4400 hours/year [7] at full load equivalent.

### 3. NACA profile runner blades

As shown in figure 3, the profiled turbine is composed of 4 blades NACA 4408 [9]. The NACA profile is kept constant over the entire blade height, simplifying thus the design and the manufacture of the blade, but decreasing the turbine performances. The guide vanes and the runner blades are fixed to simplify the manufacturing of the different parts as much as possible. The NACA profile is positioned on the hub using the velocity triangles at the inlet and at the outlet. The average velocity triangle is calculated at half blade height for a flow of 0.040 \( \text{m}^3/\text{s} \) at 1000 \( \text{rpm} \). This turbine, developed during a project leaded by the ENERGY Institute of the University of Applied Sciences in Fribourg, is a prototype validated by experimental measurements.

#### 3.1. Design and manufacturing

Figure 4 shows the three main steps used for turbine design and production with complex (profiled) blades. The design loop begins with the analytical sizing. The specifications (nominal operating point) are used to determine the velocity triangles. The blade is then modelled in 3D by CAD (Computer-Aided Design) and numerical simulations (CFD) are performed for several operating points. It is an iterative process allowing to find the optimal geometry for the imposed flow conditions. Once the geometry validated, the 3D CAD model is used to define the machining program for the CNC machine. The turbine is built in one single block with a 5-axis milling machine. This allows the turbine to be machined in a single setup. Thanks to CAM software, the machining program of the CNC machine can be defined largely automatically from the 3D CAD model. The prototype is afterwards tested to validate the numerical results and the turbine
Figure 3. Geometry of the NACA profiled turbine.

Figure 4. Diagram of processes of design and manufacturing of the profiled blades turbine.

performances characteristics. If the experimental results are conclusive, the geometry is validated and the turbine can be produced in series. Otherwise, the design process starts again.

3.2. Performances analysis
To validate the results, the parameter $y^+$ (defined by equation 1) was checked. The use of the k-$\epsilon$ turbulence model requires $y^+$ values between 30 and 300 which was verified for every simulations. A mesh sensitivity analysis was performed to ensure that the results were independent of the meshes sizes. In equation 1, $y$ is the distance to the nearest wall in $m$, $u_\tau$ is the friction velocity in $m/s$ and $\nu$ the kinematic viscosity in $m^2/s$. 

$$y^+ = \frac{y u_\tau}{\nu}$$
\[ y^+ = \frac{u r y}{\nu} \]  

The torque on the turbine shaft is extracted and the mechanical power output calculated according to the equation 2.

\[ P_{\text{mec}} = \frac{2\pi N}{60} T_{\text{mec}} \]  

where \( N \) represents the rotation speed in \( \text{rpm} \) while the \( T_{\text{mec}} \) expresses the torque measured at the turbine shaft in \( \text{Nm} \).

This first step allows checking if the desired output mechanical power of 1kW is achievable. Then, the hydraulic power is calculated according to the equation 3 with \( Q \) the volume flow rate in \( \text{m}^3/\text{s} \), \( \rho \) the water density in \( \text{kg/m}^3 \) and \( H \) the head of the turbine in \( \text{m} \).

\[ P_{\text{hydro}} = Q \rho g H \]  

The equation 4 allows to evaluate the hydraulic efficiency which represents the ratio between the produced mechanical power and the extracted hydraulic power.

\[ \eta = \frac{P_{\text{mec}}}{P_{\text{hydro}}} \]  

**Figure 5.** Performance characteristics of the profiled blades turbine.

As shown in figure 5, the best efficiency point (BEP) is characterized by 60.6 % of efficiency at a volume flow rate of 0.040 \( \text{m}^3/\text{s} \). This efficiency value is characteristic of this type of pico-turbine [10]. The mechanical power output obtained at this operating point is only of 320 W. Thus, to achieve a mechanical power output of 1 kW, it is necessary to increase the volume flow until about 0.057 \( \text{m}^3/\text{s} \). Since the performance curve is quite flat after its peak, the losses corresponding to this operating point (characterized by 0.057 \( \text{m}^3/\text{s} \)) are only 5 % related to the BEP. The power output of 1 kW is therefore not reached under the optimal operating conditions. As the NACA runner blades are directly machined in the mass, their position is fixed and cannot adapt to flow variations.
3.3. Economic analysis
The development and manufacturing costs of the turbine prototype are shown in table 1. The annual electricity production of the turbine is 4400 kWh (4400 h/year) representing a yearly electricity savings of 790 CHF. The return on the investment time for the turbine, excluding development costs, is 3 years.

Table 1. Distribution of the costs of development and manufacturing of the profiled blades turbine.

| Process                  | Duration [h] | Cost [CHF] |
|--------------------------|--------------|------------|
| Design                   | 100          | 6000       |
| CNC program              | 16           | 960        |
| Manufacturing and material| 16           | 1630       |
| Product validation       | 40           | 2400       |
| Total prototype cost     | 172          | 10990      |
| Cost per unit            | 24           | 2100       |

4. Simplified runner blades
The simplified blades are cut from a 3 mm thick sheet and bent. They are welded on a turned hub. The parameters influencing the turbine’s runner geometry are therefore, the thickness of the metal sheet, the blade surface, the bending radius and the angle of the blade with respect to the hub. To analyse the influence of these parameters, three different geometries are designed and simulated. Figure 6 shows the geometrical details of each design considered.

The first design comes directly from the blade angles calculated from the velocity triangles. Since the guide vane angle is fixed, it is possible to calculate the runner blade angle using the nominal flow rate and the rotational speed. No rotational fluid is considered at the runner outlet for the BEP. The velocity triangle is considered at half-height of the blade and allows a guide vane angle of 35° and a blade angle of 23° for a volume flow rate of 0.055 m³/s at a rotational speed of 1000 rpm. The bending radius is 400 mm.

The second design respects the guide vane angle of 35° but the bending radius is reduced to 250 mm. The blade angle is then reduced to 16°. The purpose of this design is to evaluate the influence of a smaller bending radius on turbine performance.

The third design has no bending radius. The flat blade is positioned on the hub at an angle of 29° (see figure 6).

4.1. Simplified approach
For a product or a technology to last in developing countries, it must be locally controlled and produced. The missions carried out together with CEAS in Madagascar showed that the machining of the blades with a profile was not possible. Moreover, CNC machining is not yet integrated into the current production processes. Thus, an alternative manufacturing solution, based on conventional machining, welding and sheet metal skills, was then studied. The aim was to provide manufacturing drawings and cut-out templates required for mass production. Thus, in addition to mastering manufacturing technologies, the service provider should be able to manage independently the maintenance process.
Figure 6. Geometrical dimensions of the three simplified runner blades design.

Figure 7. Diagram of process of design and manufacturing of the turbine with simplified runner blades.

4.2. Design and manufacturing

Figure 7 shows the three main steps used for turbine’s design and production with simplified blades. The design loop is almost identical to that for the profiled blades. The difference is that
the only parameters changing to achieve the best performance are the constant blade thickness and bending radius. Once the geometry validated, a prototype can be manufactured. Unlike the other turbine, machined in one single block, the simplified turbine is a mechanically welded assembly. In the beginning of the prototyping loop, the turbine’s hub must be manufactured by conventional turning. In the same time, a die to bend the runner blades, which are cut in a sheet metal, is manufactured. Stamping is done manually. Finally, the curved blades are welded to the hub. The prototype is then tested to validate the turbine performances. If the experimental results are conclusive, the geometry is validated and the turbine can be produced in series.

4.3. Performances analysis

Five operating points per runner blade design are simulated. They are all located around their respective BEPs. The validation and the analyses of the results are carried out in the same way as for the profiled turbine. Figure 8 compares the performances of the three designed and simulated designs. It appears that the three efficiency curves are similar in shape but have different offsets. The design no. 2 has the best efficiency of 59.2% for a volume flow rate of 0.060 m³/s. The BEPs of designs no. 1 and no. 3 are both at a flow rate of 0.070 m³/s. For the design no. 1, the best efficiency reaches 58.4% while for the design no. 3 only 55.2%. Concerning the shaft power output, the three curves obtained have also the same shape with offsets related to the volume flow rate. To achieve a mechanical power output of 1 kW with design no. 2, the flow required is about 0.067 m³/s, whereas for designs no. 1 and no. 3 the flow rates required are 0.072 and 0.074 m³/s respectively.

Thus, from all studied designs of simplified runner blades, the design no. 2 is the most interesting, both in terms of its maximum efficiency and its flow rate for a power of 1 kW. It is interesting to note that for this design, the 250 mm bending radius is the smallest of the three.

![Figure 8. Performance characteristics of the simplified blades turbine.](image)

4.4. Economic analysis

The development and manufacturing costs for the turbine prototype are illustrated in the table 2. The annual production of the turbine is 2200 kWh (4400 hours of full load operation) equivalent to an annual saving of 400 CHF. The return on the investment time for the turbine, excluding development costs, is 6 years.
Table 2. Distribution of the costs of development and manufacturing of the simplified blades turbine.

| Process                              | Duration [h] | Cost [CHF] |
|--------------------------------------|--------------|------------|
| Design                               | 80           | 4800       |
| Conventional turning and material    | 1            | 180        |
| Matrix manufacturing and material    | 2            | 210        |
| Folding of blades and material       | 4            | 290        |
| Welded joint                         | 16           | 1280       |
| Product validation                   | 40           | 2400       |
| Total prototype cost                 | 143          | 8520       |
| Cost per unit                        | 32           | 2230       |

5. Comparisons

5.1. Performances comparison

As described in subchapter 4.3, the design no. 2 provides the best performance of the turbine for the studied simplified runner blades. Therefore, only its results in terms of performance efficiency and economy will be compared in figure 9 to the ones obtained with the NACA profiled blades. The maximum efficiency value of the two turbines is very close with a difference of only 1.4 % at their respective BEPs. On the other hand, the BEP of the NACA profiled turbine is achieved at 0.040 \( m^3/s \) while for the simplified turbine with design no. 2 it is at 0.060 \( m^3/s \). Moreover, for a nominal flow rate of 0.055 \( m^3/s \), the two turbines provide similar efficiency values with 57.2 % for the simplified turbine and 56.5 % for the NACA profile. When looking at the mechanical power output, the NACA profiled turbine satisfies entirely the power expectations with about 1 kW mechanical power produced at 0.057 \( m^3/s \). The simplified turbine allows also to produce 1 kW mechanical power output but for a higher volume flow rate of 0.067 \( m^3/s \).

![Figure 9](image-url)  

Figure 9. Performance comparison between the NACA profiled turbine and the simplified turbine with design no. 2.
5.2. Economic comparison

Based on the production costs in Switzerland, it appears that the turbine with profiled blades is slightly cheaper (2100 CHF/unit) than the turbine with simplified blades (2200 CHF/unit). This is mainly due to the manufacturing time, relatively decreased when using advanced manufacturing technologies. However, CNC-5-axis machines, which are essential for machining profiled blades, have an acquisition cost that is exorbitant for developing countries and thus one should consider only the simplified runner blades approach to have a competitive pico turbine in order to ensure the necessary power output.

6. Conclusions

This article presents the different steps when sizing a low-cost pico turbine for developing countries. Three simplified turbine designs were proposed and investigated. They were compared with a standard profiled turbine with NACA runner blades. The simplified turbine geometry is based on conventional manufacturing methods available in developing countries, while the one with the NACA blade profile requires very expensive CNC machining operations. CFD simulations showed that the BEP is characterized by 59.2% at 0.060 m$^3$/s for the simplified turbine with blade design no. 2 and by 60.4% at 0.040 m$^3$/s for the turbine with profiled blades. The mechanical power output of 1 kW is reached for a flow of 0.057 m$^3$/s with the NACA turbine against 0.067 m$^3$/s for the simplified turbine with design no. 2. Considering that the stream allows reaching a volume flow rate of 0.067 m$^3$/s, the simplified turbine (design no. 2) is thus very interesting considering its simplicity of manufacture. A manufacturing cost estimate reveals a production price of about 2000 CHF/unit for both the NACA profiled turbine and the simplified one. However, the price of a CNC-5 axis, indispensable for machining a profiled blade, is extremely high. Therefore, the simplified turbine is a pragmatic solution, adapted to developing countries, with a very small difference in efficiency compared to a conventional turbine with NACA profiled blades.

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