WIND TUNNEL TESTS ON CASED WIND TURBINES ENSEMBLES DESIGNED FOR A CERTAIN LOCATION

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Abstract: The placement of a wind turbine in a certain location involves the achievement of preliminary studies regarding the particular wind potential of the site and also the turbine operation under those conditions. The studies presented in the paper are dealing with both aforementioned aspects being more focused on the physical modeling in a boundary layer wind tunnel of the dominant wind interaction with a horizontal shaft cased wind turbine ensemble. The developed research was made for two turbine disposals. Based on this studies several data were obtained on the operation characteristics of the ensemble.

1. INTRODUCTION

When the location is characterized by the dominant wind direction with a high frequency of occurrence, a sufficiently high mean multiannual velocity on that direction and a velocity profile described by a power law with a small exponent, as an energy capturing solution, the barrages of wind turbines orientated with their shafts on the dominant wind direction can be adopted.

Such a location can be found in the Romanian seashore area of the Black Sea, where the dominant wind direction is from the northern sector. Thus, the paper describes in its first part the determination of the wind potential for the considered location. The second part deals with the experimental research carried out in the atmospheric boundary wind tunnel owned by the “Aerodynamics and Wind Engineering Laboratory” (A.W.E.L.), Technical University of Civil Engineering Bucharest (T.U.C.E.B) on two scale models of the wind barrages, in order to determine some dimensionless values proportional to the captured wind power.

2. WIND POTENTIAL OF THE ROMANIAN BLACK SEA SEASHORE

The first part of the paper describes the assessment methods of the wind potential at the seacoast stations Sfântu Gheorghe, Constanţa, Mangalia, and the offshore station Gloria, as well as for the whole Romanian seashore.

2.1 Calculation method of the wind energetic potential

In order to assess the wind potential of the Romanian Black Sea seashore it is necessary to define the wind potential starting from the wind kinetic energy concept. The kinetic energy of the moving air masses is mainly given by the density of the energy flux which represents the quantity of energy which crosses the surface unit normal to the wind direction in the unit of time. Consequently, from the dimensional point of view the density of the energy flux is a unitary power, given for a regular unit surface placed normal to the wind direction by the following relationship:

$$P_u = \rho U^3 / 2 \qquad (1)$$

where ρ is the air density, and U is the wind velocity.

The density of the wind energy flux presents large variations in time and space. For a given location the temporal average, noted $<P_u>_t$, of the energy density flux on a sufficiently large time interval T, defines the wind potential for a considered location:

$$\varepsilon = \langle P_u \rangle_t = \lim_{T\to\infty} \frac{1}{T}\int_0^T P_u(t)dt \tag{2}$$

Considering the wind velocity as a continuous random variable and introducing the function of distribution of wind velocities $f_r(U)$, the probability that the random variable U take values less than u is expressed as follows:

$$f_r(U) = P(U < u) \tag{3}$$

The density of distribution of the random variable U is given by the probability of U to take values in the interval of length in the vicinity of the value u, on the unit of length of the interval:

$$f(U)du = P\,(U \in (u, u+du)) \tag{4}$$

Also the complementary of the function of distribution, used more often in practice, is defined as:

$$f_c(U) = 1 - f_r(U) = P(U < u) \tag{5}$$

Considering the temporal average according to relation (2) can be expressed as the average of the density of the energy flux over the static assembly defined by the density of distribution $f(U)$, results the expression of the wind potential:

$$\varepsilon = \int_0^\infty P(U)f(U)dU \tag{6}$$

For practical purposes, the density of the wind distribution velocities is approximated by the histogram of wind frequencies, determined for series of annual or multi-annual data:

$$f(U_i) = \frac{n_{Ui}}{N} \tag{7}$$

where n_{Ui} represents the number of data included in the interval (U_i, U_{i+1}) of length ΔU with $U_i = (i-1)\Delta_u$, and $N = \sum_{i=1}^{m} n_i$ is the volume of the selection. In this case the wind potential is expressed by the sum:

$$\varepsilon = \sum_{i=1}^{m} P(U_i)\cdot f(U_i) = \sum_{i=1}^{m} \frac{PU_i^3}{2}\cdot\frac{n_{Ui}}{N} \tag{8}$$

where m represents the number of intervals of wind velocities, and ρ is the multi-annual average density of the air.

2.2 Calculation of the wind potential on the Romanian seashore of the Black Sea

The assessment of the wind potential was achieved at the stations Sfântu Gheorghe, Constanţa and Mangalia for a 5 years period and at the station Gloria the considered time interval was 10 years. These time periods are sufficiently for the assessment of the wind potential.

For all four locations, the calculation of the wind potential at the reference height z = 10m was achieved in case of various wind directions. The used relationship is:

$$\varepsilon_{(10)} = \sum_{i=1}^{m} \frac{\rho [U_i(10)]^3 \cdot n_{U_i}}{2N} \tag{9}$$

where $\varepsilon(10)$ is the wind potential at the standard height of 10 m, ρ is the average multi-annual density of air; N is the total number of measurements, and n_{Ui} is the number of occurrences of the wind velocity $U_i(10)$ on velocity intervals.

To describe the profile of the average wind velocity at various heights, $U(z)$, in the Romanian seashore area and on various directions, there was applied the power law or Davenport's law, which has the expression $U(z) = U(10)\left(\frac{z}{10}\right)^{\alpha}$, where α is an exponent depending on the nature of the terrain roughness.

According to the average velocity profiles for the seashore area atmospheric boundary layer, the wind potential at various heights could be calculated. The computing relationship for the wind potential at various heights and for various wind directions is:

$$\varepsilon(z) = \varepsilon(10) \cdot \left[\frac{U(z)}{U(10)}\right]^3 \tag{10}$$

Considering that:

$$\frac{U(z)}{U(10)} = \left(\frac{z}{10}\right)^{0.16} \tag{11}$$

results the expression:

$$\varepsilon(z) = \varepsilon(10)\left(\frac{z}{10}\right)^{0.48} \tag{12}$$

where $\varepsilon(z)$ is the wind potential at the height z, $\varepsilon(10)$ is the wind potential at the standard height calculated according to $U(10)$, z is the height from the conventional surface of the soil, and 0.48 is the coefficient calculated according to the roughness of the terrain (3…0.16).

In order to assess the wind potential at the studied stations there were made the required calculations and plotted the corresponding graphs. From the analysis of these graphs a series of conclusions regarding the distribution of the wind potential values on various wind directions and data regarding the average multi-annual values of the wind potential at the four stations as well as the value of the wind potential on the entire Romanian seashore of the Black Sea were driven.

The value of the wind potential in the atmospheric boundary layer above the seashore area is strongly influenced by the friction efforts and the vertical heat flux. In the atmospheric transition layer, which spreads up to the upper limit of the atmospheric boundary layer, this value is determined outside the friction efforts and heat flux and the Coriolis forces, the influence of which can be neglected in the surface layer.

The calculation of the wind potential were made starting from the standard height of 10 m up to the height of la 220 m considered as equal to atmospheric boundary layer thickness in the seashore area. With the calculated values using the above relationship the vertical distributions of the wind potential for each sea coast station in case of the entire thickness of the atmospheric boundary layer was determined.

2.3 Assessment of the potential for the northern sector winds at the Sfântu Gheorghe, Constanţa, Mangalia and Gloria stations

As shown in the previous paragraph, for the calculation of the wind potential at Sfântu Gheorghe, Constanţa, Mangalia and Gloria stations, the average multi-annual wind velocity $U(10)$ and the roughness of the terrain or sea surface were considered. In this case, the exponent value is 0.16, a value corresponding to open field and terrains as well as sea surface for a reduced regime of waves. Considering the aforementioned and based on the made calculations, a distribution from north to south along the Romanian seashore of the Black Sea and various cardinal directions of the wind potential values $\varepsilon(10)$ were obtained.

According to the particularities of the wind regime at each station, namely wind persistence, maximum duration of the atmospheric calm periods and their distribution over a one year time span, the wind potential ε itself varies along the Romanian seashore of the Black Sea.

Based on the data presented in the section regarding the atmospheric boundary layer above the sea, several graphs of the wind potential ε variation on different heights z, up to 220 m representing the thickness δ of the atmospheric boundary layer over the sea, and for various dimensionless $z/10$ were plotted.

Using the computing method based on wind potential measurements, the values of wind potential ε for various wind direction and heights z were obtained for the Sfântu Gheorghe, Constanţa, Mangalia and Gloria stations as well as for the entire Romanian seashore. In figure 1 are shown the results for the northern wind direction.

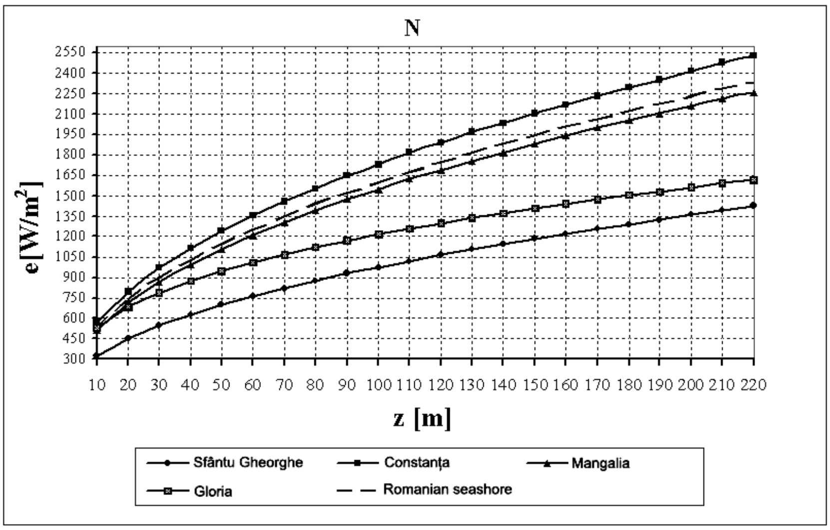


Fig. 1. Distribution of ε for the northern direction winds at the four stations and for the entire Romanian seashore.

At Sfântu Gheorghe station, for the northern wind direction, the wind potential has the maximum values in comparison with the other wind directions. This value is 325 W/m^2 at z = 10 m and 1425 W/m^2 at z = 220 m. For the north-eastern direction, the wind potential ε values range in a 50…1100 W/m^2 interval, values corresponding for the heights z = 10 m and z = 220 m. It must be noticed that, for southern, south-western and western wind directions there were recorded the lowest average multi-annual values of wind velocity as well as low average multi-annual frequencies as compared with the northern, north-eastern and north-western directions, for which both the wind velocity value and the wind potential value are high.

At Constanţa station the maximum wind potential value is obtained for a wind from the northern direction. The values are 575 W/m^2 for z = 10 m and 2530 W/m^2 for z = 220 m. For the north-eastern direction, the wind potential values ranges between 485…2148 W/m^2, for z = 10…220 m. The degree of variation of the wind potential values ε at Constanţa station according to the wind direction and the height z, is high. Thus, at z = 10 m, for the northern direction of the wind, the wind potential is 575 W/m^2, and for the south-eastern direction at z = 10 m the wind potential is only 140 W/m^2. This fact is explained by the existence of an average multi-annual wind velocity higher for the northern direction and, also, by the recording of a higher average multi-annual frequency of the wind from this direction (13,7%) as compared to the south-eastern direction (10,9%).

At Mangalia station, for the period taken into account, it must be noticed that the the maximum value of the wind potential was recorded for the northern wind direction. At z = 10 m the wind potential value is 530 W/m^2, and at z = 220 m the wind potential value reaches 2260 W/m^2. For the north-eastern sector wind the value of the wind potential ranges between 320 W/m^2 and 1410 W/m^2, for the heights z = 10 m and z = 220 m, respectively.

In order to achieve an as good and complete as possible assessment of the wind potential distribution on the Romanian seashore of the Black Sea there was also taken into account the offshore Gloria station, located at 48 km south-east of Portiţa. Using the same calculation method of the wind potential ε, fore various directions and heights z, there were plotted certain curves presenting the wind potential for this station.

The obtained wind potential graphs are highlighting the fact that for the station Gloria as well as for the other aforementioned stations, the maximum value of the wind potential corresponds to the northern sector wind. Thus, for a wind from the north-eastern direction, the wind potential value is 532 W/m^2 at z = 10 m and reaches the 1620 W/m^2 value at z = 220 m. These values are equal to the wind potential obtained for a northern sector wind.

3. EXPERIMENTAL TESTS

The experimental research is part of the energy recovering action of the existing wind potential of our country. In this framework, a separate objective is constituted by location studies. In general, such studies are attempting to find optimal areas from the point of view of the available wind energy. Once such areas are established an issue of utmost importance is to locate the wind turbines in this location in order to provide them adequate conditions of operation in view of obtaining the designed operation parameters. Thus, wind tunnel experiments were made for two types of models corresponding to the following possibilities of placement of the cased wind turbines:

- placement of the cased wind turbines in a single row barrage;
- placement of the cased wind turbines in a two rows barrage.

3.1 Similitude conditions

The turbine models were made according to a S_l = 1/250 length scale, imposed by the conditions aimed to avoid the effects of limited vein. Regarding the achievement of the Reynolds similitude criteria, the condition *Re* = idem leads in case of the wind tunnel tests to a $S_U = 1/S_l = 250$ velocity scale, a condition impossible to be achieved. In the present research the adopted solution is one used frequently for the hydraulic machines domain, namely avoiding *Re* = idem condition and the acceptance of a hydraulic scale distortion. The accuracy assessment of the results is achieved in this case starting from the loading coefficient of the rotor C_T, which is a coefficient of hydraulic resistance of the wind turbine rotor, for which in fact the problem of the Euler similitude must be considered. By definition, this is given by the following relationship:

$$C_T = 2(p_2 - p_3) / \rho U_2^2 \tag{13}$$

where p_2 and p_3 are the hydrodynamic pressures of the rotor (fig. 3 c) upstream and respectively downstream, ρ is the air density, and U_2 is the velocity in the inlet section of the rotor.

For the studied problem the propeller disc resistance was modeled using a wire net, a common solution for this type of tests. This modeling is possible since the definition of the local resistance coefficient of the wire net ζ is identical to the definition of the resistance coefficient C_T , also named as loading coefficient. The net used at the models is characterized by a coefficient of the free section of f = 0.75 and wire thickness of δ = 0.2 mm. The Reynolds number, calculated at the velocity of entrance to the grid U_2 and thickness δ of the grid, has the value *Re* = 463. According to Idelcik for Re>400 the phenomenon comes into the field of self-modeling, which justifies the adopted solution with hydraulic distortion.

3.2 Wind tunnel, experimental models, measurement equipment

The experimental tests were achieved by model measurement located in the wind tunnel with boundary layer, owned by the Aerodynamics and Wind Engineering Laboratory.

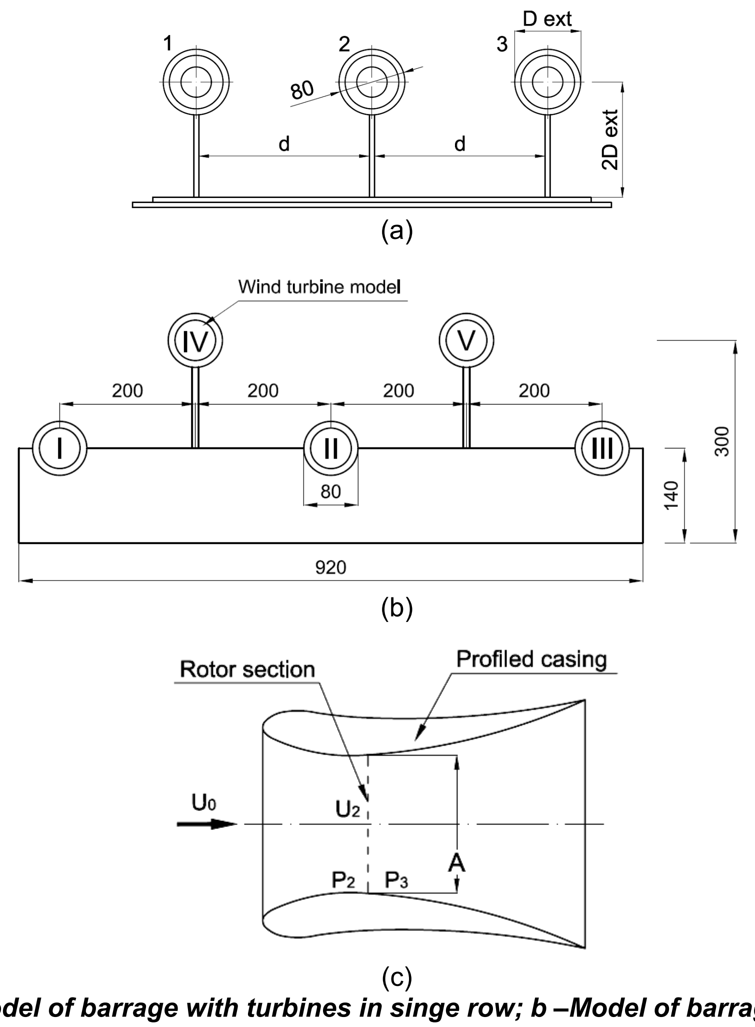
The wind tunnel with boundary layer is an open circuit one, (fig. 2) characterized by a 27 m length and a 1.7 m x 1.75 m cross-section.

Fig. 2. Wind tunnel owned by the Wind Engineering Laboratory of the Technical University of Civil Engineering Bucharest

The air current is generated by an axial fan driven by an electric motor with variable rotation. The length of the tunnel is imposed by the natural development of a boundary layer in the experimental area similar to the atmospheric one corresponding to the Romanian seashore area.

The velocity profile simulated in the vein of the wind tunnel is power law type with an exponent α = 0.14 specific to the seashore area. The turbulent intensity is $I \approx 0.015$, corresponding to the natural wind in that area.

The main element of both tested models (fig. 3 a, b), with turbines mounted in one row (experiment A) and with turbines mounted in two rows (experiment B), consists in the reduced scale model (1:250) of the cased wind turbine (fig. 3, c). This is made up of a profiled casing, a wire net to simulate rotor resistance, two hydro-dynamic pressure intakes located upstream and downstream of the wire net simulating the rotor, as well as an assembly of five Pitôt tubes of very small size located in five characteristic points of section 2 (ahead the rotor), which help to determine the velocity distribution in section 2 and the average value thereof, U_2.



a. – Model of barrage with turbines in singe row; b –Model of barrage with turbines in two rows; c – Model of cased turbine

Fig. 3. Wind turbine models

The velocity and turbulence measurements in the experimental vein of wind tunnel were made by a TSI hot wire thermo-anemometer.

The pressure and velocity measurements for the active wind distribution on the turbine model were made using a SIMULTEC-type, 48-gate scanning valve.

3.3 Experimental results

In the following the experimental tests for each of the two studied models will be presented. The experiments were achieved for velocities in the fluid vein U_0, in a 19 to 24 m/s range. The incidence angles Θ at which the tests were carried out were 0^0, 15^0 and 30^0. These angels are obtained by rotating the models placed in the experimental area of the tunnel.

Obtained results for the single row turbine barrage model

A first stage of the measurements was the determination of the coefficients Φ and C_T at various angles Θ of the turbine models. To ensure independence between them, the turbine models were mounted in the barrage on an individual supports (experiment with the general code A). The dimensionless coefficient Φ is defined as the ratio between the average velocity in section 2 and the velocity upstream of the model U_0 ($\Phi = U_2/U_0$) and is named velocity ratio.

In the experimental area of the wind tunnel three wind turbine models were mounted on a rail. The relative distance to the model located in the longitudinal axis, noted as *d*, was measured between the turbine axes (fig. 3 a). In order to study the importance of interaction between the turbines the following ratios were considered $k = d/D_{ext}$: 5; 2.25; 1.5; were D_{ext} represents the outer diameter of the turbine model (D_{ext} = 80 mm).

The particular code of a measurement is obtained starting from the general code A written as iA$k\Phi$, were i is the position of the active model (i = 1,2,3,), A is the general code of the experiment, $k = d/D_{ext}$ (k=5; 2.25; 1.5), and $\Phi = 0^0; 15^0; 30^0$.

The wind power captured by a turbine is given by the following relationship:

$$P_E = \frac{1}{2} C_T A_2 \rho U_2^3 \tag{14}$$

which can also be expressed as:

$$P_E = \frac{1}{2} \rho A_2 \Phi^3 C_T U_0^3 = m\Phi^3 C_T U_0^3 \tag{15}$$

were m = constant, and U_0 is the velocity upstream of the turbine, along its axis. Consequently it can be considered that $\Phi^3 C_T$ is an important dimensionless value, directly proportional to the captured wind power P_E.

Figure 4 shows the variation of the velocity ratios Φ with the angle θ, for the three relative dimensionless distances k. Variations of coefficient C_T under the same conditions are shown in figure 5.

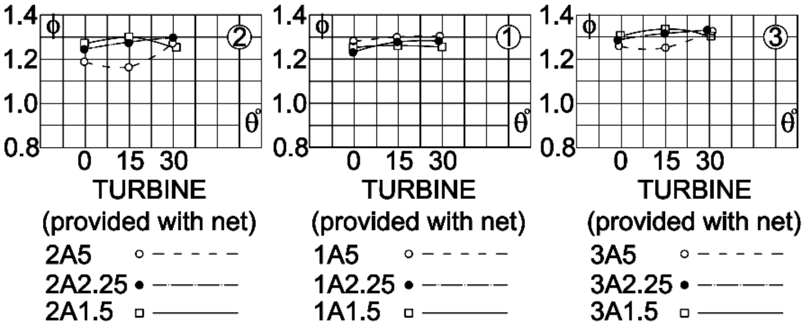


Fig. 4. Experiment A. Variation of the velocity ratio Φ according to the position of the turbine in the barrage and the angle θ.

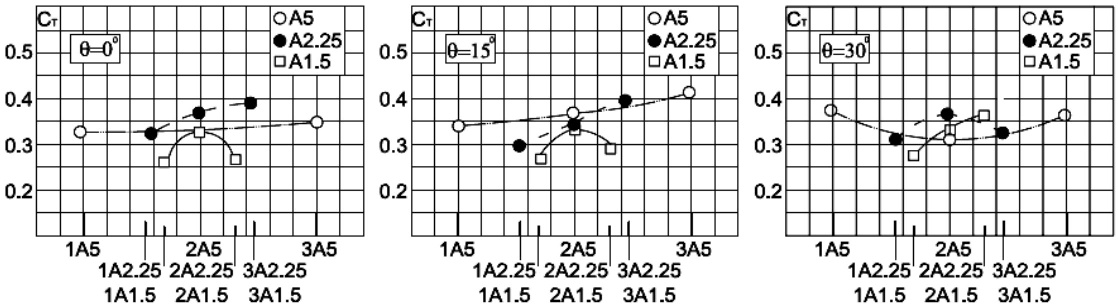


Fig. 5. Experiment A. Variation of the loading coefficient of the rotor C_T according to k, θ, and the position of the turbine in the barrage.

Obtained results for the two rows turbine barrage model

The experiments pursued the establishment of the dimensionless values Φ, C_T and $\Phi^3 C_T$ for a barrage with turbines mounted on two rows (experiments code B). The barrage is made up of five wind turbines models, all active, numbered from I to VI. The turbines I, II and III were mounted in the upper zone and the turbines IV and V were mounted in between, on individual support. The dimensional quotas of the barrage and the distances between turbines are shown in the scheme presented in figure 3 b. The tests were carried out at a velocity U_0 = 20 m/s and for incidence angles $\theta = 0^0$, 15^0 and 30^0. Figure 6 shows the graphs representing the variation of the dimensionless values Φ, C_T and $\Phi^3 C_T$ according to the position of the turbines in the barrage, at an incidence angle $\theta = 0^0$.

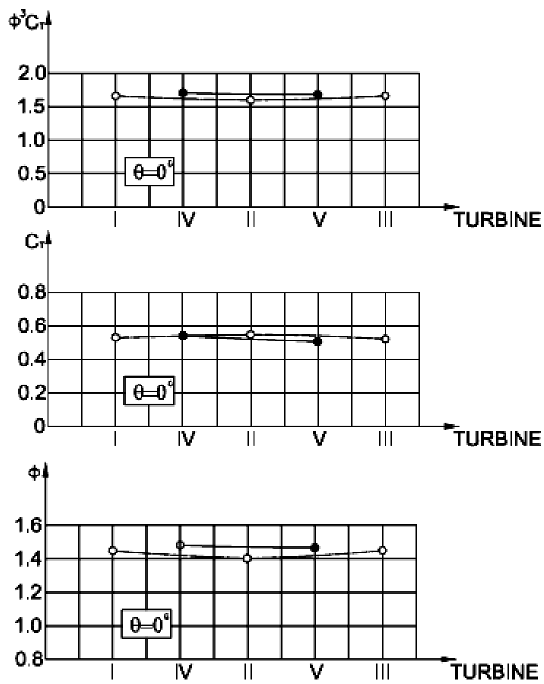


Fig. 6. Experiment B. Variation of Φ, C_T and $\Phi^3 C_T$ for cased turbines mounted in two rows barrage, for $\theta = 0^0$.

4. CONCLUSIONS

The comparative analysis of the results allows certain conclusions related to the placement of the cased wind turbines into the barrages.

Thus, from the analysis of the experimental results (experiment A) derives the fact that the effect of the relative distance *d* over the velocity ratio Φ, is minimum. Regarding the loading coefficient C_T, a effect of influence between the turbines is observed which manifests differently for the three studied relative lateral distances. At d = 1.5 D_{ext}, for the central turbine 2 yields a C_T coefficient with a higher value then for the lateral ones (for which the values are approximately equal at $\theta = 0^0$ and $\theta = 15^0$). For $\theta = 30^0$ in case of turbine 2 a intermediate value between the obtained values for the lateral turbines was obtained. For $d = 2.25D_{ext}$, at $\theta = 0^0$ and $\theta = 15^0$ a similar situation to the one described for $d = 1.5D_{ext}$ at $\theta = 30^0$, and at $\theta = 30^0$ is observed. Same remakes as for $d = 1.5D_{ext}$ with $\theta = 0^0$ and $\theta = 15^0$ can be considered. For $d = 5D_{ext}$, the effect of influence is much reduced, i.e., at $\theta = 0^0$ the coefficient C_T is practically constant, and at $\theta = 15^0$ and $\theta = 30^0$ the variations are quite pronounced.

The measurements for experiment I, with all wind turbine models operating simultaneously, showed that at the incidence angle $\theta = 0^0$ the values of the dimensionless complex $\Phi^3 C_T$, for the five turbines mounted in the barrage, are very close. Their average value is 1.65. Comparing to the average value, the differences for each of the turbines doesn't exceed 2%. For $\theta = 15^0$ the average value of the complex $\Phi^3 C_T$ is 1.55, and for $\theta = 30^0$ it is 1.40.

The obtained values for all dimensionless coefficients (Φ, C_T and $\Phi^3 C_T$) in case of the barrage model with the turbines placed in two rows are higher than the average values obtained for the model of the barrage with turbines in a single row disposal.

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