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Design of small Pelton, Kaplan and Diagonal turbines, from laboratory tests until manufacturing drawings, or an innovative development to guarantee a high long-term production

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Abstract

This article describes the steps that lead to the final design of small Kaplan, Diagonal and Pelton turbines, so just before manufacturing, using the systematization approach. Details are given on how high performances can be reached and guaranteed on a long-term basis, as well as cost efficiency.

The systematized development steps are explained from the definition of the first scale models especially designed for small hydro specificities, based on CFD modelling, laboratory tests, to hill charts definition.

An overview is also given on how this approach has led to create 3D tools to generate drawings of the hydraulic and mechanical design of each turbine, more quickly and with a higher accuracy than usual 2D drawings, while using structural calculations.

The paper ends with the current development of a spiral-casing Diagonal scale model.

1 Introduction

Small hydropower [SHP] challenge is to deal with low economic limits while facing some similar technical issues (hydraulic and mechanical) as large hydropower. Indeed SHP is characterized by a limited budget for each project due to the limited output, critical economic issues, which means limited R&D, a simplified design, enhancing spurious phenomena, and also some small economic actors, thus a high relative financial risk.

In front of these statements, Mhylab has been working, since 1993, on a large concept of turbine systemization. This concept uses different development steps, the main one being the laboratory tests, so as to generate the final manufacturing drawings of the turbine while fulfilling the specific requirements of small hydro in terms of performance to cost ratio, high flexibility, and a relative simplicity regarding manufacture, operation and maintenance.

2 Three types of turbine to cover the small hydropower field

As shown on Figure 1, Mhylab has chosen to cover the area of small hydropower between 10 till 5000 kW and for heads between 1.5 and 1000 m with three types of turbines:

- Kaplan, or, more precisely said, Axial turbine, until 30 meters, with also a Siphon profile and a specific configuration for very low heads,
- Diagonal turbine, between 25 and 80 meters,
- Pelton turbines from 60 meters.

Apart from the Diagonal lower limit, the head limits are mainly defined by cavitation constraints.

Up to now, Francis are not part of the development and replaced mainly by Diagonal turbines, as they are more flexible, then more efficient with variations of heads and discharges (cf. Figure 4).

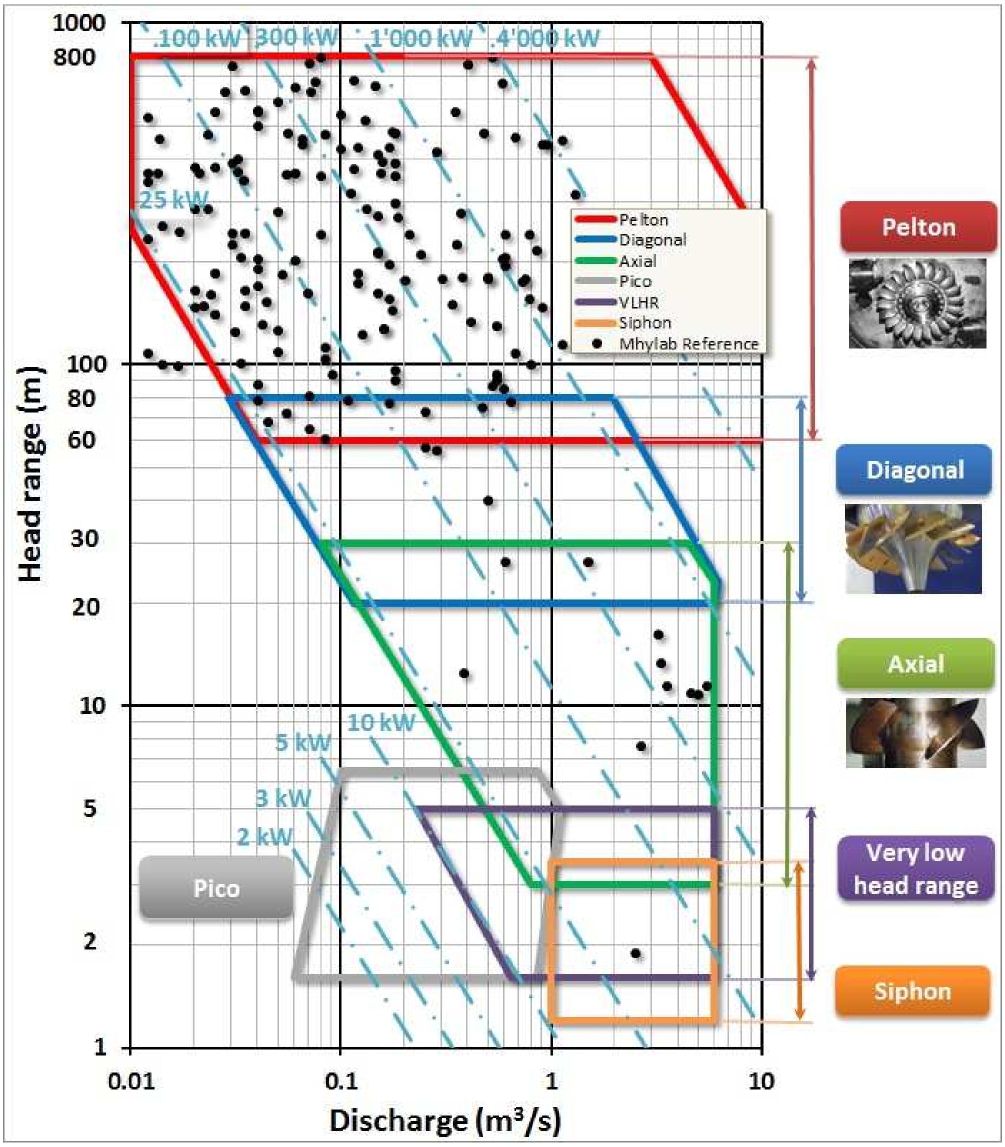

Figure 1 : Division of the small hydropower area with 3 main types of turbine (© Mhylab)

As for now, for Axial and Diagonal [1], the profiles are defined by an S-shape configuration and a single regulation (adjustable runner blades and fixed guide vanes). However, double regulation with a spiral casing is currently studied, as described in chapter § 0.

Regarding Pelton, the systemization approach has been used for vertical-axis configuration with 1 to 4 nozzles, and for horizontal-axis one with 1 or 2 nozzles.

3 Systemization

Systemization is the approach Mhylab has chosen to design turbines specific to SHP. This approach has the same objective of cost reduction as standardization, but implying a better turbine hydrodynamic behavior and thus less risks. It may be recalled here that standardization is based on a limited number of turbine profiles, each one defined for a more or less wide domain of heads and nominal discharges. Thus the wider the domain, the higher the risk of losing production and increasing operation costs due to hydraulic dysfunctions.

On the contrary, systemization aims at designing each turbine specifically for the characteristics of the site. On the test bench, this means that no-dimension figures, hill charts, similitude laws and figures from the fluids mechanisms area are used.

It can be added that the final turbine does not need to be tested again as the laboratory tests have been achieved upstream.

The used no-dimension figures are the following ones :

- For Kaplan and Diagonal turbines:

$$\varphi = \frac{Q}{s \cdot R^3 \cdot N} \qquad \psi = \frac{2 \cdot gH}{N^2 \cdot R^2} \qquad [-]$$

- For Pelton turbines:

$$\varphi = \frac{8.Q}{\pi.D_1 \cdot N.B_2^2} \qquad \psi = \frac{8 \cdot gH}{N^2 \cdot D_1^2} \qquad [-]$$

With:

gH = specific hydraulic energy supplied to the turbine [J/kg]
g = acceleration due to gravity [m/s^2]
H = net head [m]
RN = peripheral speed of runner [m/s]
R = external runner radius [m]
B_2 = maximal internal width of the bucket [m]
D_1 = Injection diameter [m]
N = angular speed [s^{-1}]
Q = turbine discharge [m^3/s]
s = relative reference area (no-dimension runner discharge area), [-]
a = characteristic of each type of turbine [-]

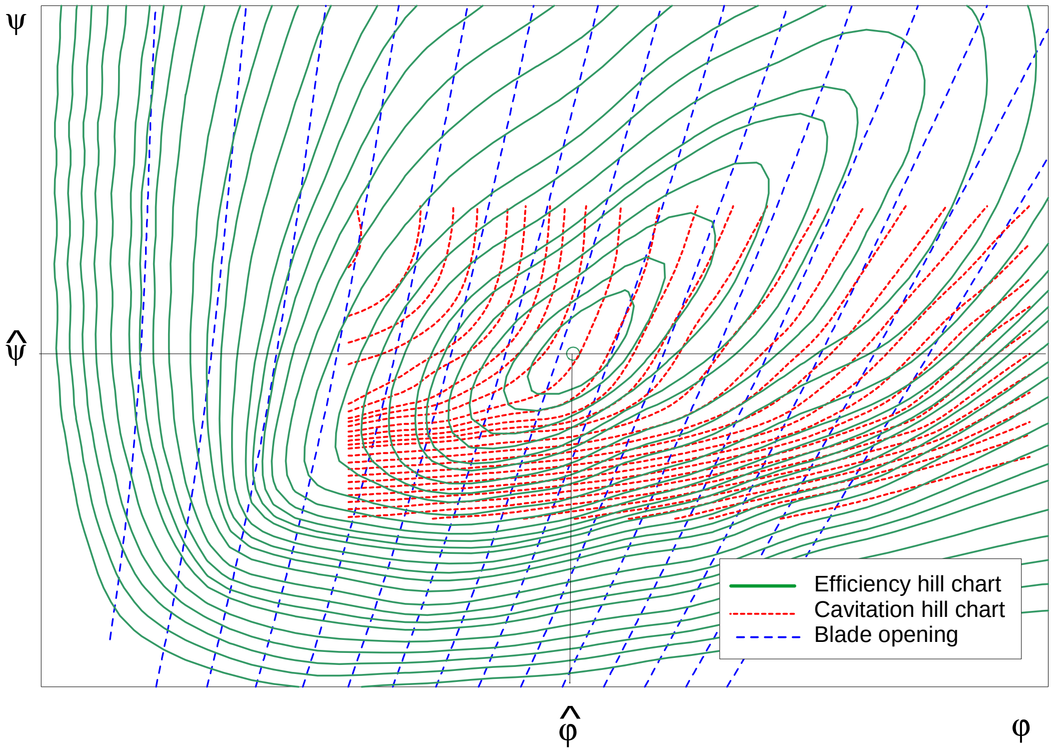

Figure 2 : Example of a hill chart for the scale model of a single-regulated Axial turbine (© Mhylab)

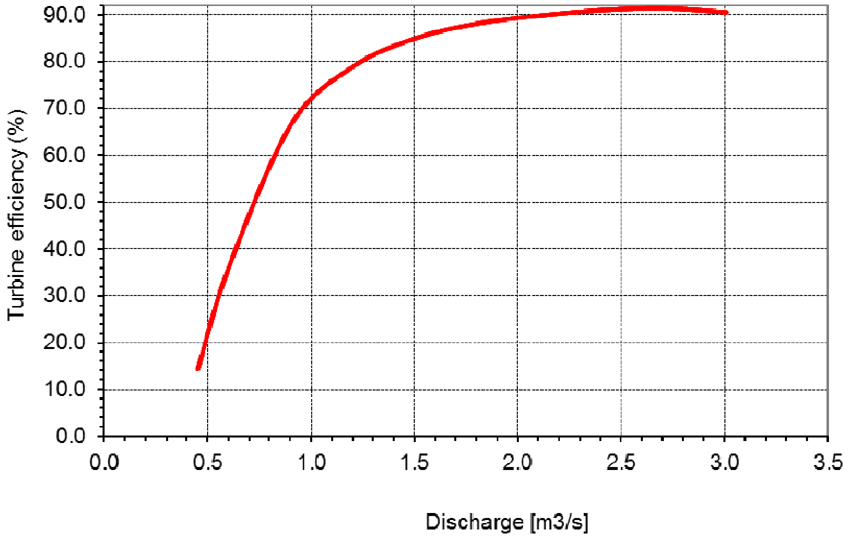

Figure 3 : Turbine efficiencies for a <u>*single*</u>*-regulated 6-blade Kaplan turbine (Qn = 3.01 m*^{3}*/s, Hn = 16.3 m, 500 rpm, Pm = 435 kW) (© Mhylab)*

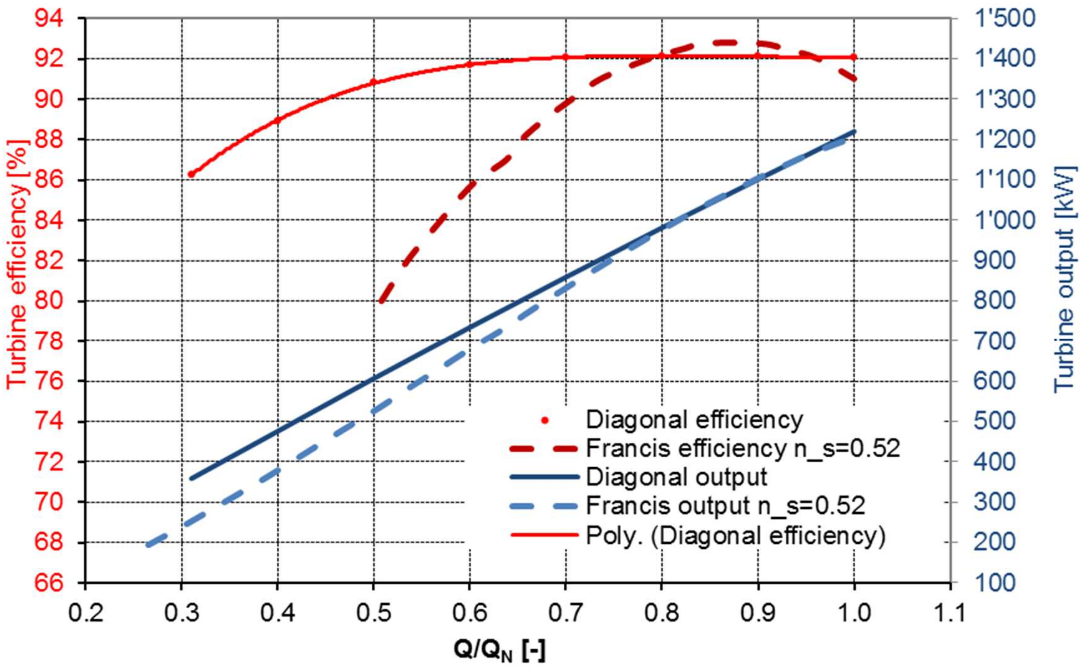

Figure 4 : Turbine performances for a double-regulated 12-blade Diagonal turbine compared to a Francis turbine
(Qn = 1.76 m^3/s*, Hn = 76.8 m, 1000 rpm, Pm = 1220 kW) (© Mhylab)*

Finally this method allows to pass from the scale model to the turbine especially designed for the site, while guaranteeing its hydrodynamic behavior and its efficiencies regarding the discharges and heads (cf. Figure 3 and Figure 4).

4 Definition steps, upstream from the laboratory tests

After the identification of the market needs, the development project carries on with a theoritical study based on the state of the art, mainly from the large hydropower, and on the basic principles of the fluid dynamics. The objective here is to define a first turbine design that gathers all the identified needs. It implies to define, on one hand, the possible simplifications so as to reduce the costs while maintening a high hydrodynamics quality. On the other hand, the elements that have an impact on the performances have to be identified. The scale model will have to be designed so that a perfect homology with the impacting elements can be respected while manufacturing the turbine.

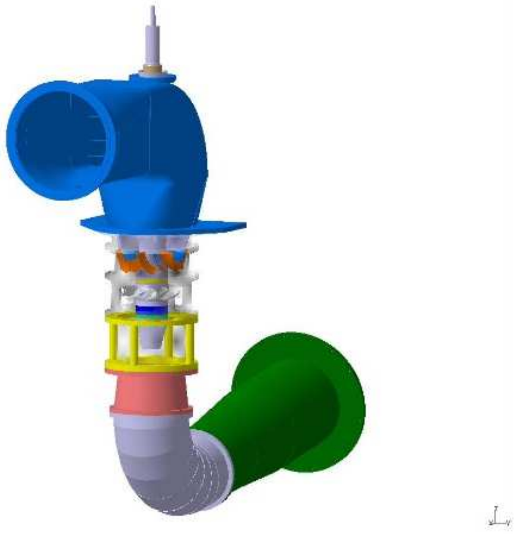

Figure 5 : 3D design of the scale model of the Axial turbine (© Mhylab)

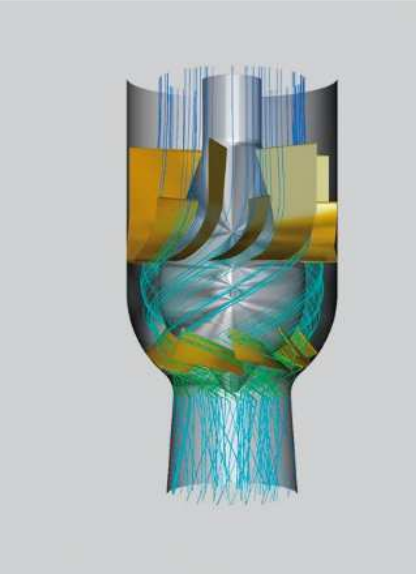

Figure 6 : CFD achieved on the single-regulated Diagonal runner for an S-shape (© HSLU)

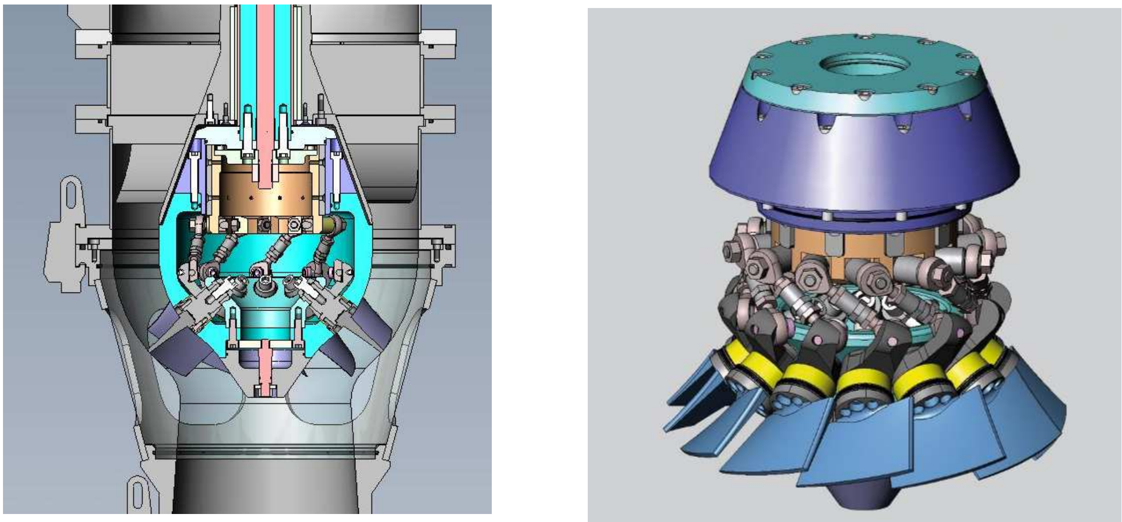

Figure 7 : Study of the mechanical design of the runner equipped with 8 blades (on the left hand-side) and with 12 blades (on the right hand side) of the Diagonal scale model (© CRSM)

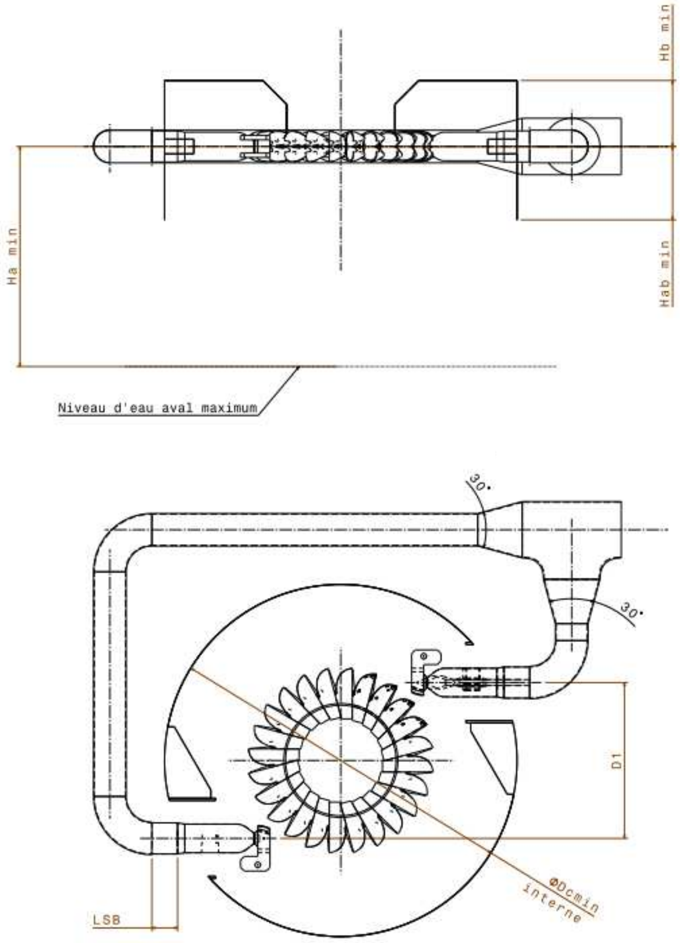

Figure 8 : Systemized hydraulic profile of the manifold and the casing for a 2-nozzle turbine (© Mhylab)

For example, for Pelton turbines, it has been identified that, for a certain output range, the manifold could be composed mainly of elbows and tes from the shelf (cf. Figure 8), whereas the runner and casing have to be in homology with the scale model (cf. Figure 21).
This development step is followed by the optimization of the hydraulic design using CFD (computational fluid dynamics), in order to come closer as possible to the initial objectives of performances, suction heads and other operation characteristics.

These studies lead to define a first parametered hydraulic design, as shown on Figure 8 and Figure 9 for a Pelton turbine, that will be then detailed and validated through laboratory testing. After the achievement of these definition steps, the laboraty tests can start.

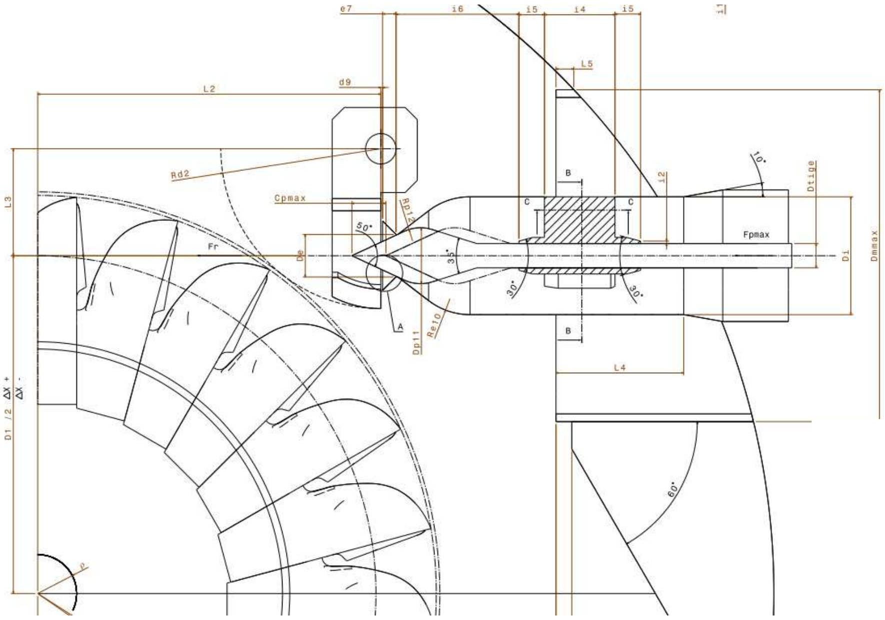

Figure 9 : Systemized hydraulic profile of the nozzle (© Mhylab)

5 Development achieved on the test bench

5.1 Description of the test bench

Mhylab's test rig, dedicated to both in-house and third-party developments and tests of small hydro turbines, is located within Montcherand hydropower plant, in Switzerland.

Figure 10 : Montcherand power plant where the test bench is set (© Mhylab)

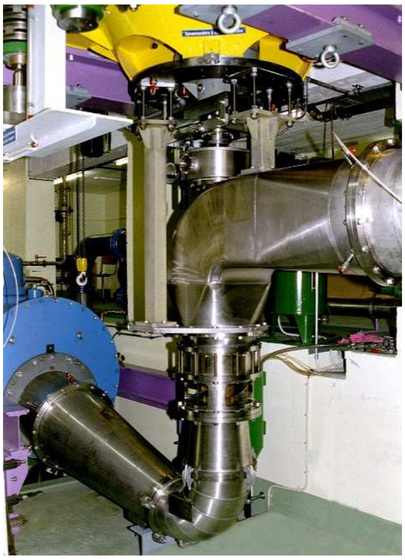

Figure 11 : Scale model of the Axial turbine set on the test bench (© Mhylab)

Figure 12 : Scale model of the Diagonal turbine set on the test bench (© Mhylab)

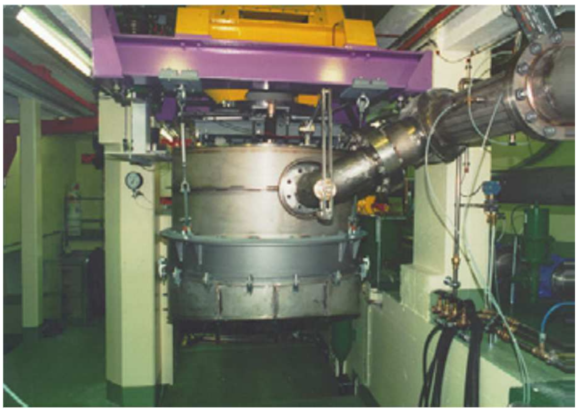

Figure 13 : Scale model of the Pelton turbine set on the test bench (© Mhylab)

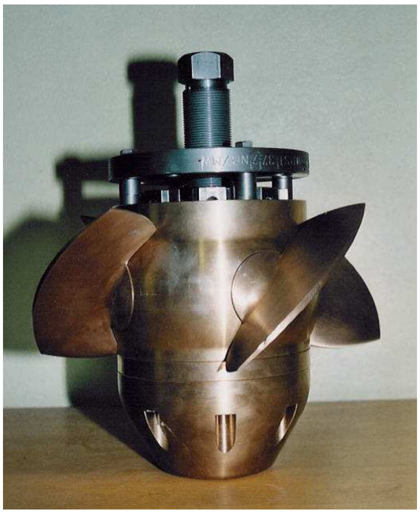

Figure 14 : Scale model of the 4-blade runner for the Axial turbine (external diameter = 300 mm) (© Mhylab)

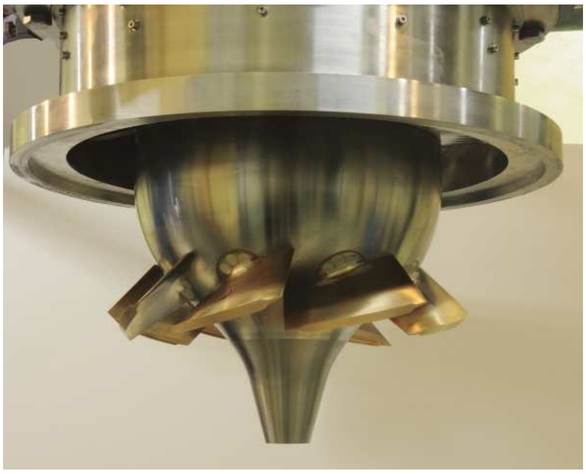

Figure 15 : Scale model of the 8-blade runner equipped with cavitation lips for the Diagonal turbine (external diameter = 330mm) (© Mhylab)

When directly connected to the power plant penstock, the rig can benefit from a head of 95 m and a maximal discharge of 80 l/s. This open circuit mode is especially used for Pelton. In a closed circuit mode, for lower heads, the test bench can operate with a maximal discharge of 450 l/s, with a maximal head of 50 m, thanks to two pumps.

5.2 Measurements of the turbine efficiencies

The first achieved test aims at measuring the turbine efficiency on a large φ and ψ range (cf. § 3).

During this test and according to International Standard IEC 60193, the following parameters are measured:

- Specific hydraulic energy: $E = gH$ $[J/kg]$
- Mass flow rate: $\rho \cdot Q$ $[kg/s]$
- Rotational speed N $[rad/s]$

- Internal mechanical torque measured at the runner coupling: T_m $[N \cdot m]$
- Water temperature: θ_w $[°C]$

The discharge, Q $[\mathrm{m}^3/\mathrm{s}]$, is measured by means of a calibrated pressure differential device inserted in a circular cross-section conduit running full, as described in the European Standard EN ISO 5167.

The internal mechanical torque measured at the runner coupling, T_m, is measured by means of the primary method described in the International Standard IEC 60193. The torque is derived from the measure of the resulting force on the swinging stator frame, at the end of the dynamometer lever arm of a length of $r = 1\ m$.

T_m is the combination of the measured torque and of the ventilation torque, calibrated as a function of the rotational speed without any runner.

The dynamometer is both used to measure the mechanical torque of the runner and to adjust the runner rotational speed. It is a variable speed 85 kW DC machine mounted on hydrostatic thrust and guide bearings. The operating rotational speed ranges from 650 to 2600 rpm.

The measured parameters allow to achieve hill charts, using the no-dimension figures presented in § 3. The area of the peak point will be particularly detailed regarding the number of measurement points, as it will correspond to the design and operation area of the future turbines.

As CFD has been achieved, the peak of the hill chart ought to be already at a high efficiency. However the tests allow to optimize the performances, on a level and flexibility point of view, as the objective is to reach at least 90 % of efficiency on a large range of head and discharges.

5.3 Cavitation characterization

The second test, achieved on Kaplan and Diagonal turbines, consists in characterizing the cavitation phenomenon, by observing the runner at different setting heights regarding the downstream level. It leads to define when the cavitation is damageable for the turbine by using Thomas figure, σ.

$$\sigma = \frac{P_{2abs} - P_{va}}{\rho \cdot gH} + \frac{v_2^2}{2 \cdot gH} - \frac{Z_R - Z_2}{H} \qquad [-]$$

With:

P_{2abs}	=	absolute pressure measured at the turbine outlet	$[\mathrm{N/m^2}]$
P_{va}	=	vapor pressure (from the water temperature)	$[\mathrm{N/m^2}]$
v_2	=	water speed at the turbine outlet	[m/s]
Z_R-Z_2	=	difference in levels between the runner axis and the turbine outlet, suction height	[m]

The cavitation test is operated by reducing σ, by a decrease of the outlet pressure, and observing the cavitation on the runner, thanks to a discharge ring in Plexiglas. As soon as cavitation appears to be damageable for the blades, the corresponding Thomas figure, σ, is defined as the admissible cavitation limit, σ_{adm}, and reported on the hill chart, so as to create a complete design tool for the future design (cf. Figure 2).

As for the efficiency tests, if the test shows that the runner has to be set at a level very low from the downstream water level, the hydraulic profile of the turbine will have to be studied again, by optimizing, most of the time, the sensitive parts of the hydraulic profile of the blades. It can be noticed that blades of the Diagonal runner and the ones for the 8-blade Axial configuration are equipped with lips so as to move away the cavitation phenomenon from the blades (cf. Figure 15).

We may recall here that the definition of the maximal suction height is important for the project design as an economic optimum will have to be found between the maintenance cost due to the matter losses implied by cavitation and the investment cost due to a setting of the runner implying more or less excavation.

Figure 16 : Cavitation test on the S-shape Diagonal turbine (© Mhylab)

Figure 17 : Cavitation observed on the runner of the Axial turbine, considered as damageable (© Mhylab)

5.4 Complementary tests and measurements

These two steps are followed by runaway tests and the measurement of the hydraulic torques on the runner blades, data that are necessary for the future manufacturers.

Finally, the laboratory tests are over when the drawn hill charts are complete and fill the objectives of high hydrodynamic performances and correct runner setting levels.

6 Steps downstream from the laboratory tests

6.1 Demonstration sites

Most of the development projects are validated by a “demonstration site”, a real commissioned project on the basis of the development project results.

The first demonstration project of the 8-blade Diagonal turbine was carried out on Montsalvens site, in Switzerland [2]. The aim of the project, led by Groupe E, was to equip the dam in order to benefit from the environmental flow which, by law, had been set at 500l/s.

The characteristics of the site equipped with this Diagonal turbine are the following ones:

- Nominal discharge : $Qn = 0.500\ m^3/s$
- Net head at Qn : $30\ m < Hn\ (Qn) < 45\ m$
- Rotation speed: N = 1500 rpm
- External diameter : De = 375 mm
- Electrical output : Pe = 180 kW
- Production : 1.5 GWh/year

Figure 18 : Montsalvens dam (CH) (© Groupe e)

Figure 19 : The Diagonal turbine set at the foot of Montsalvens dam (CH) (© Mhylab)

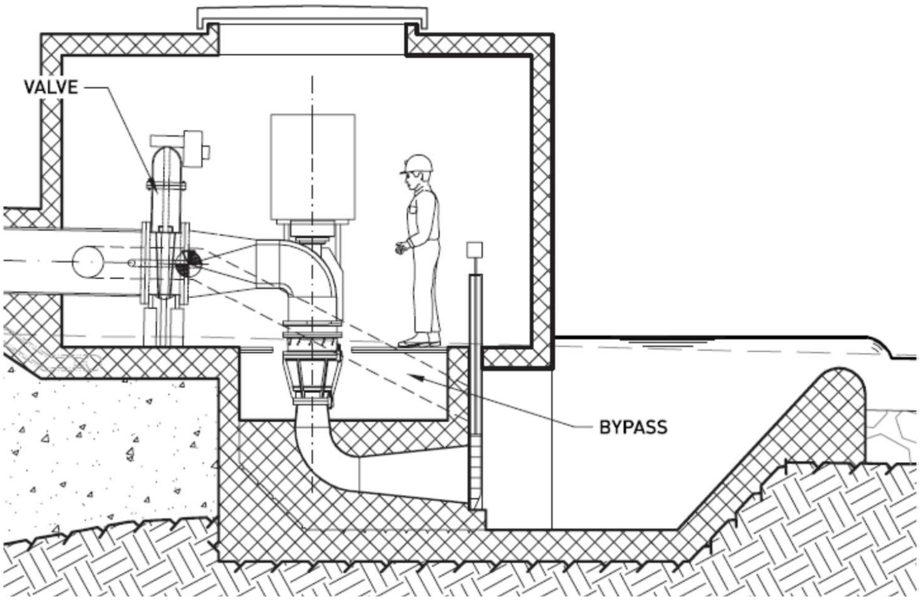

Figure 20 : The general drawing of the S-shape Diagonal turbine set at the foot of Montsalvens dam (CH) (© Mhylab) ©

This first prototype shows that the hydrodynamic behavior fulfills our expectations. The knowledge gained from this first prototype has already been included in our current development of the double-regulated Diagonal turbine (cf. chapter § 0).

6.2 Generation of the hydraulic profiles

The systemization has enabled Mhylab to develop 3D tools for the design and drawing of turbines.

For example for the hydraulic profile of Pelton turbines, the tool delivers 3D drawings of the 1, 2, 3, or 4-nozzle turbine designed specifically for the site, and generates the final files for the manufacturer. These include the 3D file necessary for the CNC machining of the bucket in the mass (cf. Figure 21), and the 2D drawings of the turbine hydraulic profile. Thus, using systemized design (cf. Figure 8 and Figure 9), Mhylab rapidly obtains turbine drawings that allow then the specific project design to be improved. Moreover, thanks to its efficiency, the tool can be used as early as the bidding stage, allowing Mhylab to submit quite an accurate bid to the manufacturer.

The tools for the hydraulic designs of Kaplan and Diagonal turbines are being developed along the same lines.

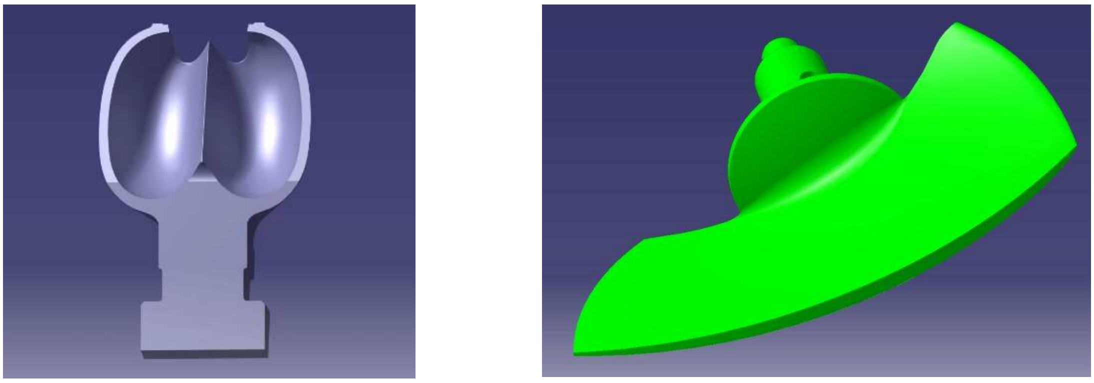

Figure 21 : Example of 3D files of the hydraulic profile of a bucket (on the left hand side) and of a blade (on the right hand side) that can be used by the manufacturers for CNC machining (© Mhylab)

6.3 Generation of the manufacturing drawings

While some manufacturers are interested in the hydraulic design only and undertake the mechanical design themselves, others wish to get technical support in this area also. This technical support implies two main subjects, which interact one to the other: manufacturing drawings and structural calculations.

Here Mhylab works with CRSM (CH) that has developed its own software-tool for mechanical design and 3D drawings, based on the specific hydraulic design of the turbine. Just like the latter, it is based on the principle of systemization.

Thus this tool allows the turbine designed from the systemized laboratory development to be drawn in 3D, while taking physical and mechanical constraints into account in view of a simple and rational manufacturing.

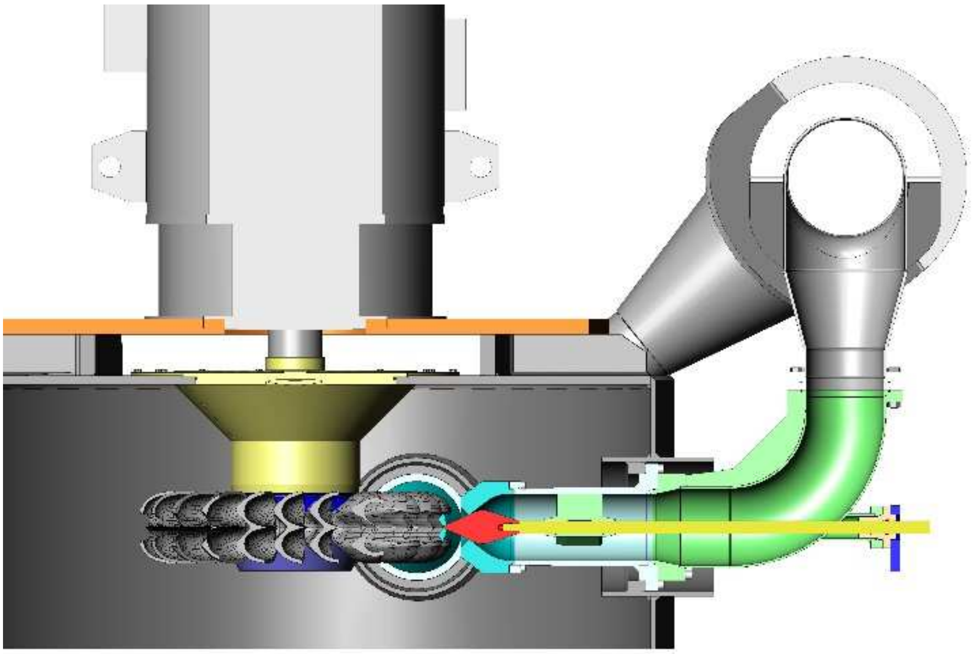

Figure 22 : Cross section from the 3D tool that systemizes the generation of manufacturing drawings for Pelton turbines (© CRSM)

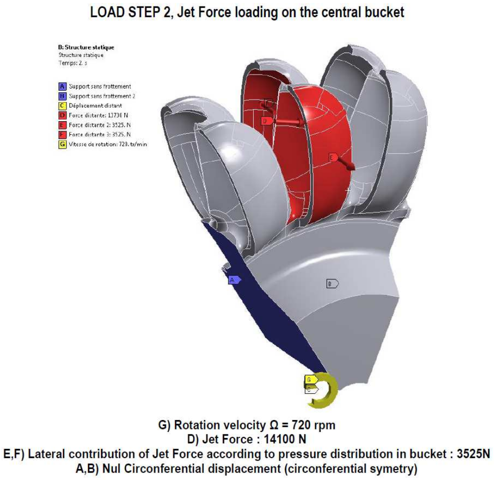

Figure 23 : Runner structural analysis for a Pelton turbine (© Heig-Vd)

Figure 24 : Makayabaru turbine (Japan) designed from Mhylab's systemization (Qn = 0.5 m^3/s, Hn = 181 m, Pm = 800 kW, 2 nozzles, 600 rpm) (© Nippon Koei)

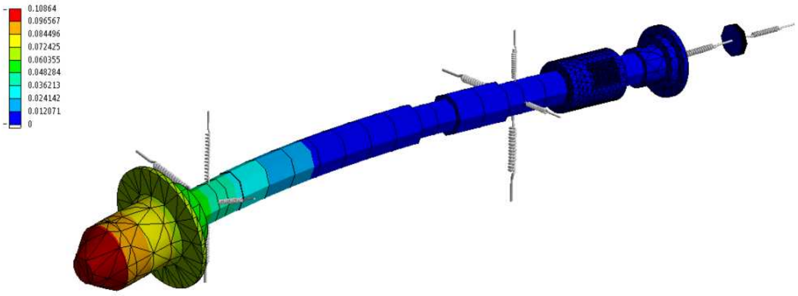

Figure 25 : Natural frequencies calculation on the shaft assembly for a Kaplan turbine (© Heig-Vd)

Figure 26 : Poggio Cuculo turbine (Italy) designed from Mhylab's systemization set within a drinking water treatment plant (Qn = 0.38 m^3/s, Hn = 12.5 m, Pm = 42 kW, variable speed) (© Mhylab)

Finally, for example for Pelton turbines, thanks to this tool, at short notice and at affordable price, the manufacturer can be supplied with:

- a complete set of manufacturing drawings
- 3D files for the direct CNC machining of the bucket, the deflector and the needle guide vanes
- DXF files for simplified cutting of sheet-metal parts
- A reference list of external parts (bearings, seals, screws…)

Before finalizing either the mechanical design or the manufacturing files, the turbine design must go through an essential procedure: structural calculations in view, among other things, of checking the critical speed of the shaft line, the runner resistance and, for Pelton turbines, manifold bifurcations. With this objective, Mhylab has entered into a partnership with the Heig-Vd, University of applied sciences, Vaud (CH).

7 Current development: double-regulated Diagonal turbine with a spiral case

As the single-regulated configuration has shown its application limits, particularly with respect to discharge and/or head possibilities, a new project has been launched to develop the double-regulated Diagonal turbine, using the same systemized approach.

A preliminary study has been made for the manufacturing of an adjustable cylindrical system for the guide vanes, for spiral casing configurations.

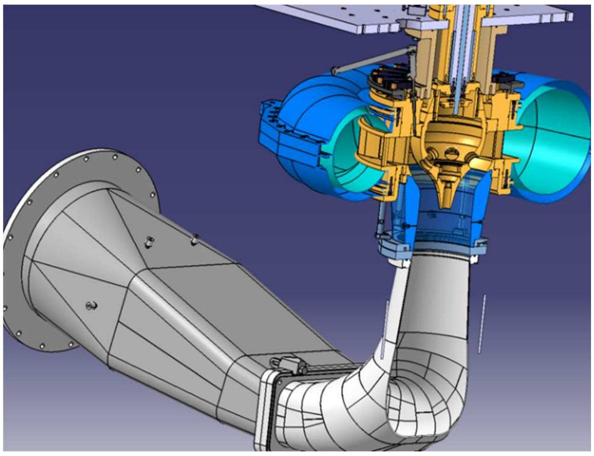

Figure 27 : 3D design of the scale model for the Diagonal turbine: cross section of the spiral casing, the adjustable guide vanes and the guide vanes (© CRSM)

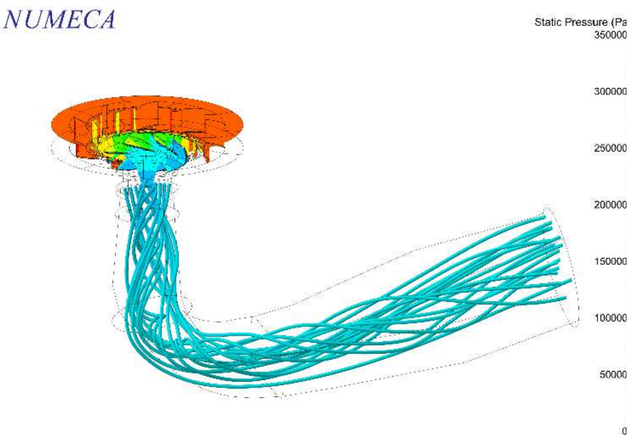

Figure 28 : CFD on the draft tube (© HES-SO)

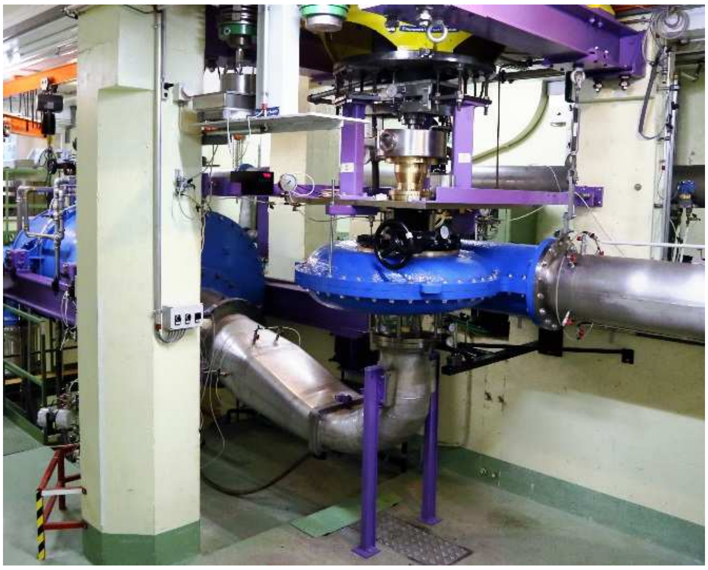

Figure 29 : Scale model of the double-control Diagonal turbine with a spiral casing set on the test bench (© Mhylab)

Results with two different runners (8 and 12 blades adapted to different head ranges) have been obtained, and further developments and configurations are being studied within this project. Up to now, the developped double-regulated configuration presents very satisfying performances in terms of efficiency, cavitation, and hydraulic behaviour. The high flexibility makes it a highly relevant solution for medium-head small plants, including the refurbishment of old Francis turbines.

The next development projects will deal with two main subjects: double-regulated Kaplan turbines with a spiral casing and pump storage at small scale [3].

8 Conclusions

Here has been shown how the whole turbine design process for small hydropower is mastered on systemization, from laboratory tests, through detailed sizing based on efficiency hill charts, to the production of the final files for the manufacturers. While limiting the dysfunction risks, often linked with standardization, the approach leads to drastic reduction of the costs and deadlines of a development that would deal with only one turbine, and perpetuates the investment made by the future owners of the power plants.

The process has been validated through the implementation, since 1993, on more than 190 commissioned turbines, mainly set in Europe and Japan, and its results are available on the market, to any turbine manufacturers.

In front of what this high-value resource implies, wherever it comes from water streams, regarding flora and fauna protection, from water networks (drinking water, wastewaters, irrigation …) or other multipurpose schemes, regarding human activities, optimization of the water use will remain a focus, in terms of quality, quantity and financial risks. And this optimization will still mean a better knowledge and know-how of the equipment.

9 References

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[3] S. Gabathuler, D. Pavanello and C. Münch: Le pompage-turbinage à petite échelle pour le stockage local d'énergie. Bulletin SEV/AES 2/2015, pages 49-54, 2015. www.hevs.ch/media/document/0/le-pompage-turbinage-a-petite-echelle-une-solution-envisageable.pdf

10 Authors' biographies

Vincent Denis is graduated in mechanical engineering and post graduated in energy systems from the Swiss Federal Institute of Technology (EPFL) in 1992. He worked for four years in the hydroelectric department of an international consulting engineering company. He joined Mhylab in 1996. After being the head of the laboratory, in charge of research and development projects for small turbines, he is now the managing director. Since 1997, he has been a member of Mhylab's executive board.

Cédric Cottin is an R&D engineer specialized in fluid mechanics and aeronautics, graduated in 2005 from ESTACA (France) and Chalmers University of Technology (Sweden). Following two professional experiences in the areas of CFD and experimental R&D at the Université catholique de Louvain in Belgium, and at the French Aerospace Agency (ONERA), he joined Mhylab in 2009 to lead both the Diagonal turbine R&D project and testing activities, while also being involved in hydropower engineering projects.

Aline Choulot is graduated in energy and environment engineering from the French National Institute of Applied Sciences (INSA) in 2000 and post graduated in energy systems from the Swiss Federal Institute of Technology of Lausanne (EPFL). She worked in the Finnish Environment Institute, and then for an industrial company, before joining Mhylab in 2004. She is currently in charge of turbine development and small-hydropower project management.