EXPERIMENTAL SETUP DESIGNED FOR TESTING A CROSS-FLOW WATER TURBINE IN A WIND TUNNEL

Andrei-Mugur GEORGESCU[1], Sanda-Carmen GEORGESCU[2], Mircea DEGERATU[3]

Lucrarea prezintă standul experimental proiectat pentru a încerca un model al turbinei Achard la scara 1:1, într-un tunel aerodinamic. În condiţii normale, turbina Achard funcţionează în apă, fiind o turbină hidraulică transversală, cu arbore vertical şi pale în formă de delta. Modelul de 1 m diametru şi 1 m înălţime ar necesita un canal foarte mare dacă ar fi încercat în apă. Aici, propunem efectuarea încercărilor experimentale în aer, pentru a investiga cu acurateţe curgerea fluidului în interiorul şi în jurul turbinei. Câmpul vitezelor va fi determinat cu ajutorul unui sistem PIV, plasat în exteriorul tunelului.

The paper presents the experimental setup designed to test a 1:1 scale model of the Achard turbine in an aerodynamic wind tunnel. Under normal conditions, the Achard turbine runs in water, being a vertical axis cross-flow water turbine, with delta blades. The model of 1 m diameter and 1 m height would require a huge channel if tested in water. Here, we propose to test that turbine in air, in order to accurately investigate the flow behaviour inside and around the turbine. The velocity field will be depicted by using a Particle Image Velocimetry (PIV) system, placed outside the wind tunnel.

Keywords: Achard turbine, cross-flow, delta blade, PIV, similitude, wind tunnel

1. Introduction

The Achard turbine is a new concept of cross-flow marine or river turbine [1], which consists of a vertical shaft and a runner with three delta blades, as in Figure 1. During the last 3 years, that turbine has been intensively studied in France, in the Rhône-Alpes region, especially at the Geophysical and Industrial Fluid Flows Laboratory (LEGI) of Grenoble, and at the 3S-R Laboratory of Grenoble, mainly with regard to marine applications, to extract energy from tidal currents in costal locations [1-6]. The desired power can be obtained by summing elementary power provided by small turbine modules, piled up in parallel towers

[1] Reader, Dept. of Hydraulic and Environmental Protection, Technical University of Civil Engineering Bucharest, Romania
[2] Reader, Dept. of Hydraulics, Hydraulic Machinery and Environmental Engineering, University POLITEHNICA of Bucharest, Romania
[3] Professor, Dept. of Hydraulic and Environmental Protection, Technical University of Civil Engineering Bucharest, Romania

within a marine hydropower farm (such farm needs a minimum of civil engineering works). The Achard turbines are also suitable to be placed in big rivers within a river hydropower farm, where the turbines can operate efficiently in free flow without dams, as in Figure 2. With respect to possible locations on the Danube River, the Achard turbine is studied in Romania since 2006, within the THARVEST Project of the CEEX Program sustained by the Romanian Ministry of Education and Research [7], in close collaboration with LEGI Grenoble. The THARVEST Project aims to study experimentally and numerically the hydrodynamics of the Achard turbine.

Fig. 1. Achard turbine runner.

Fig. 2. River hydropower farm.

The Achard turbine main geometric dimensions are: the runner radius $R = 0.5$ m, the runner height $H = 1$ m, and the shaft radius $r_S = 0.05$ m (the location of the vertical shaft is visible in the centre of the runner, in Figure 1). As depicted from Figure 1, the three vertical delta blades (analogues to delta wings) are sustained by radial supports at mid-height of the turbine. The blades are shaped with NACA 4518 airfoils [8]. Along each delta blade, the airfoil mean camber line length varies from 0.18 m at mid-height of the turbine, to 0.12 m at the extremities. Between the leading edge of blade's extremity and the leading edge of the blade at mid-height of the turbine, there is a 30° azimuth angle. The radial supports are shaped with straight NACA 0018 airfoils [9]. At the upper part, as well as at the lower part of each turbine module, the existence of a circular rim shaped with lens type airfoil (as in Figure 2), or the existence of a flat disk, prevents the formation of wingtip vortices that can trail from the tip of each blade.

Within this paper, we present the experimental setup designed to test the Achard turbine in air, namely in an aerodynamic wind tunnel, to accurately investigate the flow behaviour inside and around the turbine. The similitude criteria impose values of the different physical quantities that are to be realized on the experimental model, in order to preserve the similarities with the natural phenomena that occur in water. We will use a 1:1 scale model of the Achard turbine: a model of 1 m diameter and 1 m height. Obviously, the size of the model requires a huge wind tunnel. The upstream airflow will be uniform in a cross-section of the tunnel. The velocity field around the turbine blades will be depicted by using a Particle Image Velocimetry (PIV) system, placed outside the wind tunnel.

The vertical axis cross-flow turbines (e.g. Darrieus water turbine, Gorlov turbine, and Achard turbine) need to be powered by an electric motor when starting; then, after reaching the normal operating regime, they produce power in an electrical generator – so, those turbines are connected to one motor-generator. For the experimental setup designed here, the Achard turbine rotation will be ensured by a common electric motor with variable speed. Thus, combining the airflow velocity inside the wind tunnel and the rotation imposed by the motor, the expected velocity field can develop inside the turbine.

2. Hydraulic similitude

In order to accurately select the range of the airflow rate values inside the wind tunnel, as well as to design the system that will ensure the turbine rotation, together with the supports that will hold the 1:1 scale turbine model inside the tunnel, certain similitude criteria must be ascertained between the hydraulic phenomena that occur in nature (subscript *N*) and on the model (subscript *M*) [10].

For the phenomenon we are studying, the following 7 dominant physical quantities were identified: c, chord length of the blade; U_∞, velocity of the fluid upstream of the turbine module; ρ, density of the fluid; μ, dynamic viscosity of the fluid; ω, angular velocity of the turbine; R, radius of the turbine (of the runner); and B, number of blades.

Applying the principles of Dimensional Analysis, by choosing three of these quantities as fundamental, namely: c, U_∞ and ρ, we obtain 4 non-dimensional criteria specific to the present application: $Re_c = U_\infty c/\nu$, the *chord based Reynolds number* (where $\nu = \mu/\rho$ is the kinematic viscosity of the fluid); $\omega c/U_\infty$, a criteria related to the velocity; R/c, a criteria related to the geometry of the runner, and B, a criteria that equals the number of blades (it has to be identical on the model, to the one in nature). Combining the second and third criteria, we get $\lambda = \omega R/U_\infty$, which is known as the *tip speed ratio*. From the tip speed ratio and the chord based Reynolds number, we get $Re_b = \omega Rc/\nu$, which is the *blade Reynolds number*. Combining the last two non-dimensional criteria, we get $\sigma = cB/R$, which is known as the *solidity*.

For the case of modelling a water phenomenon in air, with the length scale of 1:1, and by considering the above mentioned similitude criteria, we obtain values of the scales of physical quantities that influence the phenomenon [10]: e.g. the imposed viscosity scale $\nu_M / \nu_N = \nu_{air} / \nu_{water} = 15$, the imposed density scale $\rho_{air} / \rho_{water} = 0.0012$, the resulting fluid velocity scale $U_{\infty_M} / U_{\infty_N} = 15$ (which equals the angular velocity scale and the rotational speed scale), and the resulting pressure scale $p_M / p_N = 0.27$ (which equals the aerodynamic force scale). Starting from the characteristics of the Achard turbine module running in water, i.e. radius $R_N = 0.5$ m, number of blades $B_N = 3$, kinematic viscosity $\nu_N = 10^{-6}$ m^2/s, tip speed ratio $\lambda_N = 2$, and solidity $\sigma_N = 1$, and by taking into account that in the area where this turbine will work (sea, large rivers), the water velocity can be considered in the range $U_{\infty_N} = 0.3 \ldots 1.0$ m/s, we can compute the values of the upstream air velocity U_{∞_M} inside the wind tunnel, together with the values of the angular velocity ω_M and rotational speed n_M for the experimental model running in air. These values are presented in Table 1.

Table 1

Upstream velocity, angular velocity and rotational speed in nature (in water), and for the experimental model (in air)

Nature (*N*)			Model (*M*)		
$U_{\infty N}$ [m/s]	ω_N [rad/s]	n_N [rpm]	$U_{\infty M}$ [m/s]	ω_M [rad/s]	n_M [rpm]
0.3	1.2	11.46	4.5	18	172
0.4	1.6	15.28	6.0	24	229
0.5	2.0	19.10	7.5	30	286
0.6	2.4	22.92	9.0	36	344
0.667	2.667	25.46	**10**	**40**	**382**
0.7	2.8	26.74	10.5	42	401
0.8	3.2	30.56	12.0	48	458
0.9	3.6	34.38	13.5	54	516
1.0	4.0	38.20	15.0	60	573

The values of $U_{\infty M}$ computed in Table 1 are quite important. To ensure such values, we will perform our experimental tests in the biggest aerodynamic wind tunnel of the Wind Engineering and Industrial Aerodynamics Laboratory, within the Hydraulic and Environmental Protection Department, Technical

University of Civil Engineering Bucharest. That wind tunnel has a cross-section of 1.75 m x 1.75 m (allowing enough space to place inside the 1:1 scale turbine model), and a total length of 20 m. In order to avoid the boundary layer development inside that long tunnel, the turbine module will be placed in the upstream part of the tunnel, where the velocity field is uniform. The maximum airflow velocity that can be reached inside that wind tunnel is about 20 m/s, the tunnel being equipped with a powerful fan of 75 kW, with variable rotational speed. From economic reasons (related to the huge electrical consumption of the fan, during such time-consuming turbine tests), as well as from the fluid-structure interaction point of view (to reduce the intensity of cyclic loadings on the turbine blades, as function of angular position), we will limit our experiments to upstream air velocity values in the range $U_{\infty_M} = 4.5 \ldots 10$ m/s. As mentioned before, the turbine will be powered by an electric motor with variable speed, in order to obtain the rotational speed of the turbine in the desired range $n_M = 172 \ldots 382$ rpm.

3. Particle Image Velocimetry system

As mentioned before, the velocity field around the Achard turbine blades will be depicted by using a Particle Image Velocimetry (PIV) system, placed outside the wind tunnel. More precisely, it is a mobile 2D-PIV system (Figure 3), purchased from the German company ILA [11].

The Particle Image Velocimetry (PIV) is a laser optical technique for the fast and non-intrusive measurement of whole flow field, providing instantaneous velocity vector measurements in a cross-section of a flow [11-12]. The technique is applicable to a whole range of liquid and gaseous flows. The flow vector can be determined in a measuring plane with two (2D-PIV) or all of its three components (stereoscopic 3D-PIV). A tridimensional data set of the fluid velocities can be generated by moving the measuring plane through the interesting volume. The use of modern digital cameras and dedicated computing hardware, results in real-time velocity maps.

In PIV, the velocity vectors are derived from sub-sections of the target area of the particle-seeded flow by measuring the movement of particles between two light pulses. Thus, a laser is generating a thin light sheet inside the flow. With the pulsed laser, a cross-correlation camera is acquiring two consecutive images of particles transported with the flow. The particles have a displacement proportional to the flow velocity. With the known pulse distance and the calibrated scaling factor of the camera, the flow velocity can be calculated. A velocity vector map over the whole target area is obtained by repeating the cross-correlation for each interrogation area over the two image frames captured by the camera. The range of flow velocities starts at several mm/s and can go up to trans-sonic flows, by adjusting the laser pulse distance.

All the components of the PIV system can be mounted in a trolley. The result is a mobile, compact and powerful measuring system (Figure 3), which can provide measurements in several locations along the wind tunnel.

Fig. 3. Mobile 2D-PIV system from ILA [11].

The PIV system consists of the light sheet generation, the synchronization, as well as the image acquisition and evaluation. The light sheet is generated by a pulsed Nd:YAG Laser. The laser power is between 25 and 350 mJ/pulse. A light arm is delivering the very powerful laser beam to the light sheet optic. Very accurate mirrors with a special coating inside the light arm are transmitting the laser light nearly without any losses. The light sheet optic generates the light sheet out of the laser beam, where the thickness and the divergence angle is adjustable infinitely variable. The synchronization between laser and camera is controlled by the PIV Synchronizer, which can be triggered by external events. The image acquisition and evaluation is realized by a special cross-correlation camera and a very fast PC. The image data is transferred through an optic fibre and is evaluated, archived and displayed by the special PIV software VidPIV [13].

The PIV software is very important, due to the amount of acquired image data and their complexity. VidPIV 4.6 ensures an easy image acquisition, puts the images in its unique tree structure (archive) and has a powerful evaluation and post-processing of the measuring data. VidPIV offers diverse Import and Export functions, efficient Mappings, nearly any Annotations, an own Software Development Kit and supports nearly any hardware. The numerous features of VidPIV are described in the ILA software brochure [13].

4. Achard turbine and electric motor setup in the wind tunnel

The 1:1 geometric scale module of the Achard turbine has been built within the THARVEST Project [7], by the company SANGARI Engineering Services – Romania [14]. The runner is entirely in Aluminium (Figure 4), while its hub and shaft are in stainless steel. In Figure 4, we present the assembly of the turbine, bearings, power transmission and electric motor, together with the upper and lower supports. In Figure 5, we present the whole Achard turbine power unit, connected to the existing structure of the aerodynamic wind tunnel.

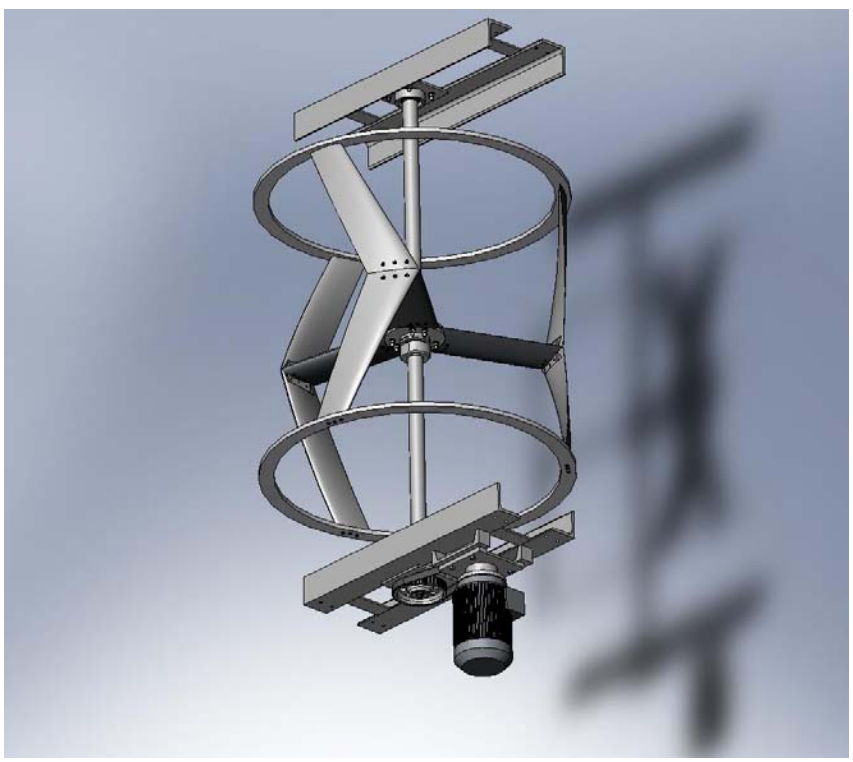

Fig. 4. Achard turbine power unit.

Within the Section 3 we presented the PIV system, which allow determining the velocity field around the Achard turbine blades. In order to estimate the aerodynamic forces acting on the experimental model of the Achard cross-flow turbine, tested in the aerodynamic wind tunnel, we need to know the pressure distribution on the delta blade.

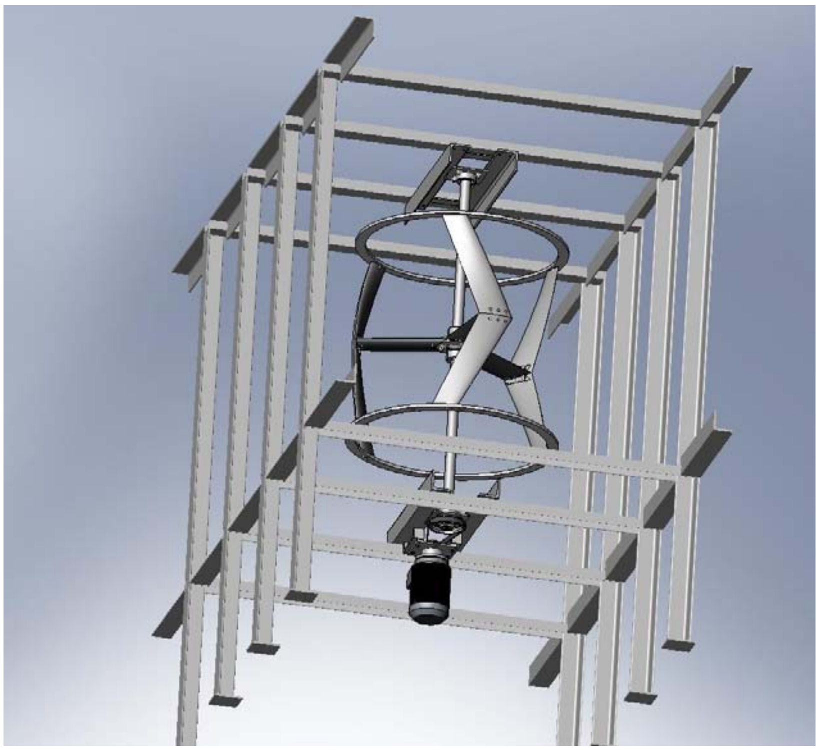

Fig. 5. Achard turbine assembly connected to the structure of the wind tunnel.

According to this requirement, one of the delta blades has several pressure taps on its surface. Thus, the pressure variation on the blade surface is transmitted through a tube inside the blade, along the radial support, then through the shaft, directly to a pressure transducer (placed at the upper part of the shaft), connected to a wireless transmission system (Data Logger wireless system), able to send the information outside the turbine. The wireless transmission system placed on the shaft was the best solution, due to the rotation of the turbine.

5. Conclusions

The paper presents the experimental setup designed to test a 1:1 geometric scale model of the cross-flow Achard turbine. Under normal conditions, the Achard turbine runs in water, but the model of 1 m diameter and 1 m height would require a huge channel if tested in water. So, we decided to test that turbine in air, within an aerodynamic wind tunnel, to accurately investigate the flow behaviour inside and around the turbine.

The similitude criteria derived for the modelling of the airflow in the turbine are accurately chosen. Basically, due to the viscosity scale (ratio between the air and water kinematic viscosity), the upstream velocity of the air inside the wind tunnel can reach 15 m/s, a value that is 15 times greater than the corresponding water velocity in marine currents or large rivers. Accordingly, the rotational speed of the turbine running in air is 15 times greater than the one that corresponds to the turbine running in water. Those values lead to economic problems, related to the huge electrical consumption of the fan, during such time-consuming turbine tests within the wind tunnel, as well as to mechanical problems related to the fluid-structure interaction (fatigue of the materials). In order to reduce both the electrical consumption and the intensity of cyclic loadings on the turbine blades, our experimental setup will ensure the air velocity inside the wind tunnel up to 10 m/s (at that value, the rotational speed of the turbine equals about 380 rpm).

The velocity field can be depicted by using a Particle Image Velocimetry system, placed outside the wind tunnel. The aerodynamic forces acting on the Achard turbine can be computed based on the variation of the pressure captured on the blade surface.

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