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Design and performance evaluation of a substitution solution for spiral casing of pico-hydroelectric plants

Design and performance evaluation of a substitution solution for spiral casing of pico-hydroelectric plants

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Abstract. A test bench for Kaplan and Francis pico-turbines was developed at the University of Applied Sciences of Fribourg (Switzerland) to test different axial turbine designs from 0.3 to 6 kW. Using the experimental results, this test bench allows comparing the results of the CFD simulations and of the measurements of the tested turbines. During the test rig design, due to the different specific components of the axial turbine, a new concept was developed to replace the spiral casing. The current paper presents the new design of a substitution solution for the spiral casing of pico-hydroelectric plants and its performance compared to the standard solution by numerical simulations. The new concept, called "water-box", had to fulfil some criteria: allow adapting to different geometrical dimensions (turbine diameters from 100 to 250 mm) as well as to different flow conditions (flow rate of up to 0.065 m^3/s and to a pressure range up to 10 bar), while ensuring the same uniform flow distribution as with a standard spiral casing. In the same time, it had to allow optimizing other parameters like the space needed and the costs. The idea is to keep the principle of a sideway inlet and an axial outlet but using standard elements of industrial piping to reduce the costs. With this geometry, the fluid is naturally rotated and pushed towards the axial exit. There, a convergent pipe is mounted and finally, a stabilization grid which homogenizes the flow and break the rotation before the turbine. The performances of the new concept were evaluated and the results compared with a "standard" designed spiral casing by CFD simulations. The results showed that with the "water-box", the pressure losses are 22 times higher. Nevertheless, the manufacturing simplicity of the water-box compared to the spiral casing achieves a substantial costs reduction of about 65 %. Thus, all the criteria were fulfilled. This simplicity associated with performances, which remain very interesting open new fields of application notably for pico-hydroelectric turbines installed for example on domestic sites.

1. Introduction

Pico hydro plants (in the range of some kW), equipped with Kaplan turbines, are very useful to provide electricity to isolated infrastructures (for example a workshop or a small house) when far from the grid or they can be used as auxiliary power supply for infrastructures connected to the grid. To study pico hydro plants, the University of Applied Sciences in Fribourg (HEIA) [1] has designed a test rig for turbines in the range of 0.3 to 6 kW that is adaptable to fit different turbine diameters from 100 to 250 mm. Within this design, a spiral casing being very expensive to manufacture, the Institute for Applied Research into Energy Systems (ENERGY)

[2] and the Sustainable Engineering Systems Institute (SeSi) [3] have developed a water-box for axial pico-turbines as substitute for the spiral casing. The water-box reduces significantly the manufacturing and installation costs of the pico turbine, inducing nevertheless a loss of efficiency. To implement this design, three potential markets are targeted: isolated infrastructures (far from grid), domestic installations as auxiliary power supply and developing countries. Thus, these pico hydro plants have to be cheap in order to achieve return of investment over a reasonable period.

The purpose of this paper is to present the economic advantages of a water-box related to a spiral casing for axial pico turbines subject to intermitent operating times. The main purpose is to identify how the relatively cheap development and manufacturing costs of this new component compensates the lower efficiency of the water-box.

2. Approach

The main idea is to replace the spiral casing with a water-box. The main advantage is that, using standardized components of industrial piping in order to manufacture the water-box leads to a cheaper and easier fitting solution than the spiral casing.

A spiral casing is sized and its performance evaluated by numerical simulations (CFD) for the axial pico-turbine already installed in the test rig of the HEIA. The manufacturing process and costs are then analysed together with the Swiss company Stephan SA [4], specialized in welded construction.

In parallel, a water-box is designed to obtain the same flow conditions at the turbine inlet as the ones with the spiral casing. The water-box system is easily adjustable to fit different turbine diameter sizes, by simply adding a convergent between the water-box and the turbine. The water-box performances are evaluated by CFD simulations. Similar to spiral casing, a complete analysis of the design and manufacturing processes are performed together with Stephan SA.

Finally, the water-box and the spiral casing are compared from economical point of view. The water-box is much simpler to manufacture and to install than the spiral casing, thus reducing drastically the investment costs. However, its efficiency is lower than the one of a spiral casing. A quantification of the time duration on which implementing a water-box instead of a spiral casing is performed depending on the operating profile.

2.1. Studied configurations

To characterize the water-box as well as the spiral casing, the performances of a pico turbine designed at the HEIA are simulated close to its best efficiency point (BEP). The four-blades axial turbine in figure 1 has fixed blades with constant NACA profile [8]. Fixed guide vanes whose geometry is adjusted according to the configuration studied create the pre-rotation of the fluid. Their position and place related to the runner depends on the 2 studied configurations: with water-box and with spiral casing.

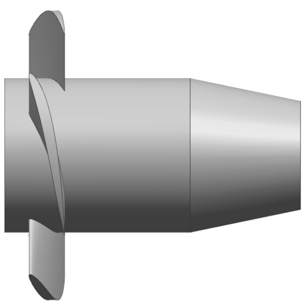

Figure 1. Turbine used to characterize both spiral casing and water-box.

When spiral casing configuration is used, the guide vanes are radial. The figure 2 shows the configuration studied for the spiral casing.

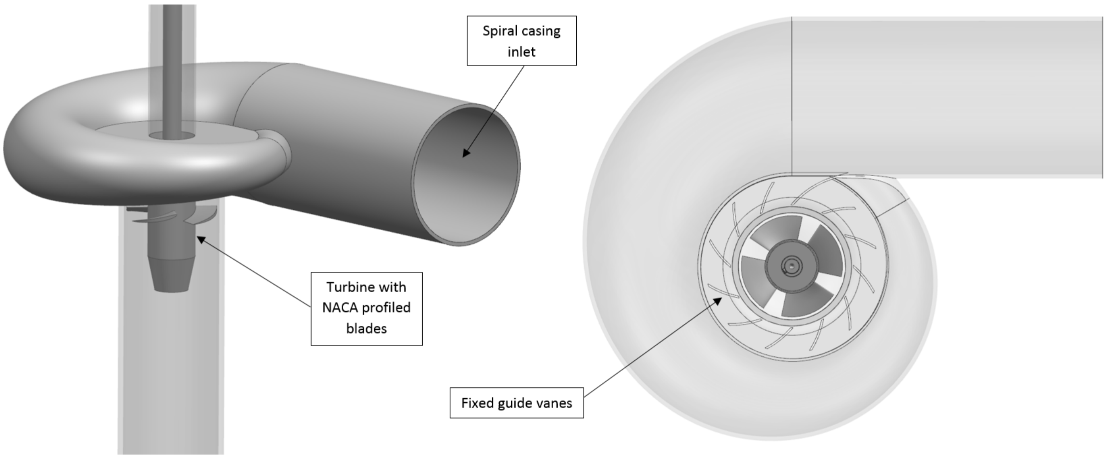

Figure 2. Spiral casing configuration.

The water-box has no integrated guide vanes: its purpose is to homogenize the flow. Guide vanes located downstream of the water-box are required to create a pre-rotational flow, as shown in the figure 3.

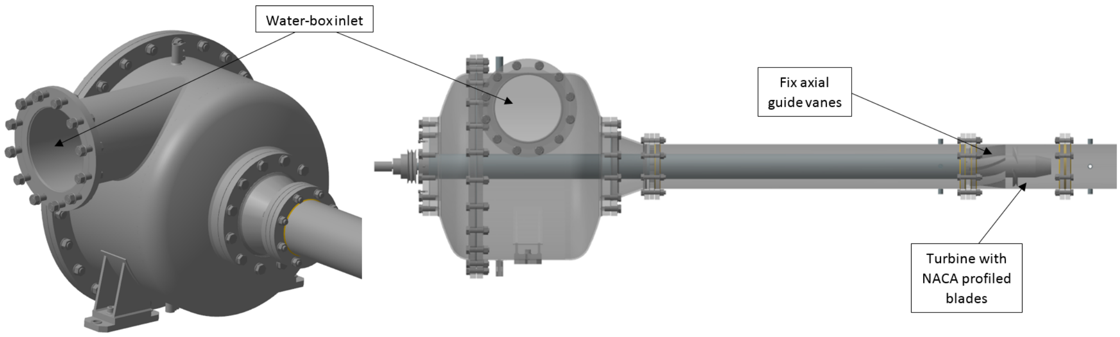

Figure 3. Water-box configuration.

2.2. General hypotheses

2.2.1. Numerical analysis (CFD). All simulations are steady state, Reynolds averaged Navier-Stokes (RANS), and use the k-ϵ turbulence model. Five operating points for both configurations are simulated close to the turbine BEP. The nominal operating conditions of the turbine are 0.040 m^3/s volume-flow rate and 1000 rpm rotation speed. Volume flow rates are simulated in the range 0.030 to 0.055 m^3/s with increments of 0.005 m^3/s. A periodic flow assumption allows the use of symmetries for the turbine and the outlet pipe. The spiral casing and the water-box are both fully (without symmetries) simulated in order to check the flow homogeneity at the outlet. A mass flow rate at the inlet and a relative pressure at the outlet are imposed as boundary conditions.

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2.2.2. Economic analysis. The costs comparison for the development, manufacturing and operating processes is based on Swiss prices. Thus, the development costs are based on an hourly rate of 60 CHF. Manufacturing costs depend on the material and on the manufacturing techniques used. They are based on the offers made by Stephan AG. The operating costs are based on an average electricity price in Fribourg in 2018 of 17.86 cts/kWh [6] and the turbine operating time is estimated at 4400 $hours/year$ at full load [7].

3. Spiral casing.

The distance between the centres of the inlet and outlet pipes diameters for the spiral casing corresponds to the dimensions of the test rig [1]. The diameter of the inlet pipe is 250 mm. The output section is annular for the shaft located in the center and measures 175 mm for the outer diameter and 88 mm for the inner diameter. The spiral casing has 12 fixed guide vanes visible in figure 2.

A version intended for industrial production has also been designed and is shown in figure 4. The different parts allow the spiral casing to be manufactured by rolling sheet metal. In addition, the standardised flanges allow the spiral casing to be connected to the upstream and downstream pipes. For numerical simulations, the version visible in figure 2 is used.

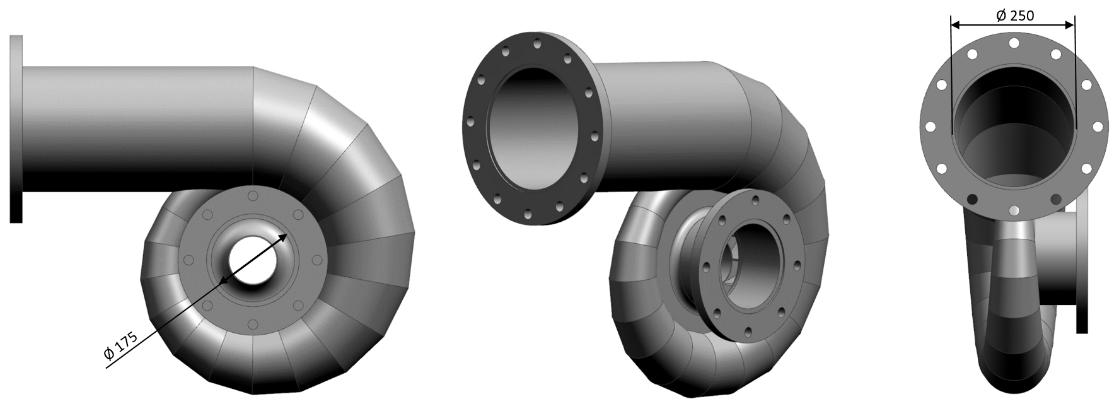

Figure 4. Spiral casing design for manufacturing.

3.1. Design and manufacturing

Figure 5 shows the three main steps used for the design and manufacture of the spiral casing. The design loop begins with the analytical sizing. The geometry is designed in 3D by CAD (Computer Aided Design). Numerical simulations (CFD) are performed for several operating points to analyse the performance. Once the geometry has been validated, the CAD model is used to produce the manufacturing drawings. Due to the manufacturing process, a thorough analysis of the manufacturing techniques and the selected materials is necessary to attest compliance with the required level of resistance to pressure. This mandatory step for manufacturing certification and commissioning is expensive. Finally, the manufacturing is a two-steps process: the machining of the spiral casing's core (including the guide vanes) and then the cutting and rolling the sheet metal for the spiral. An accurate and specific positioning is required to weld the different parts together. Once the various quality controls being performed, the spiral casing can be installed and tested.

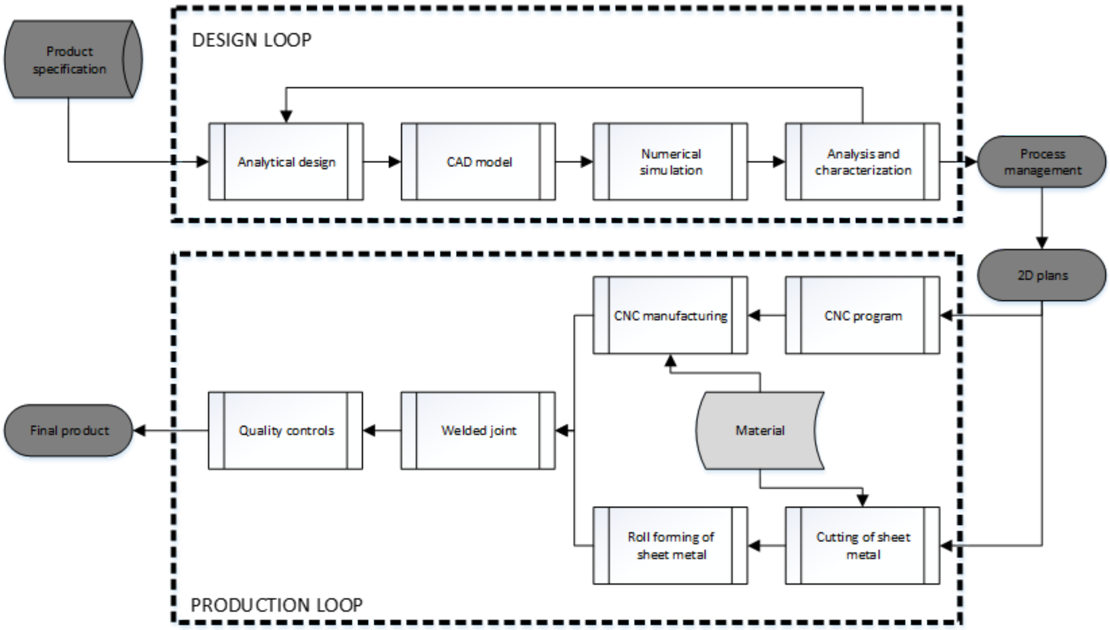

Figure 5. Diagram of design and manufacturing for the spiral casing.

3.2. Performances analysis

The turbine efficiency curve is calculated according to equation 1, and shown in the figure 6:

$$\eta = \frac{P_{mec}}{P_{hydro}} \tag{1}$$

where P_{mec} is the shaft power output in W and P_{hydro} is the hydraulic power in W. The mecanical power (equation 2) is calculated by considering the torque (T_{mec}) on the runner in Nm:

$$P_{mec} = \frac{2\pi N}{60} T_{mec} \tag{2}$$

where N is the rotational speed in rpm. The hydraulic power (equation 3) in W is considered and evaluated between the inlet of the spiral casing and the end of the outlet pipe:

$$P_{hydro} = Q\rho g H \tag{3}$$

where Q represent the flow rate in m^3/s, ρ the water density in kg/m^3, g the acceleration due to gravity in m/s^2 and finally, H is the net head in m.

As the equation 3 shows, the losses induced by the spiral casing are taken into account in the calculation of the turbine's overall efficiency. The best turbine efficiency reaches 60 % for a flow rate of 0.04 m^3/s thus providing a mechanical power output of 360 W.

3.3. Economic analysis

The development and manufacturing costs of the spiral casing are distributed according to table 1. For the economical analysis, a volume flow rate of 0.050 m^3/s is used. Thus, at this flow rate the turbine with spiral casing provides a mechanical power output of 750 W with a drop in efficiency of only 3 % compared to the BEP and it produces approximately 3300 $kWh/year$.

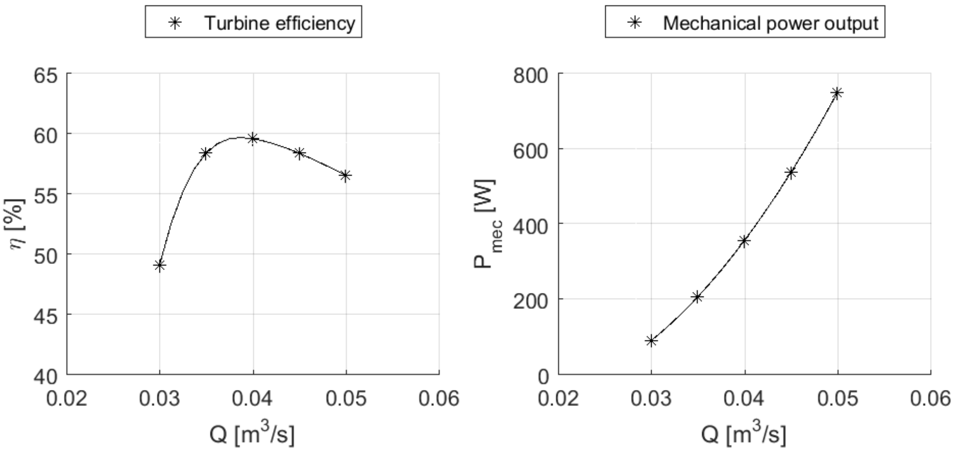

Figure 6. Turbine (with spiral casing) performances characteristics at 1000 rpm.

Table 1. Distribution of spiral casing development and manufacturing costs.

Process	Duration [h]	Cost [CHF]
Design	120	7'200
Manufacturing and material	240	45'000
Product validation	40	2'400
Total product cost	400	54'600

4. Water-box

The distances between the centres as well as the different diameters for the inlet and outlet pipes are similar to those of the spiral casing. As shown in figure 7, a grid is placed at the water-box outlet to restrict the flow rotation. The guide vanes are located in the annular outlet pipe, 1300 mm from the water-box outlet.

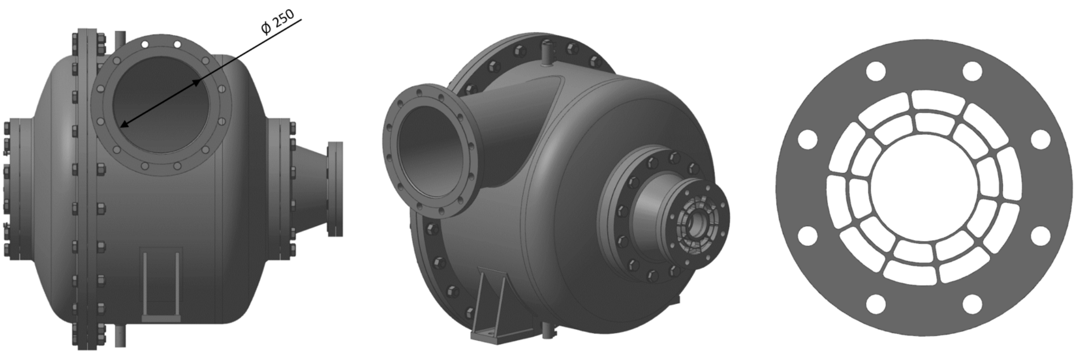

Figure 7. Water-box design and stabilization grid.

4.1. Manufacturing approach
The use of standardized industrial pipe components (DIN 2576, DIN 28011, DIN 2616, EN 10216-1) welded together to build the water-box reduces drastically the manufacturing costs.

4.2. Design and manufacturing

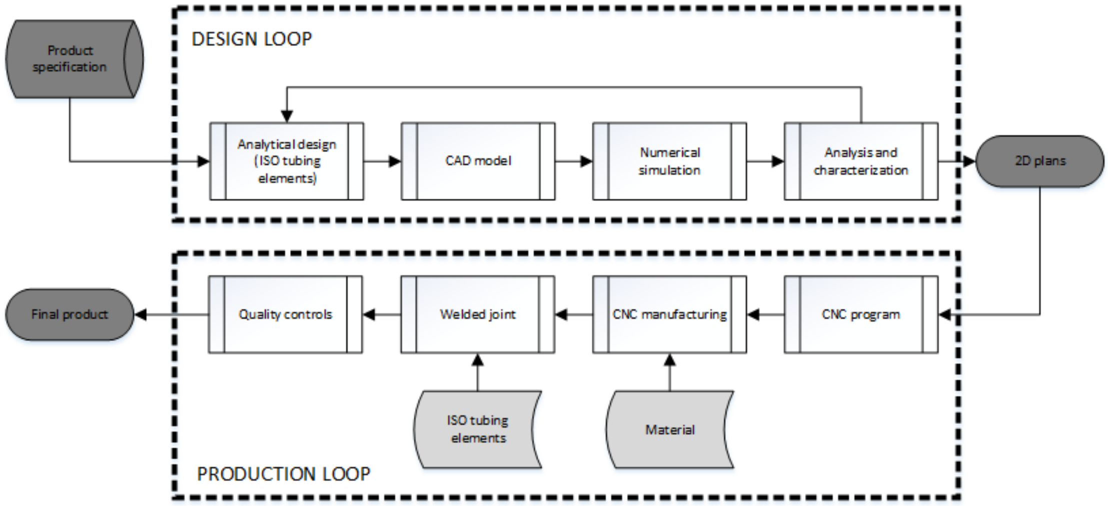

Figure 8. Diagram of design and manufacturing processes of the water-box.

Figure 8 shows the three main steps required for the design and production of the water-box. The design loop is almost identical to the one of the spiral casing, the only difference being that the sizing is based on existing standard elements. Therefore, a good compromise is found between different parameters (diameters, positioning and size), the performances obtained and the location on the site, in order to develop the most suitable technological solution.

Using only standard components, all of them certified to operate under pressure, the manufacturing becomes extremely simplified and reduced compared to the one of the spiral casing. The only machined component is the stabilization grid.

4.3. Performances analysis
The performance parameters are calculated in the same way as in subchapter 3.2. Figure 9 shows a very low turbine efficiency with a value of roughly 28 % associated with a flow rate of 0.045 m^3/s. The mechanical power output produced is 450 W. The BEP doesn't precisely match with the 0.040 m^3/s flow rate due to the slightly smaller blade angle of the guide vanes than the one in the spiral casing.

Very high pressure losses in the water-box explain the low efficiency value. The distribution of losses is analyzed in subchapter 5.1.

4.4. Economic analysis
The development and manufacturing costs of the water-box are shown in table 2. For the economic analysis, a flow rate of 0.050 m^3/s is considered, which allows a power output of 640 W. The efficiency is the same as the one at the BEP. The turbine's annual production with the water-box is approximately 2800 kWh.

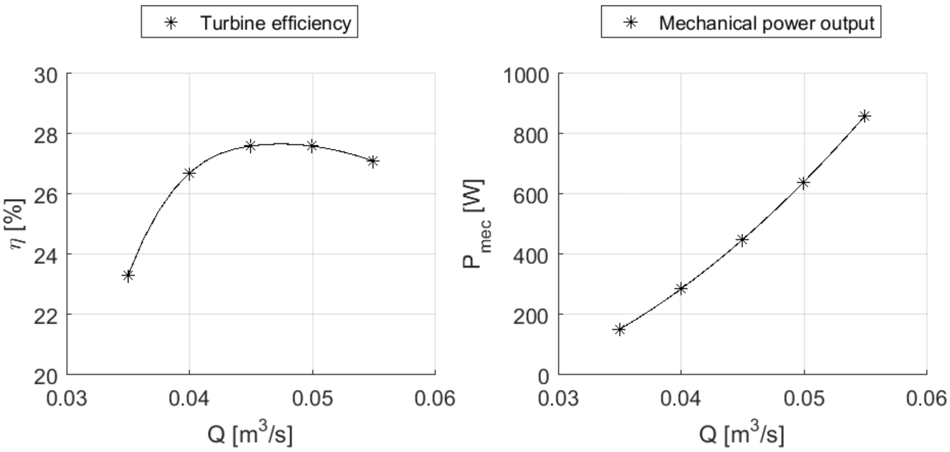

Figure 9. Turbine (with water-box) performances characteristics at 1000 rpm.

Table 2. Distribution of water-box development and manufacturing costs.

Process	Duration [h]	Cost [CHF]
`Design`	120	7’200
`Manufacturing and material`	80	10’000
`Product validation`	40	2’400
`Total product cost`	240	19’600

5. Comparison

For comparison purpose, the flow rates for both the water-box and the spiral casing are assumed to be guaranteed independent on the real installation of the pico turbine. In addition, to compare the two turbines performances under similar conditions, a flow rate of 0.040 m^3/s is used.

5.1. Performance comparison

For the same flow rate of 0.040 m^3/s, the pressure losses in the water-box reach 16’000 Pa compared to only 720 Pa in the spiral casing, which means about 22 times higher at this operating point. The flow is entirely guided in the spiral casing, unlike in the water-box, where strong backflows lead to high pressure losses. Figure 10 represents the pressure losses distribution for each component for both spiral casing and water-box configurations. The efficiency of the turbine with spiral casing (60% - Figure 6) is higher than the one with water-box (28 % - Figure 9). The losses occur mainly in the runner (about 95 % of total losses) for the spiral casing configuration while they represent only 5 % of the total losses, in the spiral casing, as shown in figure 10. The same figure 10 shows that 59 % of the overall losses for water-box configuration occur inside this water-box, due to strong backflows, while in the runner they are reduced at 40 % of the total losses. The loss of potential energy inside the water-box can be reduced by adding guiding components (similar to guide vanes) to prevent the backflows. This solution has nevertheless the disadvantage to increase the manufacturing costs and to lose the simplicity of the initial design. Finally, for the same flow rate of 0.040 m^3/s, both turbines with spiral casing and with water-box produce power outputs in the same order of magnitude: 360 W for the spiral casing configuration and 290 W for the water-box configuration (see figure 11), meaning a relative difference of less than 20 %.

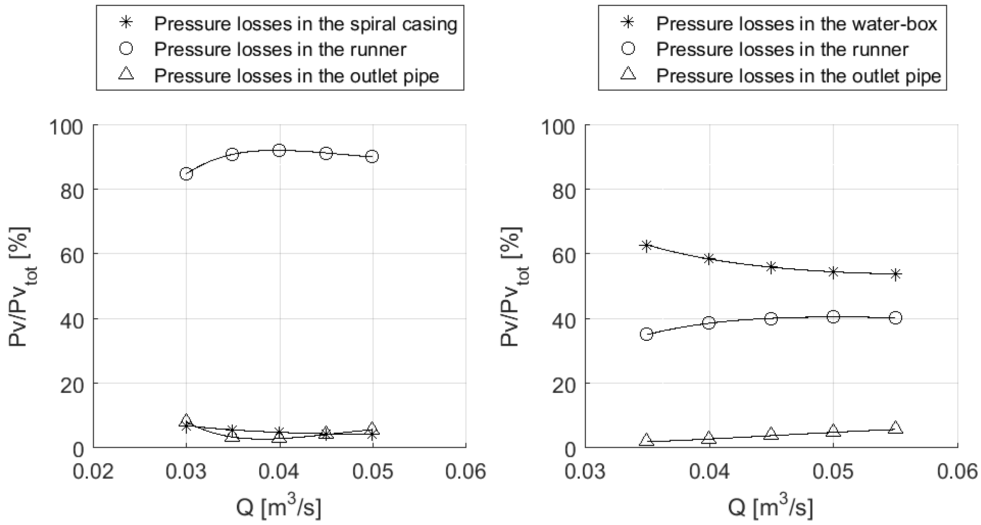

Figure 10. Pressure losses distribution for the spiral casing configuration (left) and the water-box configuration (right).

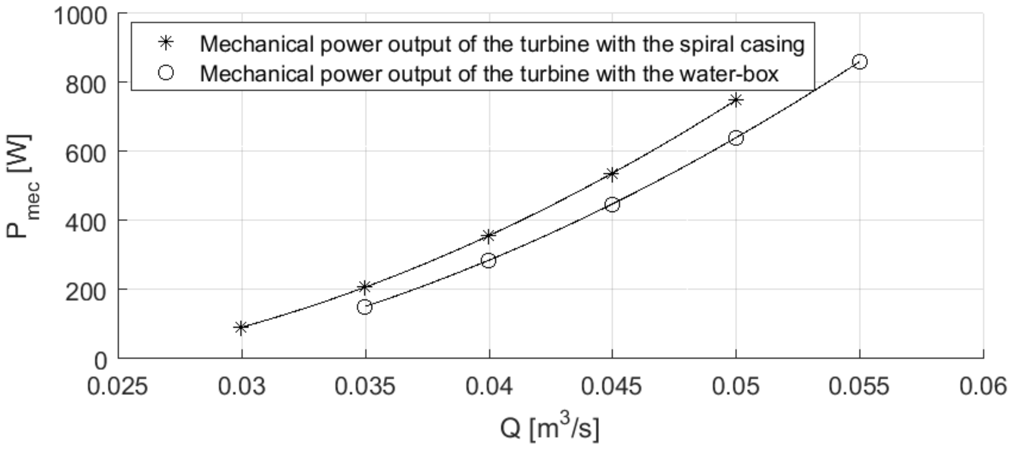

Figure 11. Shaft power output comparison of the turbine in 2 configurations.

5.2. Economic comparison

For an equivalent volume flow rate of 0.050 m^3/s, the turbine with the spiral casing produces about 3300 kWh/year compared to 2800 $kWh/year$ for the one with water-box corresponding to a very low economic loss of operating costs of 100 $CHF/year$. However, the price difference for the development and manufacture of the spiral casing compared to the water-box reaches 35'000 CHF. Therefore, the water-box configuration is more competitive during all its operation lifetime than the spiral casing configuration under the same operating conditions.

6. Conclusions

A water-box for pico hydro turbine is designed and developed to substitute the spiral casing in order to have an adapted, simpler and cheaper solution for isolated infrastructures, for domestic auxiliary power supply or for developing countries. Both solutions are investigated from performance and economical point of view. With the spiral casing, the BEP of the turbine is of 60 % for a flow of 0.040 m^3/s, while with the water box, it drops to 28 % for a flow of 0.045 m^3/s. This is due to large backflows in the water box, which cause high-pressure drops. 59 % of the total losses are caused by the water box, while the spiral casing produces only 5 % head loss. Nevertheless, despite its lower efficiency, the water box remains a very interesting solution because its development and manufacturing costs are much lower than those of a spiral casing. The results show that the water-box is extremely cheap to manufacture compare to the spiral casing as it is built as an assembly of standard components welded together. The water-box can also be adapted to different turbine sizes unlike the spiral casing. Despite a lower efficiency, due mainly to backflows, the water-box remains competitive over its whole operating lifetime as long as the pico turbine is operated sporadically, ie 50 % compared to a 24/7. Finally, the water-box performances can be improved by reducing the backflows, thus increasing its efficiency.

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