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The Very Low Head Turbine for hydropower generation in existing hydraulic infrastructures: State of the art and future challenges

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A R T I C L E I N F O

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A B S T R A C T

The Very Low Head turbine (VLHT) is an axial flow turbine developed for heads below 4.5 m and flow rates up to 30 m^3/s. In this work, the state of the art, the technological advancements and the scientific gaps were discussed and generalized, with a special focus on design, ecological behavior, costs, performance at different flows, heads and rotational speeds. The flow field and the hydraulic behavior under different configurations (e.g. in presence of cavitation and with an upstream obstacle) were described, with the aim of deriving engineering suggestions. Results of ecological tests were generalized (fish survival rate is more than 90%) by using the blade strike model, proposing an expeditious method for a preliminary appraisal of the ecological impact on downstream migrating fish. Despite the hundreds of installations worldwide, especially in existing barriers, some scientific gaps need to be better addressed yet, e.g., the influence of the number of blades and axis inclination on the efficiency, the influence of flow, head and rotational speed on the flow field and a quantification of the head losses through the trash rack above the runner.

Introduction

The use of renewable energy for electricity generation at large scale is an important strategy for reducing greenhouse gas emissions and for ensuring a sustainable development [1] [2] [3]. Among renewable energy sources, the global installed hydropower capacity reached 1,330 GW in 2021 and it supplies 16% of the global electricity generation [4]. Hydropower generates several benefits in addition to fossil-free electricity generation, that other renewable energy sources, e.g. wind and solar plants, cannot provide. Hydropower plants with a large reservoir mitigate floods and allow for water storage and water control. Pumped storage hydropower plants consume electricity by pumping and storing water in the form of potential energy during low demand and low price periods, and generate electricity during the peak energy demand periods, with a regulation effect on the electric grid. Small hydropower can contribute to decentralized electricity generation [20]. However, hydropower can also generate environmental impacts, e.g. the interruption of the longitudinal connectivity of the river, hydropeaking and hydro-eco-morphological alterations [5].

In order to minimize environmental impacts, the exploitation of existing very low head (VLH) barriers and weirs (e.g. old mill sites) in irrigation canals, existing hydraulic infrastructures and water distribution networks is an emerging option, especially when these barriers are already in place for other purposes [6] [7] [8] [9]. In [10] a review of VLH hydropower converters has been presented, and in Table 1 their main characteristics are listed. Although there is not a precise definition of VLH, it is generally used to indicate heads below 5 m, and sometimes below 2.5 m [10]. In our paper, the threshold of 5 m is used to define very low head. The Very Low Head turbine (VLHT) (the aim of the present paper) is included in this context.

In the very low head context, costs and environmental impacts of gravity machines (e.g., water wheels [13] [14] and Archimedes screws [15] [16]) are lower than those of very low head Kaplan and Francis turbines. Furthermore, design tools of low head Kaplan and Francis turbines have been mostly developed for high head conditions [17]. However, gravity machines are limited in the flow rate capacity: the maximum flow that can be discharged by the Archimedes screw is 8 m^3/s with a 4 m diameter, while water wheels can generally exploit flow rates below 1.2 m^3/s per metre width [14]. Therefore, they are typically

; VLHT, Very Low Head Turbine.

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Nomenclature

C	chord length (m)	VLH	very low head (–)
D	runner diameter at the blade tip (m)	l	distance between two blades (pitch) (m)
D_{hub}	runner diameter at the blade root (m)	n	number of blades (–)
H	head difference (m)	pc	pitch to chord ratio
H_c	head coefficient (–)	t	time (s)
L	fish length (m)	u	tangential runner speed (m/s)
N	rotational speed (rpm)	v	flow velocity (m/s)
N_1	unitary speed (–)	α	angle of attack (°)
P	power output (kW)	β_∞	angle of relative stream velocity (°)
Q	flow rate (m^3/s)	δ	blade pitch angle (°)
Q_1	unitary flow rate (–)	γ	stagger angle (°)
Q_c	flow coefficient (–)	λ	gliding angle (°)
S	pitch length (m)	η	efficiency (–)
		W_∞	relative stream velocity (m/s)

Table 1

Summary of very low head hydropower converter characteristics, with machine efficiency, ecological characteristics in relation to fish passage (impacts: high, low, medium), costs (high, medium, low) and allowing of sediment passage (Yes or Not). The turbine type can be Hydrostatic/Gravity (H), Reaction (R) or Action (A). The vortex turbine can be A or R depending on the design. The flow rate of water wheels is per metre width.

Type	H (m)	Q (m^3/s)	η (%)	costs	fish	sediments	type
Overshot wheel	3–6	⩽0.2	75–85	L	L	Y	H
Breastshot wheel	0.5–4	⩽0.8	75–85	L	L	Y	H
Undershot wheel	0.5–1.5	⩽1.2	75–85	M	L	Y	H
Archimedes screw	1.0–6	0.1–5.5	75–85	M	L	Y	H
Hydrostatic Pressure machine	1.0–2.5	1.0–5.0	50–60	L	L	Y	H
Low head Francis	0.75–5.0	1.0–10.0	75–85	M	H	N	R
Low head Kaplan	1.8–5.0	1.0–25.0	82–92	H	M	N	R
VLH turbine	1.4– 4.5	10.0–30.0	80–91	L–M	L	N	R
Vortex turbine [1]	0.5–4	0.5–5.0	40–50	M	L	Y	A/R
Mariucci turbine [2]	1.0–3	⩽6.0	80–90	L	H	N	A

[1] [11].
[2] [12].

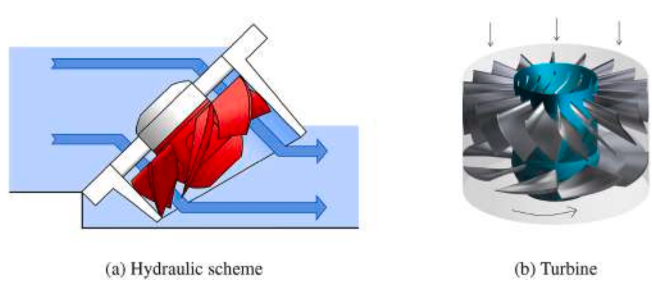

Fig. 1. (a) VLHT concept with indication of flow direction; (b) stator and rotor blades.

used for power output below 100 kW and 30 kW, respectively. To overcome the flow rate limitation of gravity machines, Vortex turbines and Mariucci turbines, and the above mentioned limitations of low head Kaplan and Francis turbines, the VLH turbine (VLHT) has been introduced on the market in 2007, in order to exploit flow rates up to 30 m^3/s, and head differences between 1.5 and 3.4 m, and up to 4.5 m in customized reinforced version. More than 110 VLHTs have been installed in 7 countries [18]. The power output typically ranges between 100 kW and 700 kW per unit. Therefore, following the classification of UNIDO, the USA Organization for the Industrial Development, the VLHT can be classified as mini hydropower converter (installed power between 100 kW and 1 MW). Fig. 1 shows a sketch of a VLHT.

In this paper the scientific literature on the VLHT was reviewed to define the state of the art. The working principle of the VLHT and its design were discussed. The performance was described as a function of the rotational speed, flow rate and head difference, generalizing the results. Flow field and the hydraulic behavior under adverse conditions (e.g., cavitation and presence of upstream obstacles) were presented. The ecological tests performed by several Authors to define the VLHT ecological efficiency were reviewed and elaborated by using the blade strike model. Finally, data about costs and practical installations were presented. The specific aims of this paper are the followings: 1) to discuss the performance and the design in order to help engineers in the design of the VLHT; 2) to generalize cost-related results, in order to support investors to quantify costs; 3) to highlight the open research gaps that should be investigated, stimulating the research community; 4) try to give tools to biologist to preliminary assess the ecological impact of a VLHT on migratory fish.

Potential for application in different contexts

The VLHT can be installed in existing hydraulic infrastructures, e.g., canals and navigation locks, in correspondence of hydraulic barriers, e.g. weirs, spillways and structures for water level control [9] (Fig. 2 and Fig. 3). Obviously, a VLHT installed in existing barriers should be carefully evaluated within its context, since sometimes the exploited infrastructures need to be optimized/reshaped to house a VLHT [19], and this may generate additional environmental impacts.

The VLHT can also be installed in navigation locks, and in [20] two Italian case studies are described. The first one is located in Canda (Rovigo, Italy, 3 m head), the second one is located in Bussari (Rovigo, Italy, 2.56 m head). The Canda power plant is equipped with two VLHTs (runner diameter 3150 mm) for a total power of 512 kW (2x256 kW) generating 2888 MWh/year. The Bussari power plant is equipped with a

(a) *Before construction* (b) *Post construction*

Fig. 2. Undisturbed conditions in an irrigation canal with existing infrastructure, and post operam with VLHT and fish passage. Installed power 100 KW and cost of about 5000 €/kW, Marnate (Italy), photo courtesy Artingegneria.

(a) *Upstream view* (b) *Downstream view*

Fig. 3. VLHT installation in a canal, Mazzè, Italy. 2.60 m head, two VLHTs for a total of 54.2 m^3/s, 5 m diameter each, 1000 kW of installed capacity and 25 m long derivation canal. Photo Courtesy Geasiste.

VLHT (runner diameter 5000 mm) of total power 481 kW and annual production of 2751 MWh. The capacity factor is 64%, higher than the average one for small hydropower plants (the capacity factor is the ratio of the annual energy generation to the energy that would be generated if the plant would always work at its full power [21]).

VLHTs can also exploit tidal ranges [22], while contributing to protect shores because the related structure brakes storm waves, in a similar way to natural reefs [23]. VLHTs have also been employed in dam-bridge systems [24].

1. Design of the VLHT

1.1. Equipment and working behavior

The VLHT is an axial flow turbine, with the rotation axis normally inclined of 30°-50° on the horizontal. This allows the flow to better enter into the runner, avoiding an abrupt 90° change of direction, as it would occur in a traditional vertical axis turbine (where the direction changes from horizontal -upstream-, to vertical -through the runner-).

The VLHT was chosen with bigger runners (more or less twice the size of the equivalent conventional Kaplan for the same head and flow) in order to reduce the water velocity through the unit. In this way, the intake and the machine could be significantly simplified, thus resulting in a reduction of concrete volume of the civil infrastructure of 1/3 to 1/5, as well as reduction of the power plant length of 1/3 to 1/5, with respect to a Kaplan unit [18].

The VLHT is made of an integrated turbine-generator; the runner is similar to a Kaplan runner with eight adjustable blades, and the distributor is composed of 18 fixed guide vanes. The unit with 8 runner blades and 18 guide vanes is the standard configuration, although the effects of blade number on the efficiency have never been investigated in the scientific literature. This is an important point, since the optimal number of blades may depend on the diameter, i.e. on the flow rate, as for Kaplan turbines [25]. The ratio of hub diameter D_{hub} to the tip diameter D generally ranges between 0.45 and 0.55 [26], although higher values of 0.6 are possible [27].

The permanent magnet generator is directly coupled to the turbine. The magnets are assembled at the stator periphery. VLHTs operate with a variable rotational speed, thus the generator speed varies according to the instantaneously-measured net head. In this way, the VLHT keeps its design efficiency up to 40% of the design power (thus it can effectively work at part load). Therefore, the yearly production capacity is equivalent to that of a conventional double-regulation Kaplan turbine. The rotational speed control is formed by a power rectifier associated with a capacitor bank and an inverter providing a 50 Hz or 60 Hz signal, depending on the grid frequency. The turbine efficiency can be optimized by making the turbine operate at its best efficiency point as a function of head and flow rate. The generator is pressurized with a pressure which is 0.2–0.3 bar above the operating water pressure, minimizing flooding of the stator due to possible lacks of tightness. A

Fig. 4. Focus on the rack of the VLHT (Mazzè, Italy), photo Courtesy Geasiste.

trash rack above the distributor avoids large sediments entering the turbine (Fig. 4) [28].

1.2. Characteristic numbers

The fluid dynamic theory of the VLHT is the standard turbomachinery theory for the design of axial flow machines, based on the triangle velocity theory and turbomachinery characteristic numbers [29,30].

The unitary flow rate is defined as $Q_1 = \frac{Q}{D^2H^{0.5}}$ and the unitary rotational speed is defined as $N_1 = \frac{ND}{H^{0.5}}$. Their range is, respectively, $0.2 \leqslant Q_1 \leqslant 1.2$ and $65 \leqslant N_1 \leqslant 280$, with Q the flow rate [m^3/s], D [m] the external diameter, H [m] the head difference and N [rpm] the rotational speed [31]. Additional turbomachinery numbers are the flow coefficient $Q_c = \frac{Q}{ND^3}$ and the head coefficient $H_c = \frac{gH}{N^2D^2}$, typically ranging between 0.005 and 0.007, and between 0.0005 and 0.0015, respectively.

By interpolating collected data (see Table 3), the relation between N_1 and Q_1 can be expressed by $N_1 = 180.5Q_1$, while no correlation was found between Q_c and H_c at the design power, although results are generally correlated within each study. For example, in [32] $Q_c = 0.54H_c^{0.37}$, while in [33] $Q_c = -11 + 27H_c$.

The turbine specific speed $N_s = NP^{0.5}H^{-1.25}$ (with P the power output expressed in kW) is suggested to be kept at 257 for a VLHT at the rotational speed of 40 rpm, which is a conventional value for external diameter higher than 4 m and is a normal value for axial turbines in micro–hydro systems [31].

1.3. Blades

The design of the blades involves both the selection of the optimal number and the most efficient profile. The common number of adjustable runner blades is 8, while 18 is the common number of fixed guide vanes, up to 24 in certain cases [27,32]. Preliminary studies did not provide a specific criterion for the turbine design. Therefore, several researchers used axial turbine and pump design criteria [34] [35] to design the VLHT.

Fig. 5 and Table 2 show the set of geometric and hydraulic parameters involved in the blade design [31]. In addition to the parameters in Table 2, the hydrofoil profile, the selection of hydrofoil for each section and their installation angle, number of blades, and clearance at the blade tip affect turbine performance [31]. Accordingly, the ratio of hub diameter to tip diameter D_{hub}/D was assumed to be 0.45. The axial velocity is constant at the runner inlet and outlet, considering the free vortex assumption, and velocity triangle theory is considered at the inlet and at the outlet. The process of finding the angle of attack involves an

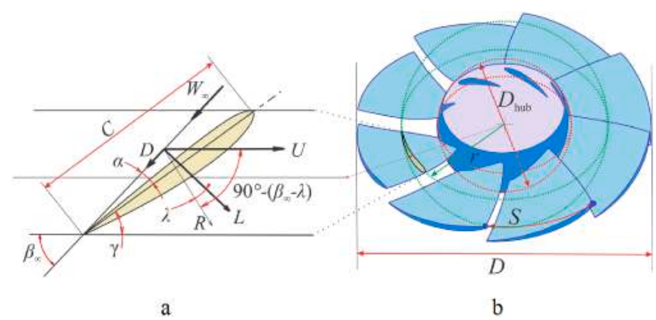

Fig. 5. Hydrodynamic forces on two-dimensional hydrofoil, speeds and angles required in the design process (a); Three-dimensional scheme of radial cross-sectional elements (b) [31].

Table 2
Main geometric parameters for the design of the blade cross section.

Symbol	Parameter
D_{hub}	Blade diameter at the root (m)
D	Blade diameter at the tip (m)
S	Pitch length (m)
C	Chord length (m)
W_∞	Relative stream velocity (m/s)
β_∞	Angle of relative stream velocity (°)
α	Angle of attack (°)
γ	Stagger angle (°)
λ	Gliding angle (°)

Table 3
Summary of VLHT characteristics. D = diameter, P = installed power, η = efficiency, H=head, Q=design flow, N= rotational speed, N_1, Q_1, Q_c, H_c are the characteristic numbers.

Ref.	D (m)	P (kW)	η	H (m)	Q (m^3/s)	N (rpm)	Q_1	N_1	Q_c	H_c
[31]	4.5		0.86	2.6	14	30	0.43	83.72	0.0051	0.0014
[31]	4.5		0.86	2.6	18	38	0.55	106.05	0.0052	0.0009
[31]	4.5		0.86	2.6	22.7	50	0.70	139.54	0.0050	0.0005
[31]	4.5		0.86	2.6	26	55	0.80	153.49	0.0052	0.0004
[31]	4.5		0.86	2.6	30	65	0.92	181.40	0.0051	0.0003
[46]	5		⩽0.8	1.81	17	28.2	0.51	104.80	0.0048	0.0009
[47]		450		2.6	22.7	40				
[38]	0.6		0.91	0.3	0.128	90	0.65	98.59	0.0066	0.0010
[38]	0.6		0.91	0.3	0.1	75	0.51	82.16	0.0062	0.0015
[38]	0.6		0.91	0.3	0.15	105	0.76	115.02	0.0066	0.0007
[48]	4.5	400		2.4	22	38	0.70	110.38	0.0064	0.0008
[32]	1.82	297	0.85	2.9	12.19	65	2.16	69.47	0.031	0.0020

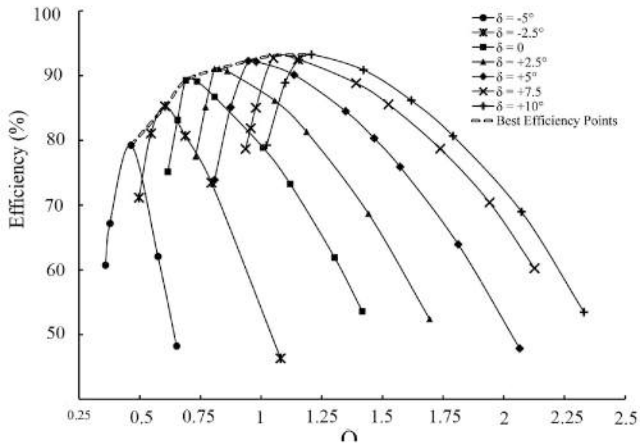

Fig. 6. Efficiency versus unitary flow rate at different blade openings [31].

iterative solution, starting with an initial gliding angle (e.g., assumed to be 1). Then the lift coefficient is calculated, and again the new gliding angle is calculated. This process continues until a certain convergence criterion is reached [31].

Another criterion is that of the minimum pressure coefficient (Eq. 1) on the blade suction side, which should exceed the water vapor pressure at the corresponding temperature to avoid cavitation. According to [36] [37], the possibility of cavitation in Kaplan runners, as well as in VLHTs, in the areas of clearance between the turbine case and the blade is higher due to the high flow velocity gradient, and on the suction side of the blade attack edge due to low local static pressure.

$$C_p = \frac{p - p_0}{0.5\rho w^2} \tag{1}$$

where p is the static pressure (N/m^2) on the blade cascade surface, p_0 is the reference pressure (N/m^2) and w is the relative flow velocity (m/s).

In [38], the minimum pressure coefficient criterion was applied to design a VLHT. In this process, by defining different values for the cascade solidity coefficient of turbine blades, the criterion of minimum pressure coefficient determined the minimum pressure on the suction side of the blade, from the blade root to the maximum radial distance. This can lead to a more suitable loading of the blades and better aerodynamic performance. Furthermore, according to the radial equilibrium in the governing equations for the inviscid flow in the initial design, free vortex flow at the inlet and at the outlet of the runner can lead to a uniform distribution of the axial velocity at different sections of the runner [39].

In [32] the VLHT was optimized by acting on the two dimensional cross-section of the blades, using CST (Class/Shape Transformation) methods and CFD simulations. The CST method is an effective tool to parameterize airfoils by amalgamating analytical class functions with parametric shape functions. The efficiency was increased by 2.4% at the flow rate of 12.19 m^3/s and rotational speed of 65 rpm. Power and effective head of the optimized turbine increased by 7.75 kW and 0.07 m, respectively. The minimum increase in efficiency (0.83%) was observed at the flow rate of 10 m^3/s, while the 1.1% increase in efficiency was found at the flow rate of 7 m^3/s.

In [31,33] the fluid dynamic design of the VLHT has been discussed using the triangle velocity theory, and the equation to calculate the lift coefficient of a blade was reported. The rotor solidity (the ratio of the chord length to the blade pitch in each radial section) for the VLHT was chosen as equal as 1, while in Kaplan turbines it generally ranges from 2/3 to 1. In [40] the pitch/chord pc ratio was tested, and it was found that the value $pc = 0.9$ performed better than $pc = 1$. At $pc = 0.9$ the maximum efficiency decreased of one percentage point, but the efficiency curves versus the rpm were smoother. The alteration of the runner speed reduced the efficiency, with a higher decrease at $pc = 1$ with respect to $pc = 0.9$. This is because at $pc = 0.9$ the pitch is smaller, thus the blades are closer one another: therefore, the flow is more guided, with less possibility of generating secondary flows and eddies [41].

Since guide vanes are fixed, runner blades and rotational speed are controlled to optimize the performance. In [31] it was shown that the efficiency can be maintained constant at about 90% within (0.75 $\div$ 1.25)Q_1 by acting on the adjustable runner blade angle δ, and varying their opening within a range of 15° (Fig. 6).

In [43] the effect of the blade pitch angle was tested (angle between chord line and tangential speed). For a constant flow rate, the effect on the efficiency by varying the speed was tested, testing pitch angles of $10^\circ, 14^\circ, 18^\circ$ and 24°. The pitch angle 14° was the optimal one (the design one, i.e. that generating the highest efficiency). By varying the pitch angle, and maintaining constant the flow rate, the pitch angle had effects both on the maximum efficiency and on the efficiency curve shape. A smaller pitch angle led to a flatter efficiency curve as a function of the rotational speed, while as the pitch angle increases, the efficiency curve became steeper and with a well identifiable maximum. This can be explained considering that at higher pitch angles the flow tends to impact the blades on the back side of the blades rather than on their positive-pressure side.

In [31] the blade opening angle was varied within a range of 15°. The opening angle of the rotor blades is defined by the blade angular deviation from the design point configuration, i.e., positive opening angles represent the situation in which larger flow rates pass through the turbine passage (analogously to the pitch angle). The positive opening angles led to higher efficiencies and flatter efficiency curves, in disagreement with [43]. However, in [31] the flow rate was varied instead of the rotational speed.

Although a detailed and unified report on how to optimally select blade parameters is not available (there is a lack of study in this area, and more research should be carried out) few general considerations can be achieved. The hydrofoils should be selected in such a way that the stagger angle from the root to the tip of the blade changes uniformly from 10° at the tip to 31° at the root of the blade [31]. However, these upper and lower limits are not definite and should be further examined. Thin hydrofoil should be used at the tip of the blade and hydrofoil thickness should increase as the hydrofoil approaches the root of the blade [31]. If a high flexibility is the target, smaller pc values should be selected. In [26] regression analyses were proposed to determine empirical equations relating the efficiency, the head and the flow rate with the geometry of the runner blades, in particular with their inlet and outlet angles. These equations can be used to predict the turbine performance.

Blade design should also consider ecological aspects in order to obtain an ecological efficient design. The peripheral velocity at the runner tip must be less than approximately 12.2 m/s in order to minimize fish mortality [42]. When small fish are expected to interact with the turbine, like an eel or a smolt, the cylindrical discharge ring (the external wall where the VLHT is installed) of the VLHT at the end of the blades lets enough space for them to undergo a strike. It is thus necessary to modify the hydraulic contour at the blade tip towards a spherical profile to minimize the gap, hence minimizing the probability of fish mortality through the gap [44]. A similar concept has also been developed for the Minimum Gap Runner turbine, an optimized Kaplan turbine that reduces fish mortality in a similar way [45].

1.4. Axis inclination

Tests have been performed with different inclined axis positions from 35° up to 55° by steps of 5° showing that there are very small differences of efficiency [18]. [40] tested 50° and 90° with respect to the vertical direction. The discharge coefficient of the turbine inclined of 90° was higher than for the 50° inclination, because the flow path is less tortuous for the 90° case, but no substantial change in other output results was

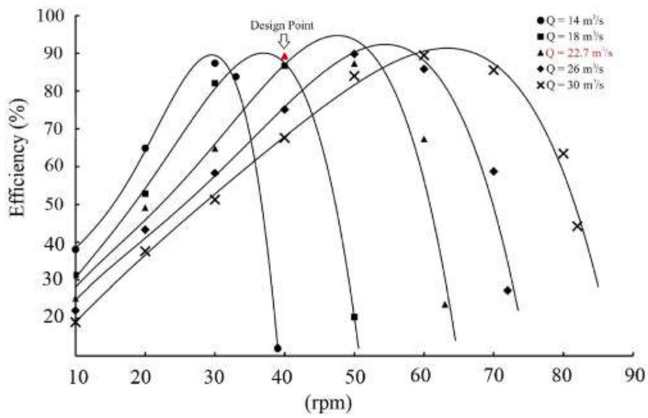

Fig. 7. Efficiency versus rotational speed at different flow rates [31].

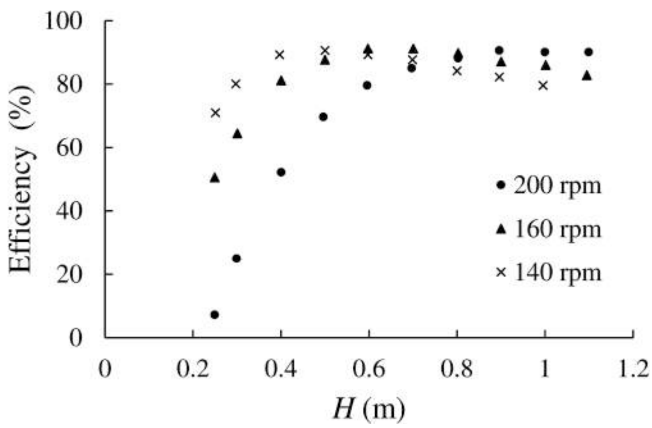

Fig. 8. Effect of head on the efficiency at different rotational speeds (rpm) [33].

observed. Nevertheless, the inclination adopted in practice is usually between 45° and 50° for practical reasons. Although no ecological tests have been performed at different axis inclination, it is expected that it may also have an effect on fish risk passing through the turbine, due to the more abrupt direction change in the case of 50° axis. This aspect should be further investigated.

2. Performance

The efficiency of a VLHT depends on its design and on the hydraulic conditions, as for any other turbine. For a given design, the power output and the discharged flow rate of a VLHT can be adjusted by varying the pitch angle of runner blades and the rotational speed. The control of a VLHT consists in adjusting the runner blade opening to accomodate for the flow rate, and then to adjust the rotational speed to achieve the best efficiency point. Therefore, being a double regulated turbine, similarly to the Kaplan turbine, the VLHT performance can be maintained optimal at off-design conditions.

In Table 3 the literature studies with known efficiency are listed, focusing on the design point (head, flow rate and rotational speed). Results are also normalized to obtain the unitary flow and speed (Q_1 and N_1, respectively). The maximum hydraulic efficiency ranges from 0.86 to 0.91.

2.1. Efficiency vs head

The variable rotational speed N exhibits positive effects in case of water level variations. In [33], the efficiency could be maintained at 90% by varying the rotational speed from 140 to 200 rpm, from a head of 0.4 m to 0.8 m (Fig. 8). The flow rate was 0.29 m^3/s and the runner diameter was 0.4 m. The efficiency did not undergo appreciable decrease at heads higher than the optimal one (the head that, at a given rotational speed, determines the optimal efficiency), while the efficiency steeply decreased at smaller heads. The optimal rotational speed N depended on the head H, as a consequence of the increase in flow velocity through the runner with the head.

The effect of N on the head was investigated in [38]. As the head increased, the discharged flow increased, and the optimal runner speed to accomplish this variation increased. The turbine with pitch/chord ratio equal to 0.9 better performed with respect to that with ratio equal to 1, as explained in Section 1.3. From [38], considering the turbine pitch/chord ratio of 0.9, flow rates of 0.10, 0.128 and 0.150 m^3/s were tested. For each flow, the maximum efficiency occurred at a certain rpm, that increased with the flow. The variation of the head with the speed was also tested for each flow. For each flow there was a certain rpm N_h that maximized the head, and N_h was generally one half of the N that gave the maximum efficiency. Above N_h, the head reduced probably due to the higher discharge capacity (while the efficiency increased), while below N_h the head reduced (while the efficiency reduced) probably due to the increase of the downstream water level, although this aspect was not investigated.

2.2. Efficiency vs rotational speed and flow rate

In [31] the rotational speed was tested at different runner blade opening angles and flow rates. Each flow rate exhibited its optimal rotational speed, which increased as the flow rate increased to maintain the velocity triangles and accomodate for the larger flow. Considering a certain flow rate (22.7 m^3/s), the value of the opening angle of the blades had a significant influence on the hydraulic efficiency trend versus the rotational speed (Fig. 7). The higher the rotor passage was (i.e. the larger the blade opening), the higher the maximum efficiency was, probably due to the less friction losses trough the canal between two blades. The efficiency peak occurred at slower rotational speeds with the increase of the opening, in order to satisfy the velocity triangle theory. By adjusting the rotational speed it was possible to maintain a constant optimal efficiency above 90% from flow rates of 14 m^3/s to 30 m^3/s, thus from $Q_1 = 0.42$ to $Q_1 = 0.92$, from 30 rpm to 70 rpm.

In [43] the efficiency was maintained constant by acting on the combination of runner blade opening and rotational speed, within a range of 14° and 50 rpm (from 60 rpm to 110 rpm), respectively.

In [33], the efficiency was maintained at 90% by varying the rotational speed from 110 to 180 rpm, from an head of 0.4 m to 0.8 m. The flow rate was 0.29 m^3/s and the runner diameter was 0.4 m. Furthermore, for a fixed rotational speed, the efficiency exhibited a maximum value at the optimal head, and then decreased as the head changed.

The VLHT was tested in [27] with a diameter of 0.6 m and a design flow rate of 0.128 m^3/s. Different flow rates and rotational speeds were tested. The rotational speed had to be changed from 60 ($N_1 = 65$) to 100 rpm ($N_1 = 109$) to maintain an efficiency of 92% from 0.10 m^3/s ($Q_1 = 0.51$) to 0.150 m^3/s ($Q_1 = 0.76$).

2.2.1. Rotational speed effects on start and stop cycles

Variable speed exhibits several advantages on system stress, regulation quality and smoothness of operation. Shut down operations and startup are smooth, and the turbine can be stopped in emergency situations. In a turbine at constant rotational speed, startup and shutdown phases generate stresses on the equipment due to the need to keep the generator synchronized to the grid. The turbine can be coupled or disconnected at zero speed during normal operation.

During the startup procedure, the inverter is synchronized to the grid as a first operation, then the drive is started and the blades are opened to their initial opening position. In order to reach the desired speed in a minimum time, a small kick-off is provided to the turbine by the drive, using a fraction of the grid power. Once the turbine has reached the

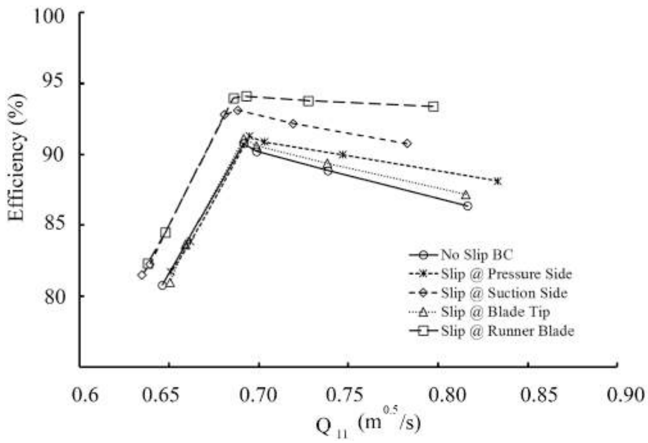

Fig. 9. Efficiency improvement using superhydrophobic coat from numerical results [47].

minimum speed, the upstream level regulator is activated and the blades are opened by pulses until the output power reaches the maximum available. The rotational speed also changes during ramp-up as a consequence of the water head changing upstream.

During a trip or a stop of the operation, the power goes down to zero slowly due to a continuous closing command on the blades. During the ramp-down of the power, the rotational speed is maintained at the optimal value as long as it is possible, and at the end it ramps down to zero. The variable speed allows the VLHT to also work off-grid, thus in isolated contexts. In [49,50] these aspects are discussed with more details and practical examples. The generator voltage depends on the speed of the turbine; when the load of the electrical grid goes down (runaway condition), the generator voltage increases a lot. This situation may damage the variable frequency converter or the drive; to protect the drive, the drive is equipped with an extra generator contactor that allows to isolate the generator from the drive [9].

2.2.2. Efficiency improvement due to new materials

New materials are under development for the hydropower sector to improve efficiency, reduce costs and extend lifespan [51]. Within this context, in [47] a new superhydrophobic coated material was tested by CFD (Computational Fluid Dynamic) simulations for a VLHT, by an ad hoc modeling of the wall boundary condition. Simulations were performed in a single-phase mode, with SST turbulence model on a periodic geometry. The turbine efficiency was improved by 4% at the design point. Furthermore, superhydrophobic material have the benefits of being self-cleaning, anti-icing and resistant to corrosion. Superhydrophobicity is a surface property caused by combination of nano-structured roughness and low surface energy. Superhydrophobic coatings is compatible with water quality. If they are made of titanium oxide nanoparticles or oxides of some metals such as magnesium, provided that their concentration is not too high, it does not adversely affect the water quality and therefore the body of aquatic organisms [52] [53]. On a superhydrophobic surface, contact angle hysteresis (the difference between advancing and receding contact angles, related to the trapped air in cavities between surface asperities) is less than 10°, while the contact angle of water droplets is more than 150°. On a superhydrophobic surface, shear stresses at the interface between water and trapped air are smaller, thus the skin drag is reduced due to the generation of an apparent slip. In the case of high load, the recommended surface for coating is the suction side.

2.3. Free surface studies

Computational Fluid Dynamic (CFD) tools have been widely used to analyze the behavior of the VLHT. The most used turbulence closure

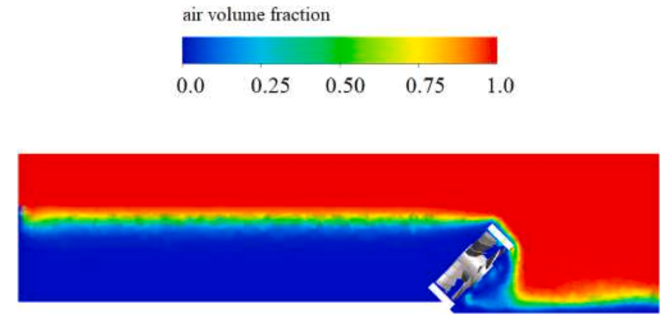

Fig. 10. Formation of free surface flow along the channel and overflow from the turbine.

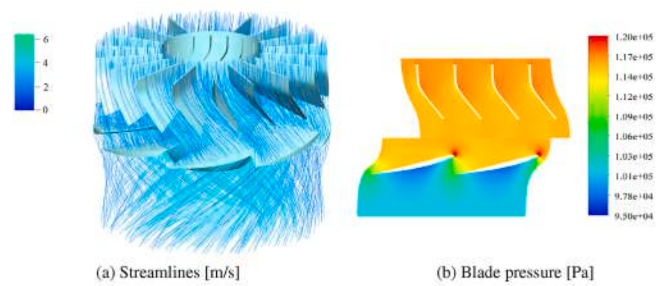

Fig. 11. (a) Flow field for a VLHT 4.5 m in diameter, 2.6 m head and 23.5 m^3/s of flow [31], and (b) example of pressure distribution from CFD simulation of Amir Bahreini.

model has been the k-ω SST, and less commonly the k-ϵ model [54]. The preference for the k-ω SST is likely due to shortcomings in the k-ϵ turbulence model for separated flows, and the higher accuracy of the k-ω SST. Different specific procedures in C++ have also been developed to design the distributor geometry and runner blades [55]. One complex behavior to be simulated is the interaction with the free surface. In general, the structure is simpler because there is no need for a penstock, a draft tube, or the main inlet valve. On the other side, free surface related losses, due to the mixing phenomena air–water at the interface, are a disadvantage of such hydropower facilities [56]. Despite the importance of this issue, most numerical analyses related to VLHTs have been done without considering the free surface interaction. For example, in [32], although the numerical solution was performed with free surface conditions, the effect of this phenomenon was not directly evaluated. Fig. 9.

In a numerical study under development by the authors of the present paper, the effect of free surface flow on the hydraulic performance of the turbine has been evaluated (Fig. 10). In this study, the turbine is designed for a channel with a flow rate of 0.0386 m^3/s due to a dimensional analysis based on [55]. However, the effect of overflow from the turbine due to fact that the channel was unclosed, shows a reduction of 18.5% in the flow rate passing through the turbine. By increasing the volume of flow entering the channel by 25%, the reduction in flow rate through the turbine reaches 31%. Therefore, the flow loss has a severe adverse effect on efficiency and further investigation of VLHT including the free surface flow should be carried out.

3. Flow field, cavitation and obstacle influence

The understanding of the flow field is of extreme importance in the design of any turbine, because it affects pressure distribution on the blades (i.e., the power) and phenomena like cavitation and erosion. Several papers [43] [40] [54] speak about the influence of upstream obstacles on the flow field. Few studies investigated the flow field with the main aim to determine how changes in the flow field affect the

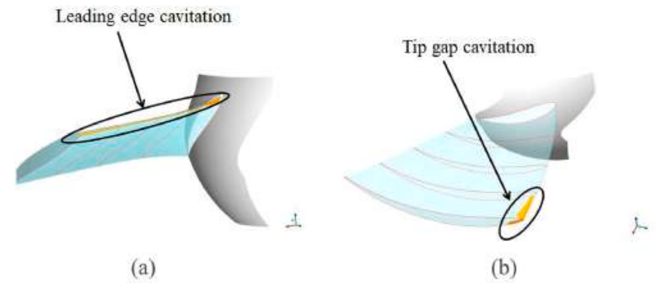

Fig. 12. Isosurface of vapour volume fraction < 0.1. (a) Attached cavitation at 44 m^3/s, 40 rpm and opening angle 7.5°; (b) tip gap cavitation at 22.7 m^3/s, 90 rpm and -5° [31].

turbine performance. No study was found on the flow field at different hydraulic conditions (e.g. head and flow) and rotational speeds. This should be better investigated in the future.

To the best of the Author knowledge, a study that relates the flow field to the turbine performance, in addition to those discussed in the next section, is presented in [47], where the flow field was investigated by CFD simulations for a new superhydrophobic coating material (Fig. 11). The entropy generation method was used to calculate the zones with energy dissipation and to find the influence on the dissipation mechanisms of superhydrophobic walls. At the design condition, the efficiency of the turbine decreased due to partial slip on the guide vanes and casing, related to the improper flow field on the turbine blades. The entropy generation in the draft tube significantly increased due to the formation of vortical structures and eddies at the back flow, because of the partial slip at the spiral case and guide blades. The vortical structures generated a head increase, thus a decrease in turbine efficiency, although the efficiency decrease could be due to both the energy dissipation and back flow in draft tube. [47] performed RANS simulations incorporating the SST turbulence model using a periodic approach, reducing thus computational time.

3.1. Obstacle influence

The VLHT is generally installed in existing hydraulic structures, thus the influence of upstream obstacle is of practical interest.

In [43] an efficiency drop of approximately 7% was observed with the introduction of a step upstream of the turbine at a spacing of $x/D = 0.5$, while the no-step and the distance $x/D = 1$ configurations had comparable efficiencies. In the former case, this was due to the vortex that detached from the edge of the obstacle and that interacted with the VLHT. The variable x is the distance between the turbine and the downstream edge of obstacle (a steep step) upstream of the turbine, while D is the turbine tip diameter. The efficiency decrease was due to a highly non-uniform velocity profile entering the turbine. The optimal flow rate was 0.0135 m^3/s at x/D=0.5, while 0.0130 m^3/s at x/D=1.

In [40] a non-rotating VLHT model was tested. It was recommended to locate the turbine at least at $x/D = 2$ downstream from the step to reduce the non-uniformity of the flow into the turbine. Non-uniformity, generating an efficiency drop, was also identified at close spacings of $x/D \leqslant 1$. The results of the non-rotating and rotating models were in good qualitative agreement, thus the non-rotating model can be used for a preliminary and quick design of a VLHT.

These results have also been confirmed in [54]: when the turbine was placed at a distance of x/D=1, a maximum of 4% pressure drop was observed. As the turbine was located closer to the step, the same area on the face of the turbine was affected, but to a greater extent. When the turbine was located at a distance of x/D=0 from the step, a 8% drop in pressure was found on the lower third of the turbine.

3.2. Cavitation

Cavitation is a phenomenon in which the static pressure of the liquid reduces to below the liquid vapour pressure, leading to the formation of small vapor-filled cavities in the liquid. When subjected to higher pressure, these cavities collapse and can generate shock waves that may damage the machinery.

In [31] the leading edge cavitation was observed at larger flow rates than the design flow when opening angles of blades were positive (Fig. 12). Instead, at rotational speeds above 60 rpm, the tip gap cavitation occurred for negative opening angles. Two cavitation types were identified: 1) the attached cavitation bubbles at low rotational speeds at the suction side and at leading edge of the runner blade (the thickness of the cavitation region was bigger near the hub, Fig. 12a). 2) The tip gap cavitation, which occurred at the leading edge of the blade tip radial section; this type was observed at the highest rotational speeds, and at opening angles below 0 (Fig. 12b). Cavitation was generated because of the high flow speed region near the turbine casing, and because of the high rotational speed of the blade configurations. When the rotational speeds overcame 60 rpm, the cavitation area may be transferred to the pressure side of the near tip region of the blade.

4. Ecological behavior

The ecological status of rivers is a major concern in the hydropower sector [57], especially when migratory fish risk to pass through the turbines. Therefore, new turbines with higher survival rate are being introduced on the market (e.g., the Alden and the Minimum Gap Runner turbine [58] [45]). The damages that fish may undergo passing through turbines can be of four main types [20]: 1) strike and grinding after a collision with the structural components: the blade strike on fish is generally considered the main cause of fish mortality, especially at low head sites; 2) shear stresses (with effects on the fish skin) and turbulence; 3) pressure: a very low pressure and a rapid decrease of pressure affect mainly physoclistous fishes, generating swim bladder rupture or internal haemorrhaging; 4) cavitation.

Based on a biological study, [55] proposed the criteria for estimating the fish-friendliness of a VLHT. Quantitative criteria were the maximum peripheral velocity of the runner, the minimum absolute pressure in the turbine, the maximum pressure gradient, the maximum velocity gradient through the shear zones, the maximum tip gap, optimum efficiency of the turbine, and a range for flow velocities at inlet and outlet proportional to fish species. The qualitative criteria also included increasing the water passage and reducing the number of blades as much as possible. Among the quantitative characteristics, the vast majority of conditions other than tips gap are generally satisfied. Besides, due to the

Table 4
Summary of fish mortality for VLHT at different conditions (FRT = farmed rainbow trout).

Fish	t_f (s)	t_b (s)	t_f/t_b	Mortality (%)	Ref
Eels	0.58	0.20	2.93	2	[44]
Large FRT	0.40	0.26	1.53	1.1	[62]
Large FRT	0.54	0.26	2.04	1.1	[62]
Large FRT	0.81	0.26	3.06	4.4	[62]
Small FRT	0.19	0.26	0.74	0	[62]
Small FRT	0.26	0.26	0.98	0	[62]
Small FRT	0.39	0.26	1.47	0	[62]
Large carp/tench	0.38	0.26	1.45	0	[62]
Large carp/tench	0.51	0.26	1.93	0	[62]
Large carp/tench	0.76	0.26	2.90	0	[62]
Small carp/tench	0.18	0.26	0.68	0	[62]
Small carp/tench	0.24	0.26	0.91	0	[62]
Small carp/tench	0.36	0.26	1.36	1.1	[62]
Smolt	0.19	0.19	1.01	3.1	[48]
Northern pike	0.29	0.19	1.57	6.25	[63]
Rock bass	0.12	0.19	0.66	0	[63]
Smallmouth bass	0.19	0.19	1.01	0	[63]
Largemouth bass	0.18	0.19	0.94	0	[63]
Walleye	0.22	0.19	1.18	0	[63]

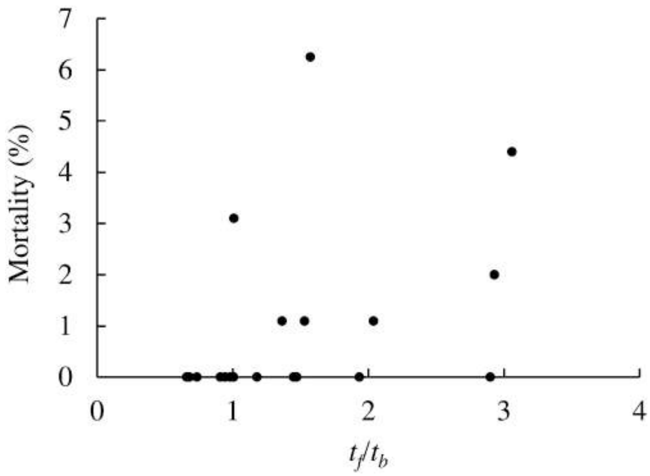

Fig. 13. Mortality of fish versus blade strike model time for VLHTs.

installation of the turbine in very low heads and the jumping ability of some fish from 2.1 meters to 3.3 meters, these turbines may not cause much disturbance to fish species such as salmon.

In light of this, [46] assessed the hydraulic conditions experienced through a VLHT, an Archimedes screw and horizontal Kaplan turbine. Decompression was rarely more than 10 kPa below atmospheric pressure, and rare at the VLHT and Archimedes screw turbines. In contrast, the Kaplan runner generated pressures as low as 45 kPa below atmospheric pressure (55.5 kPa), although over shorter periods of time. Strike was another source of fish injury (detected in 69–100% of deployments); strike severity was the highest in the Kaplan runner, but its was more likely to be encountered at the Archimedes screw and VLHT. Therefore, results showed that low-head hydropower plants could harm downstream migrating fish, thus there is a high interest in investigating the fish-turbine interaction.

[58] summarized some ecological tests, also listed in Table 4. Overall immediate turbine passage survival rates were 96.9% for smolts, in particular 94.5%, 98.6%, and 99.0% for fish released at the periphery, mid-blade, and hub, respectively. Extended survival for all release groups combined (72 h to 96 h) had an average of 98.6%. However, extended survival for control groups had an average of 97.9%; therefore, latent effects of passage were dismissed as negligible. Additional fish passage tests were completed with the VLHT with 150 European eels (Anguilla anguilla). Survival rates varied from 100% for fish injected near the hub, to 84% for fish injected near the blade tips (probably due to the higher tangential speed of the blade tip), with an average overall survival rate of 95%.

In [59] 1.16% of total entrained fish of all species and 6.25% of entrained pike were killed by turbine strike. The most common injury was related to abrasion. Passage of the tagged fish through the VLHT did not occur throughout this study, supporting the fact that the risk of entrainment through the VLHT is low. In a recent experimental study [63], the effects of the VLHT on several groups of fish were investigated. Only the northern pike experienced a partial decapitation (1.16% on the total number), due to the gap between the runner and the turbine structure. Therefore, the design should minimize the risk of fish injury in these spaces, as found in [62]. In [62] it was found that from 1.1% to 4.4% of mortality was dependent on blade opening and fish size, while a previous study [48] demonstrated that the mortality rate of 3.1% to 7.7% depended on the size of fish. Ref. [63] found that the mortality was 6.25% in the 7 days study, and the most significant injuries were caused by abrasion effects (external bleeding, scale losses and tear in fins).

The above-mentioned results show that results have never been generalized. Since mechanical injury mechanisms are considered dominant, in this section the blade-strike theoretical model was applied [60] [61] to generalize the results. In general, a fish is not injured by the blade strike if the fish enters the turbine in a shorter time t_f with respect to the time of the blade passage t_b. The entering time is $t_f = L/v$, where L is the fish length and v is the fish absolute velocity entering the turbine. The velocity can be considered to be axial for the VLHT, thus equal to the flow rate divided the frontal area of the turbine, that is a function of the diameter. Instead, the time employed by a blade to pass from the inlet is $t_b = l/u$, where $l = \pi D/n$ is the distance between two blades (wheel diameter D and number of blades n), and the tangential speed u is $u = ND\pi/60$ (m/s), that depends on the wheel rotational speed N (rpm) and diameter. Although this is a simple model, fish injury is expected to theoretically increase when t_f/t_b increases.

(a) *Transport and uplift by crane* (b) *Installation on the movable guide*

Fig. 14. VLHT installation in a canal, Mazzè, Italy, courtesy of Geasiste.

Table 5
Costs of VLHTs.

Ref.	name	D (m)	P (kW)	H (m)	Q (m^3/s)	€/kW
[26]	Nam Pung, Thailand		86	2	5	1950
[18]	Canal d'Huningue, France	3.55		1.42–1.98	13	2716
[20]	Canal Bianco, Italy	5.00	481	2.56	25	3650
[20]	Canal Bianco, Italy	3.15	2x256	3	16.5	3950
[18]	Isola Dovarese, Italy	5		3.2	23.5	4403
[18]	Mayenne River, France			2 (median value, 16 turbines)	13.5	4450
	Marnate, Italy		100			5000

Considering the literature studies where previous data are available, Table 4 was realized. As it can be seen from Fig. 13, fish mortality is typically below 2%. Although there is not a strong correlation between mortality and t_f/t_b, it can be seen that the mortality risk increases as t_f/t_b becomes higher than 1. Therefore, to minimize mortality risk, t_f/t_b should stay below 1. It should be noted that many of the fish injury studies may probably result in high survival rates because of the technology limitations. The fish tagged with balloons were not acclimated to the natural depth before released and no injury related to pressure change was accounted for. Nevertheless, the blade strike should be considered the most dominant, being the VLHT a very low head machine with no so much high pressures or too much negative pressures.

As a comparison, the mortality rate of fish through water wheels is below 0.1% at $t_f/t_b \leqslant 1$ [61], while it is 30% for Francis turbines and 10% for Kaplan turbines [60] although new types of reaction turbines are under development as emerging technologies with fish-friendly behavior, like the Alden turbine and the Minimum Gap Runner turbine, with fish mortality below 2% [45].

In [64], the integration of CFD and surrogate-based modeling was implemented to estimate the mortality rate of salmons passing through a VLHT using the Biological Performance Assessment (BioPA) method, that has been introduced by the Pacific Northwest National Laboratory [65]. This integrated technique has been used to determine the relation between the installation angle of the turbine runner and the distance of the turbine from the step in the upstream channel as two design parameters, and the BioPA score as the response parameter. For this purpose, the surrogate-based modeling was used to design the sample space of design parameters and predict the output function corresponding to different points in the design range (in [64] installation angle ranges from 30° to 60° and the distance from the step to the turbine is between half and twice the runner diameter) leading to reduction the cost and time of calculations. Also, the safest region in terms of barotrauma was near the middle of the blades compared to the proximity of the hub and the tip of blades.

5. Practical installations and costs

The VLHT, as specified in Section 1, is of easier installation and construction with respect to an analogous Kaplan turbine. The VLHT is a standardized product with standard diameters, and the modular construction of the turbine and generator help in cost reduction. There is no need for traditional penstocks and spiral casings for the turbine inlet. At the turbine outlet, no draft tube is usually required, depending on the turbine installation site. These characteristics reduce the civil cost to 40–50% [31]. Practical information on the VLHT installation can be found in [66], where the construction procedure is described. Fig. 14 depicts some installation stages of a VLHT installation, while [67] discusses the transport stage of a VLHT: the distributor is generally composed of two identical parts. Furthermore, the VLHT exhibits good acoustic performance: it is possible to build buildings in proximity of the turbine and no vibration occurs due to low rpm [66].

Table 5 summarizes the cost per kW for various installations, showing that the cost is below 5000 €/kW. The cases reported in Table 5 are here discussed.

[26] presented the feasibility study of the Nam Pung hydropower plant, Thailand. The power output was 86 kW, with an average flow rate of 5 m^3/s and an head of 2 m. The civil work costs, control equipment, turbine set and management costs were quantified in 167,604 €, with a payback period of 4 years, lifespan of 25 years, below the payback time of Kaplan turbines [68]. The quite low cost compared to the other case studies may be related to the different country where the VLHT was installed.

The quite fast payback time was confirmed in the project Canal d'Huningue (1 million euros of investment costs and payback time of 4 years) equipped with two VLHTs with diameter 3.55 m, flow rate 13 m^3/s each and head difference of 1.42 m and 1.98 m. The Isola Dovarese power plant, equipped with two VLHTs 5 m in diameter, 3.2 m head and flow rate 23.5 m^3/s each, required 5.4 million € of investment, and a payback time of 5.5 years. The most complex developed project was in Mayenne River, involving 16 VLHTs in cascade, with net heads from 1.6 m and 2.4 m, and with flow rate 13.5 m^3/s. The overall investment cost was 16 million €, with a payback time of 10 years, and with a higher cost with respect the previous examples probably due to the local design complexity [18].

Another example can be found in [24] in the Coimbra dam-bridge, thus maintaining its use as multipurpose plant. The VLHT unit produced more energy comparatively to the StrafloMatrix unit layout. However, the VLHT unit layout needed of the radial gate removal, some demolition of the spillway sill, and the installation of an upstream vertical lift gate. Instead, the layout with the StrafloMatrix unit produced less energy, but the original radial gate could be preserved. The characteristics of the VLHT were 3.55 m diameter, for a maximum power output of 389 kW, 15.8 m^3/s and 3.2 m head, while the Straflo turbine was 1.32 m diameter, 311 kW, flow rate 12.4 m^3/s and 4.3 m head. Furthermore, the VLHT unit showed a smooth operation, with less vibrations. The maximum estimated annual revenues were 228,475 € for the VLHT and 139,092 € for the Straflo turbine.

In [20] it was shown that the use of the existing structures of navigation locks allowed to reduce costs per installed kW. The control building and cable trenches were less expensive and their costs were reduced by 80%, while the design of the steel structure for the VLHT increased the cost of mechanical structures by 40%. The final and total cost of the two VLHT was 3950 and 3650 €/kW respectively (a similar plant in which civil works were needed would have a total cost of 5000 €/kW), with an estimation of the cost reduction between 20 and 30%. Both costs are very similar because the installation contexts were similar and the engineering company was the same.

Instead, in [22] VLHTs were installed in a tidal context. The higher the number of turbines was, the higher was the discharge that could be exploited, but the lower the head that could be generated. Therefore, an optimization process was performed in order to find the optimal number of VLHTs, and 7 was identified as the optimal value to maximize energy production during one tidal cycle.

6. Maintenance

Thanks to the geometric simplicity of the unit, the VLHT requires only a square concrete channel and can be raised or removed for maintenance interventions or repairs. However, lot of attention should be devoted to the maintenance aspects for the VLHT, especially when flow level changes and parts of the turbine may become exposed to the air. Furthermore, a radial trash rack allows to clean the runner on the

Fig. 15. VLHT installation in the canal, Mazzè, Italy.

distributor nose (Fig. 4), but this induces head losses, especially due to the interaction with the free surface (no study was found about the induced head losses), and it requires a frequent cleaning.

One of the criticisms of VLHTs is their sensitivity to frost [69]. For example, during winter months when the downstream water level is lower, the VLHT runner is completely submerged on the upstream side but it may be partially submerged on the downstream side. Therefore, when the temperature is very cold, a significant temperature gradient across the unit may be generated. The parts of the unit in contact with the water are at the same water temperature ($\simeq 0^\circ$C) while the other components are close to the air temperature ($\leqslant 0^\circ$C). Therefore, the structure of the turbine can undergo physical changes. As a consequence, additional stresses may reduce tolerances creating misalignment of moving parts, and lead to an efficiency decrease.

Frazil ice is another problem in the cold seasons. In regions where the water temperature can drop into supercooled area due to weather conditions, these active crystalline particles form, stick to each other and other cold objects, and even by sticking to turbine components can reduce the flow through the turbine and thus turbine efficiency. The formation of ice on the water level can generate unbalanced forces and loads on the turbine. Therefore, the turbine must be removed from the water [9].

In contexts where flows are significantly less in winter, plant owners may prefer to remove the turbines during winter months, and reduce maintenance costs. To efficiently operate in winter conditions, or, in general, at reduced downstream water levels, the VLHT design is equipped with a downstream steel hood of the same diameter of the runner that operates as a draft tube to maintain a suction pressure at the turbine exit. Insulation, electric heaters beside the guide vanes, and antifreeze coating on the upstream side of the turbine can be used to reduce ice formation [9].

Seals, electrical components and grease have to be protected from severe cold temperatures by using an insulation layer on the upper part of the downstream area of the runner structure. The obstructions generated by ice can be reduced using electric heat tracing along the guides, or one other option is to equip the guides with steam jet ports. A cover of a resilient ice-phobic rubber is used to reduce the ice adherence and the negative effects of the heat transfer [9].

Conclusions

The VLHT is a recent turbine introduced on the market to exploit higher flow rates at very low head sites. The variable pitch of the blades and the variable rotational speed make it a flexible machine, that can be used with a variable flow and head. The costs are lower than Kaplan turbine costs, since pressurized hydraulic penstock and spiral casing are not required, resulting in a reduction of concrete volume of the civil work infrastructure of 1/3 to 1/5, as well as reduction of the power plant length of 1/3 to 1/5, with respect to a Kaplan turbine. Payback times range from 4 to 10 years, with costs generally below 5000 €/kW.

This literature review shows as the design of the blades has a great influence on the performance. The general rules of turbomachinery design can be applied for the blade design, and in literature empirical metamodels have been found to predict the efficiency as a function of the blade shape. The blade design also affects the ecological behavior of the VLHT, especially the gap between the discharge ring and the blade tip. Fish mortality is in general below that of low head Kaplan turbines, and the application of the blade strike model, here applied, allowed to generalize the results and to suggest empirical tools for a preliminary ecological behavior estimation.

A good qualitative agreement between the non-rotating and rotating models during some tests suggests that non-rotating models can be used for a relatively quick and first-approximation design of a VLHT, simplifying the preliminary design stage. The design can be optimized by CFD simulations, and the most performing method is the k-ω SST model. However, CFD simulations underly that cavitation is possible in the VLHT, and the blade inclination significantly affects cavitation distribution and intensity.

The influence of upstream obstacles has been deeply investigated, and all the studies agree on the fact that the distance (x) between the turbine and the obstacle should be $x/D > 1$ to avoid significant efficiency reduction, with D the turbine diameter.

Suggestions for future VLHT research are the investigation of the number of blades and axis inclination, although from a practical point of view, the adopted solutions with 8 blades and axis inclination between 40° and 50° can be considered effective. Due to the lack of a unique pattern for selecting hydrofoils of different blade sections, further studies on blade design are recommended. Head losses in the radial trash rack should also be investigated, as well as more light should be done to show how the flow field is affected by the variable rotational speed and hydraulic conditions.The free surface interaction (open channel flow) is an issue with high investigation potential.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. E.Q. coordinated the research, carried out the literature review and wrote/revised the paper. R.R. carried out the literature review and revised the paper. A.B. and A.R. helped in writing the section on the blade design, on the free surface and on new materials, addressed some reviewer comments, provided some pictures and collected some literature studies.

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Appendix A. Case study

One example of VLHT is that on the right bank of river Dora Baltea, Mazzè, Italy (see Figs. 3,4), on an existing weir. The plant fits into an existing barrier having the function of promoting the collection of water from irrigation canals called Lama and Gabriella (Fig. 15).

The catched river basin is 3872 km^2. The maximum river flow rate is $Q_m = 269$ m^3/s, with an average flow of 96 m^3/s. The maximum flow rate that can be discharged through a hydropower plant is 54.2 m^3/s, for an average value of 19 m^3/s. The ecological flow is 15 m^3/s. The head difference is 2.60 m, while the elevation of the inflow is 201.6 m on the sea level. Two VLHTs with 5 m diameter have been installed, for an average energy generation of 3.2 GWh/year.

Based on the ecological flow value, the flow rate to be released through the ichthyofauna fish passage was determined following the D.G.P. n. 746–151363/ 2000 of 18/07/2000 "Criteri tecnici per la progettazione e la realizzazione dei passaggi artificiali per l'ittiofauna [Technical criteria for the design and construction of artificial passages for the ichthyofauna]". The ecological flow rate through the fish passage is 2.5 m^3/s. About 200 m away from the intake, in a safe area against flooding events, the hydroelectric power station was built alongside an existing road.

The two production units with nominal external diameter of 5 m are installed inside the channels 10 m downstream of the sluice gates. The VLHTs are made of 8 regulating runner blades with a power of 527 kW each, combined with a permanent magnet generator with variable speed of 607 kVA. The runners are installed at an angle of 45°. The blade control mechanism is located at the end of the hollow shaft that supports the rotor of the turbine and generator.

Since the turbine and generator are completely submerged, there is a total reduction of noise outside, a significant reduction in the volumetric footprint of the plant and, consequently, a reduced visual impact.

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