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INFLUENCE OF AMBIENT CONDITIONS ON WIND SPEED MEASUREMENT: IMPACT ON THE ANNUAL ENERGY PRODUCTION ASSESSMENT

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ABSTRACT

The Annual Energy Production (AEP) estimations are crucial to analyze the potential of wind energy projects. To calculate the AEP of a wind farm, it is necessary to accurately measure the wind speed, because small errors in these measures lead to significant deviations in the wind turbine power curve. In-field wind speed is usually measured by means of cup anemometers, which are calibrated within wind tunnels. In-field ambient conditions differ from those at the laboratory, which increases the uncertainty of the wind speed measures performed at the location of the turbine. The present work is focused on analyzing the effect of the following ambient parameters on the cup anemometer behavior: temperature, humidity and atmospheric pressure. In order to reach this target, experimental tests in a wind tunnel were performed, which allows minimizing the effect of the rest of influence parameters: turbulence, average flow inclination angle and flow direction. With this work it is determined how flow air viscous forces affect the cup anemometers, changing its rotation frequency. This explanation concludes that a variation on air temperature, humidity and/or pressure modifies moist air kinematic viscosity, which leads to change the friction between air and cups and, consequently, the cup anemometers rotational frequency. In most cases, the kinematic viscosity is inversely proportional to the air density and therefore, higher in-field densities, compared to those at the laboratory where the anemometer was calibrated, lead to underestimate the wind speed, and vice versa. The fact that this effect has been quantified during the calibration process is quite important, since it allows removing the influence of the environmental parameters studied; so that by modifying the calibration methodology, the accuracy of cup anemometers would be optimized. In order to clarify how the moist air kinematic viscosity influences the calibration curve, the calibration measurements of a real cup anemometer are mapped into a new dimensionless abacus, with the Tip Speed Ratio (TSR) and the Reynold's number as coordinates. The key idea is that the rotation frequency of the cup anemometer is related to both wind speed and moist air kinematic viscosity. This relation is mathematically described by the equation of a hyperbolic paraboloid surface up to a value of wind speed of 15.3 m/s.

1. Introduction

Cup anemometers, developed by Robinson in 1847, are reliable and robust devices that measure the wind speed. These devices help to assess the power performance of wind turbines and the Annual Energy Production (hereafter AEP), by means of the determination of wind kinetic energy through the rotor swept area, and because of that, the increment of installed wind power has fostered the use of these measuring equipment.

The cup anemometer physical base consists of relating the anemometer rotation frequency f_r, with the wind speed V; to establish such relationship, each cup anemometer is calibrated in a wind tunnel, which provides the regression parameters A and B that determine the mathematical function (Eq. (1)) corresponding to a specific cup anemometer. By means of those regression parameters, the wind speed measured with that anemometer can be determined until it will be calibrated again. Note that A is the slope of the calibration curve, and B is the regression intercept. Hereafter A is the "slope coefficient", and B is the "intercept coefficient".

$$V = A \cdot f_r + B. \qquad (1)$$

The motivation of the present paper arose from the observation of a low repeatability (idem for reproducibility) in the calibration results of the same cup anemometer when the same wind tunnel is used in consecutive days. The dispersion of the calibration results can only be attributed to the air density variations between different tests because other parameters influencing cup anemometers are highly controlled inside the wind tunnel, since these facilities are specially shaped to decrease turbulence, average flow inclination angle and direction.

Nomenclature

A	Slope of the linear regression [m]
a	Factor depending on the shape of the structure within the wind tunnel
AEP	Annual Energy Production
B	Intercept or offset for linear regression [m/s]
b	Blockage ratio
c	Coefficient of cup-anemometer air density sensibility
c_{f}	Force coefficient of the structure within the wind tunnel
C_h	Pitot tube head coefficient
C_{P}	Power coefficient
d	Slope coefficient of surface regression
D	Cup anemometer rotor diameter
e	Coefficient of cup-anemometer air kinematic viscosity sensibility
f	enhancement factor, Eq. (6)
f_r	Anemometer rotation frequency [rad/s]
$F(V_i)$	Wind speed Weibull cumulative distribution
IEC	International Electrotechnical Commission
k_{c}	Wind tunnel calibration factor
k_{f}	Blockage correction factor
l	Number of measurements of Δp_i for each operating condition
m	Number of measurements of f_{rj} for each operating condition
M_a	Molar mass of dry air [kg/mol]
M_v	Molar mass of water [kg/mol]
P_i	Electrical power in the bin *i* [W]
P_{B}	Barometric pressure [Pa]
P_v	Partial vapor pressure [Pa]
P_{vs}	Saturated vapor pressure [Pa]
R	Ideal gas constant [J/(mol·K)]
r	Correlation coefficient
Re	Reynolds number
R^2	Coefficient of determination
t	Air-dry bulb temperature [ºC]
T	Absolute temperature [K]
TSR	Tip Speed Ratio
T_v	Absolute wet bulb temperature [K]
u	Standard uncertainty
V	Wind speed [m/s]
V_b	Mean flow field velocity inside wind tunnel, with blockage effect [m/s]
V_i	Wind speed in the bin *i*
x_v	Mole fraction of water vapor
Z	Compressibility factor, Eq. (7)
	Greek symbols
Δp	Mean wind dynamic pressure. Fluid kinetic energy per volume unit [Pa]
μ	moist air dynamic viscosity
ν	Air kinematic viscosity
ρ	Moist air density [kg/m^3]
ρ_{c}	Air density at the calibration laboratory
$\emptyset$	Relative humidity
φ	Psychometric constant pertinent to the standard wet-bulb temperature
φ_0	Psychometric constant pertinent to the standard wet-bulb temperature of 0 °C

A review of the available literature on cup anemometers reveals that other authors have discussed this lack of repeatability. Pindado et al. [1] studied a large cup anemometers calibration database, trying to quantify mathematically the air density effect over the calibration parameters A and B. Although their results do not let to correct the deviations caused by air density, they proved that 0.1 kg/m^3 density variations cause great deviations in AEP predictions. On the other hand, Kristensen [2] found discrepancies between consecutive calibrations of the same anemometer in different laboratories, which points out a lack of reproducibility in the anemometer calibration process. Similar works observed dispersion on wind speed measures, but none of them clarifies this fact, and while traditionally this is attributed, without a closed theory, to wind turbulence, more recently works point out to air density and viscosity [3].

Researchers such as Diaz, Carta and Matias [4,5] have recently described the notable influence of air density variability on turbine power. Based on tests with different machine learning models, they concluded that the most accurate approach considers wind speed and air density as input separate variables. Ulazia et al. [6] have studied temperature, pressure and wind speed data from the pioneering floating wind farm Hywind-Scotland, and have demonstrated that seasonal air density variations imply errors in the capacity factor and energy production assessments. In the study conducted by Martin et al. [7] points out that small differences in AEP values lead to large deviations in the associated investment risks, so that they recommend to compute different power curves for different ambient conditions. Note that considering the European market, at the present cost (0.04 €/kWh), a relative uncertainty of 1% in wind speed measurements represents more than 400 M€ [8].

The AEP estimations are essential for the management of any wind farm. Furthermore, there are plenty of papers where AEP assessments are basic, for example, to validate an equivalent model for wind farms, as in the case of Jin et al. [9]; or to determine what rated power must have the wind turbines in order to maximize the AEP, as Sedaghat [10] proposes.

With regard to regulations review, the international standard IEC 61400-12-1, about "Power performance measurements of electricity producing wind turbines" [11], stands out. Its annex F establishes the "Cup anemometer calibration procedure" and presents the linear regression equation (Eq. (1)). Even more, this standard also details the reporting format, which must include: the regression parameters, the uncertainty and the environmental conditions during calibration (air temperature, atmospheric air pressure and humidity). Note that air density is likewise a function of temperature, humidity and especially atmospheric pressure, so consequently, the calibration procedure does not happen at a prescribed air density.

The annex I of the aforementioned standard [11] deals with the "Classification of cup and sonic anemometry" and shows how, during the fieldwork, cup anemometers are affected by turbulence, average flow inclination angle and ambient conditions, which differ significantly from the conditions during the calibration procedure. The aims of this annex are to establish five classes of cup anemometers according to a range of values for each influence parameters and to assess an uncertainty coverage factor for each range. The coverage factor must be determined for every particular anemometer model by testing a sample of five units of that model. Once the covering factor is determined, the expanded uncertainty of the cup anemometer is the product of this factor and the uncertainty certified by means of the calibration procedure. The influence parameters included in the standard for cup anemometers are: turbulence intensity, turbulence structure, air temperature, air density and average flow inclination angle.

In summary, the international standard [11] establishes the ambient conditions that influence the wind speed measurements performed with cup anemometers and assumes that ambient conditions at field differ from those in the calibration wind tunnel. In order solve this problem, the standard just proposes to expand the calibration uncertainty and does not offer any correction to reduce the errors on wind speed measurements due to ambient conditions.

It is important to clarify that, in chapter 9.1 "Data Normalisation" of the discussed standard [11], several normalisations before the AEP assessment are proposed, for example, a normalisation of the output power due to air density oscillations at the wind turbine location. This normalisation does not correct wind speed measurements to takes into account the different in-field air density respect to that of the calibration process.

It is beyond question that the power curve of a wind turbine and the AEP are determined by means of the wind speed. Not considering any corrections to compensate for the ambient conditions variation between the calibration laboratory and the location of the wind turbine, leads to a very expanded uncertainty of wind speed measures and consequently, to high errors in energy production prediction.

The present work contributes to explain and quantify the effect of air temperature, humidity and atmospheric pressure on wind speed measures obtained via cup anemometers. This effect of ambient conditions, which was observed during the calibration process, seems to be greater than what users believe. In such a way, once these influence parameters are quantified, it would be possible to remove the uncertainty-covering factor due to the effect of air density and temperature on wind speed measures of cup anemometers.

The current paper fills the gap of explaining the physical mechanism that relates the main ambient conditions during the calibration process to wind speed measurements and quantifies this relation. The conducted experiments demonstrate that the friction between air and cups decreases the value of wind speed provided by cup anemometers for those locations where the density is higher than that at the calibration laboratory, and vice versa. In fact, the influential parameter is the kinematic viscosity. This affirmation is demonstrated through the calibration of a small cup anemometer based on dimensionless variables.

The experimental results obtained in the present work clearly show that, considering a set of constant wind speeds within the wind tunnel, Reynolds number is linearly related to the inverse of Tip Speed Ratio (speed coefficient). Taking into account the aforementioned dimensionless relationship, the mathematical function which relates wind speed, anemometer rotation frequency and air kinematic viscosity describes a hyperbolic paraboloid surface. In order to assess the proposed approach, the uncertainty of the new calibration parameters has been estimated. The resulting uncertainty is lower than that obtained by the conventional calibration curve (Eq. (1)).

Finally, the present paper demonstrates that it is possible to reduce the uncertainty of the wind speed measured with cup anemometers by means of two methods. Firstly, by including the new equation in the calibration process of cup anemometers, and secondly, by making corrections to the measurements provided by the cup anemometers that were calibrated without taking into account this new equation. A reduction of this uncertainty would significantly improve the estimations of power and AEP of wind turbines.

The manuscript is organized as follows: the experimental equipment and the measurement strategy are explained in Section 2. Figures in Section 3 show calibration measures, a dimensionless mapping and a comparison between the proposed model and the conventional calibration curve (Eq. (1)). The main conclusions are drawn in Section 4.

2. Materials and Methods

2.1.- Experimental set-up

The device used to obtain experimental data is a cup anemometer extracted from a meteorological station Auriol model IAN 114435 (see Fig. 1). The rotor of the anemometer consists of three semi-spherical cups of 26 mm diameter each one. The distance between the rotor axis and the centre of each cup is 52 mm, and the rotor diameter is $D = 130$ mm. The vane of the cup anemometer has not been removed, due to it does not disturb the experimental results and it will be useful in future in-field tests.

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Fig. 1. Testing device: cup anemometer from an Auriol IAN 114435 meteorological station.

The cup anemometer was tested in the closed jet-type wind tunnel showed in Fig. 2. A uniform flow is produced within this wind tunnel by means of a 5 kW rotating fan. The fan is equipped with a variable frequency drive engine, which allows providing a flow velocity between 1 m/s and 30 m/s. The turbulence levels of the wind tunnel are lower than 2% and the ratio of flow uniformity is within 0.2 % for *x*, *y* and *z* axis. The useful transversal area for testing is 40 cm × 40 cm.

Fig. 2. Wind tunnel for testing the cup anemometer.

In the present study, a Pitot tube is considered as the standard reference device for measuring flow velocity. This measurement instrument is a stainless-steel Pitot tube Testo (reference 06352045), 500 mm length and Pitot tube factor = 1. A Testo 512 2hPa differential micro-manometer is connected to the Pitot tube. This micro-manometer has a 0.1 Pa of resolution, an accuracy of ±0.01 hPa in a measuring range from 2 to 17.5 m/s and is capable to provide two lectures per second. The rotation frequency of the anemometer is determined via a digital Photo Tachometer model RM-1501, with a sample rate of one second and an accuracy of ±0.2 rpm.

Three thermometers allow obtaining the air conditions: two Tecpel 305 thermometers placed inside and outside the wind tunnel provide the dry bulb temperature in both places, and one alcohol thermometer placed inside the tunnel provides the wet bulb temperature. The ambient barometric pressure is determined via the barometer placed at the top of building where the wind tunnel is located. These data are published on the MATRAS webpage [12]. In order to determine the ambient barometric pressure in the testing laboratory, the data obtained from MATRAS have been corrected according to the standard atmosphere formulation specified in ISO 2533:1975, which shows how to determine the variation in the ambient barometric pressure due to a variation in height.

2.2.- Measurement strategy

The testing wind speeds range from 1.6 m/s to 17 m/s at intervals of approximately 1.7 m/s, which means 10 values of velocity tested. This experimental sequence is repeated fourteen times under different environmental conditions; seven of these sequences are tested by increasing wind speed (tests 1s to 7s in Fig. 4) and the rest of them by decreasing wind speed (tests 1b to 7b in Fig. 4), which results in 140 lectures of the following testing variables: dry bulb temperature, wet bulb temperature, barometric pressure, mean wind dynamic pressure and mean cup anemometer rotation frequency.

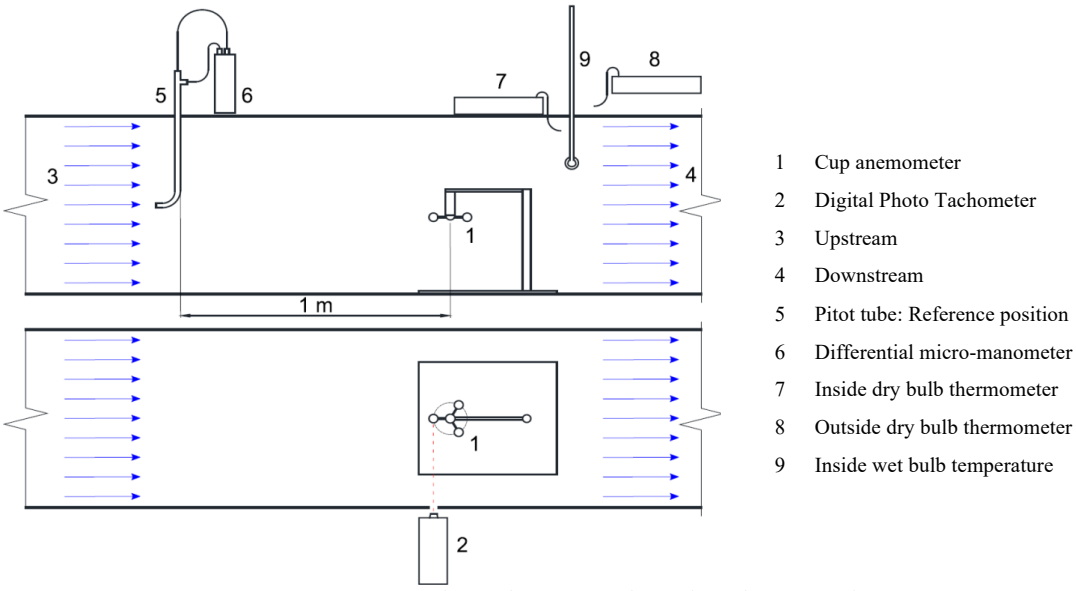

Fig. 3. Experimental setup. Up: front view, down: top view.

During the tests, the dry bulb temperature inside the tunnel varied between 22.3 ºC and 26.6 ºC; the tunnel wet bulb temperature between 16 ºC and 22 ºC; and the laboratory barometric pressure between 1012.81 hPa and 1023.84 hPa. These changes in the variables correspond to the natural environmental changes recorded during five days of testing. Once the barometric pressure, dry and wet bulb temperature are measured for each operating condition, the relative humidity $\emptyset$ can be determined by means of the Ferrel equation [13]:

$$\emptyset = \frac{P_{vs}(T_v) - \varphi \cdot P_B \cdot (T - T_v)}{P_{vs}(T)} = \frac{P_{vs}(T_v) - \varphi_0 \cdot (1 + 0.00115 \cdot (T_v - 273.15)) \cdot P_B \cdot (T - T_v)}{P_{vs}(T)}, \quad (2)$$

where T_v is the absolute wet bulb temperature (K), φ is the so-called psychometric constant pertinent to the standard wet-bulb temperature, φ_0 is the so-called psychometric constant pertinent to the standard wet-bulb temperature of 0 °C, which was experimentally adjusted by Ferrel. Table 1 provides the values of the coefficients in Eqs. (2)-(4), (6)-(7), P_B is the barometric pressure, and T is the absolute temperature (K). Eq. (3) is used to obtain the saturated vapor pressure, P_{vs}:

$$P_{vs}(T) = 1Pa \cdot e^{\left(\hat{A} \cdot T^2 + \hat{B} \cdot T + \hat{C} + \hat{D}/T\right)}. \quad (3)$$

Once the relative humidity is known, the moist air density for each operating condition can be obtained via the CIPM-2007 revised formula [14], which is valid for the temperature and barometric pressure ranges of this work:

$$\rho = \frac{P_B \cdot M_a}{Z \cdot R \cdot T} \cdot \left[1 - x_v \left(1 - \frac{M_v}{M_a}\right)\right], \quad (4)$$

R is the ideal gas constant, M_a is the molar mass of dry air and M_v is the molar mass of water. The following equations are used to determine: the mole fraction of water vapour x_v, the enhancement factor f and the compressibility factor Z:

$$x_v = \emptyset \cdot f(P_B, t) \cdot \frac{P_v(T)}{P_B}, \quad (5)$$

$$f = \alpha + \beta \cdot P_B + \gamma \cdot t^2, \quad (6)$$

$$Z = 1 - \frac{P_B}{T} \cdot [a_0 + a_1 \cdot t + a_2 \cdot t^2 + (b_0 + b_1 \cdot t) \cdot x_v + (c_0 + c_1 \cdot t) \cdot x_v^2] + \frac{P_B^2}{T^2} \cdot (d + e \cdot x_v^2), \quad (7)$$

where t is the air-dry bulb temperature expressed in ºC and P_v is the partial vapor pressure (Pa).

In Section 3, a dimensional analysis based on the Reynolds number is performed. Thus, the determination of the moist air dynamic viscosity μ is required. This property can be calculated via the theoretical formulation of Mason & Monchick [15],which was experimentally validated by Kestin & Whitelaw [16] by means of an oscillating disc viscometer, and it is recommended by "NASA Langley Research Centre" [17] for outdoor-indoor air applications considering atmospheric pressure, a temperature between 10 ºC and 50 ºC, and a relative humidity in the range from 0.3% to 92%:

$$\mu = \alpha_0 + \alpha_1 \cdot T + (\alpha_2 + \alpha_3 \cdot T) \cdot x_v + \alpha_4 \cdot T^2 + \alpha_5 \cdot x_v^2, \quad (8)$$

According to the obtained results, the relative humidity during the tests was always within the interval 37.4%-66.8%; the moist air density within the interval 1.1738 kg/m^3 - 1.1982 kg/m^3, which means an air density variation equal to 2.44 g/m^3; and the dynamic viscosity remained almost constant since the measures were within the interval from $1.82 \cdot 10^{-5}$ Pa·s to $1.84 \cdot 10^{-5}$ Pa·s.

The anemometer rotation frequency, for each tested wind speed, is recorded with a sampling frequency of 1 Hz during 50 s, so that steady-state conditions can be considered. The cup anemometer rotation frequency f_r is calculated as the mean value of the m measurements recorded:

$$f_r = \frac{1}{m} \sum_{j=1}^{m} f_{rj}. \quad (11)$$

Table 1.- Constant coefficients for the determination of environmental properties.

Constant terms			Value	Units	Notes
Ferrel Eq. (2)		α_0	$6.6 \cdot 10^{-4}$	$^{o}C^{-1}$	Adjusted by Ferrel
Vapour pressure Eq. (3)		$\hat{A}$	$1.2378847 \cdot 10^{-5}$	K^{-2}	Specified by P. Giacomo [18]
		$\hat{B}$	$-1.9121316 \cdot 10^{-2}$	K^{-1}	
		$\hat{C}$	33.93711047		
		$\hat{D}$	$-6.3431645 \cdot 10^{3}$	K	
Moist air density Eq. (4)	*Ideal gas constant*	R	8.314472	$J \cdot mol^{-1} \cdot K^{-1}$	Recommended by Codata 2006 [19]
	Molar mass of dry air	M_a	$28.96546 \cdot 10^{-3}$	$kg \cdot mol^{-1}$	It is assumed a background of 400 $\mu mol \cdot mol^{-1}$ for the mole fraction of carbon dioxide in air
	Molar mass of water	M_v	$18.01528 \cdot 10^{-3}$	$kg \cdot mol^{-1}$	
Enhancement factor Eq. (6)		α	1.00062		Specified by P. Giacomo [18]
		β	$3.14 \cdot 10^{-8}$	Pa^{-1}	
		γ	$5.6 \cdot 10^{-7}$	K^{-2}	
The compressibility factor Eq. (7)		a_0	$1.58123 \cdot 10^{-6}$	$K \cdot Pa^{-1}$	Specified by P. Giacomo [18]
		a_1	$-2.9331 \cdot 10^{-8}$	Pa^{-1}	
		a_2	$1.1043 \cdot 10^{-10}$	$K^{-1} \cdot Pa^{-1}$	
		b_0	$5.707 \cdot 10^{-6}$	$K \cdot Pa^{-1}$	
		b_1	$-2.051 \cdot 10^{-8}$	Pa^{-1}	
		c_0	$1.9898 \cdot 10^{-4}$	$K \cdot Pa^{-1}$	
		c_1	$-2.376 \cdot 10^{-6}$	Pa^{-1}	
		d	$1.83 \cdot 10^{-11}$	$K^2 \cdot Pa^{-2}$	
		e	$-0.765 \cdot 10^{-8}$	$K^2 \cdot Pa^{-2}$	
The dynamic viscosity Eq. (8)		α_0	$8.4986 \cdot 10^{-7}$	$Pa \cdot s$	Determined by Mason & Monchick. Recommended by NASA [17]
		α_1	$7 \cdot 10^{-8}$	$Pa \cdot s \cdot K^{-1}$	
		α_2	$1.13157 \cdot 10^{-6}$	$Pa \cdot s$	
		α_3	$-1 \cdot 10^{-8}$	$Pa \cdot s \cdot K^{-1}$	
		α_4	$-3.7501 \cdot 10^{-11}$	$Pa \cdot s \cdot K^{-2}$	
		α_5	$-1.00015 \cdot 10^{-6}$	$Pa \cdot s$	

In the middle of the rotation frequency sampling interval, the dynamic pressure is recorded by means of the Pitot tube, which provides the mean value of $l = 20$ measurements obtained during 10 s previous to trigger it. The mean wind dynamic pressure Δp at the anemometer position for each operating condition is corrected through several factors detailed below:

$$\Delta p = \frac{k_c}{C_h} \cdot k_f^2 \cdot \frac{1}{l} \sum_{k=1}^{l} \Delta p_i . \qquad (9)$$

The comparison between measurements from the Pitot tube placed at the reference position and at the anemometer position (Fig. 3) allows obtaining the wind tunnel calibration factor k_c and its uncertainty. The alignment accuracy of the Pitot tube with the wind flow direction is determined via the Pitot tube head coefficient C_h. In the present study, the value of this coefficient is determined according to the recommendations given by the ISO 3966, which deals with measurement of fluid flow velocity using Pitot static tubes [20]. Finally, the influence of the anemometer shape on the mean flow field velocity V_b is quantified by the blockage correction factor k_f calculated by applying the Maskell theorem [21]:

$$k_f = \frac{V_b}{V} = 1 + \frac{1}{2} a \cdot c_f \cdot b, \qquad (12)$$

where b, the blockage ratio, is the ratio of front area to the tunnel cross section; in our case $b = 0.025$. According to the recommendations of Barlow et al. [22], regarding unusual shapes tested in a wind tunnel, the product of the shape factor a and the force coefficient c_f is 0.5. The value of k_f is experimentally checked in our wind tunnel by comparing the measurements provided by the Pitot tube placed at the anemometer section with and without the cup anemometer inside the tunnel.

Finally, Eq. (10), which is obtained from Bernoulli's equation, provides the wind speed V at the anemometer location:

$$V = \sqrt{\frac{2 \cdot \Delta p}{\rho}}, \qquad (10)$$

The uncertainties of the different magnitudes are obtained following the Guide to the Expression of Uncertainty, commonly referred to as GUM [23]; besides that, the methodology employed by CENAM [24] is useful to determine the uncertainty of the moist air density and viscosity.

3. Results and discussion

3.1. Direct measurements and dimensionless abacus

Fig. 4 shows the f_r and V measures accomplished in the wind tunnel. It is remarkable the variations observed in f_r for a specific V, this means a low repeatability due to ambient conditions variability. Wind speed increases those variations from indistinguishable differences at low V=1.6 m/s to a 15 rad/s difference for V=17 m/s.

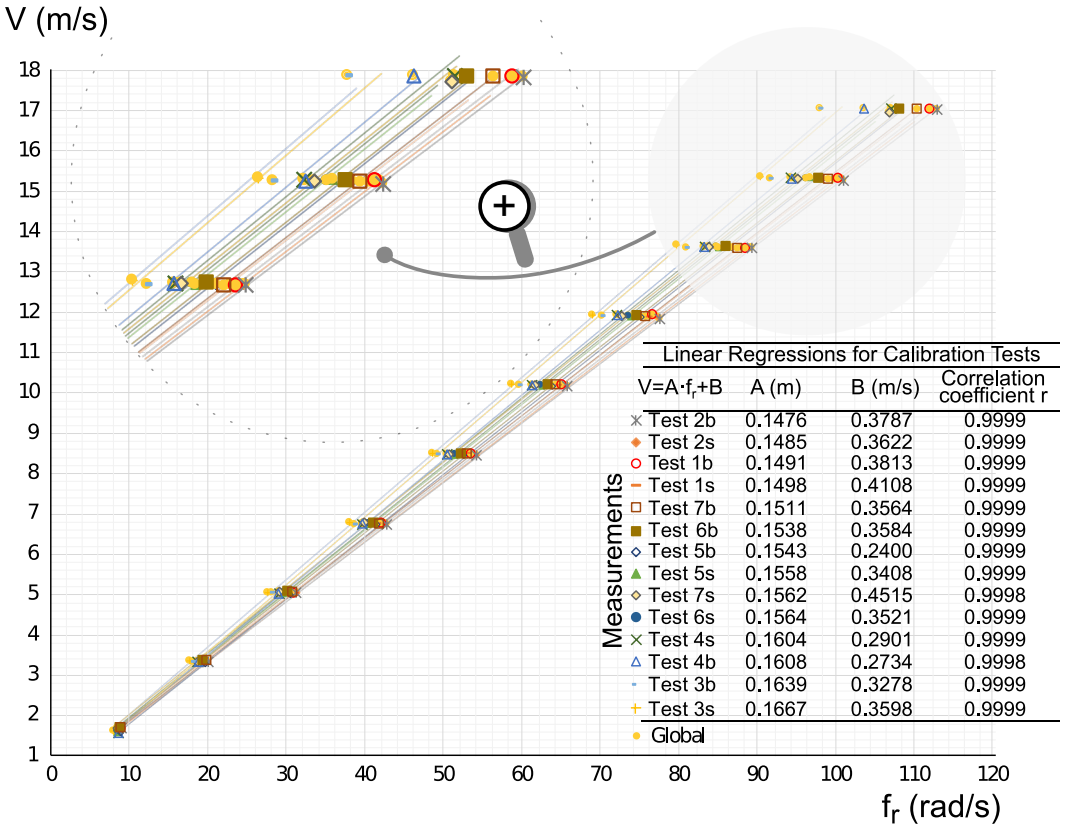

Fig. 4. Fourteen calibrations performed on the same cup anemometer at different ambient conditions.

In order to explain the discrepancies observed in the slope of the calibration lines in Fig. 4, the mean moist air density is calculated for each experimental test (Tests 1s-7s and Tests 1b-7b). The slope coefficients A are represented in Fig. 5 respect to their corresponding densities ρ. The large dispersion observed in each point (ρ, A), considering 95% confidence level, demonstrates that is difficult to fit ρ and A values by a linear regression, hereinafter referred to as "direct method".

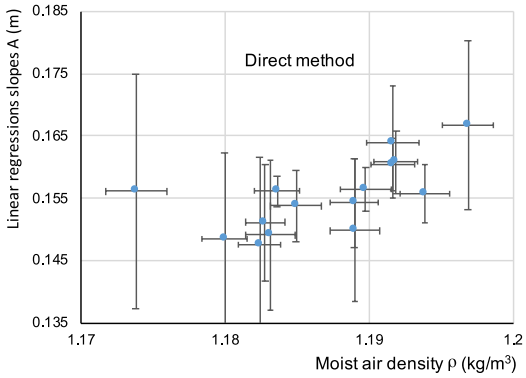

Fig. 5. Moist air density versus anemometer calibration slope: Direct Method. Bars represent a 95% confidence level.

In order to overcome the large uncertainties showed in Fig. 5, a dimensional analysis is conducted (Fig. 6). Applying the Buckingham Pi Theorem, the f_r - V domain is mapped into a new domain Π_1 - Π_2:

$$\Pi_1 = Re(f_r) = \frac{\rho \cdot f_r \cdot D^2}{\mu}, \qquad (11)$$

$$\Pi_2 = TSR^{-1} = \frac{V}{f_r \cdot D}, \qquad (12)$$

Reynolds number Re measures the ratio of inertia forces to viscous forces in a flow [25], and the Tip Speed Ratio TSR is the relation between the cup velocity and the free stream air speed.

The resulting "dimensionless abacus" is presented in Fig. 6. In this domain, the regression lines correspond to each tested wind speed, while the set of hyperbolic curves describes the measurements evolution respect to the inverse of the kinematic viscosity. Regression and correlation coefficients, as well as the correspondence of the hyperbolic lines with the moist air density (considering the dynamic viscosity quasi-constant during the experimental tests) are included in Fig. 6. Note that, the relative uncertainties of $Re(f_r)$ have low values. On the other hand, small density changes (in the order of hundredths of a kg/m^3) can modify the cup anemometer rotation frequency.

Considering a linear relation $V=A\cdot f_r+B$, such as in the direct method, and the dimensionless abacus, it is possible to determine A value as a function of the inverse of the kinematic viscosity ν^{-1} and f_r. Once the regression lines are determined, these lines and the Eqs. (11)-(12) provide the rotation frequency $f_{r,i}$ and ν_i^{-1} for specific Reynolds Re_i and wind speed V_i:

$$\frac{1}{TSR_i} = {Re_i}/{a_i} + b_i\,, \qquad (13)$$

$$f_{r,i} = \frac{TSR_i}{D}\cdot V_i\,, \quad (14)$$

$$\nu_i^{-1} = {\rho_i}/{\mu} = \frac{Re_i}{f_{r,i}\cdot D^2}\,. \qquad (15)$$

Finally, the slope coefficient A_i corresponding to $f_{r,i}$, and therefore to ν_i^{-1} is:

$$A_i = \frac{V_i - B}{f_{r,i}}\,. \qquad (16)$$

The following assumptions have been considered: firstly, if air density remains nearly constant during a calibration test, kinematic viscosity remains constant as well, and consequently, it is possible to determine a constant value for A; and secondly, the intercept coefficient B does not depend on kinematic viscosity (all calibration lines in Fig. 4 seem to have a similar intercept). The dynamic viscosity μ remains quasi-constant in the present research and in many practical applications, so it is easy to compute ρ_i from ν_i^{-1}.

The dimensional analysis provides the ρ-A values portrayed in Fig. 7 and the following linear model that estimates A for a specific ρ:

$$A = c\cdot\rho - d. \qquad (17)$$

The observed low dispersions, at 95% confidence interval, explain the high determination coefficient R^2=0.995 for the linear regression (Eq. (17)) provided by the hereafter called Dimensionless Abacus Method, compared to other studies [1], which use a Direct Method. Fig. 7 also shows the relative uncertainties of the calibration slope, moist air density and kinematic viscosity.

Eq. (17) shows how calibration lines change with the variation of air density at the laboratory, so that if air density increases, the slope of the calibration line increases as well, and vice versa.

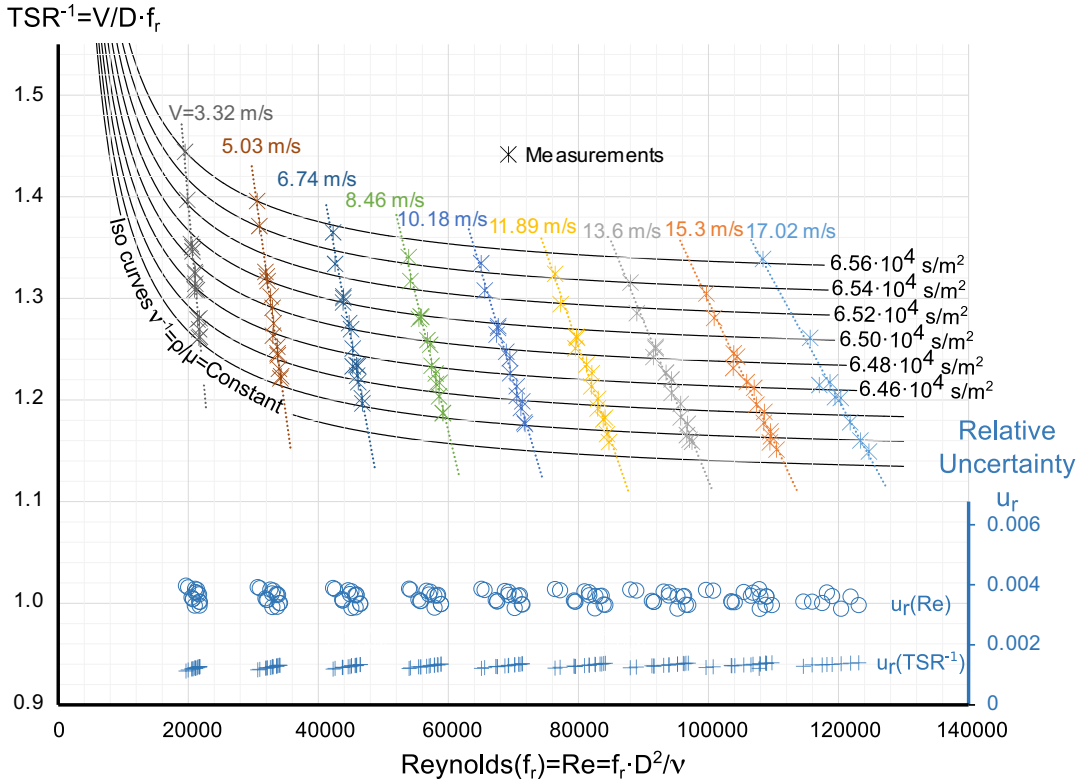

Fig. 6. Dimensionless abacus $Re(f_r)$ – TSR^{-1}. Experimental values for several wind speeds at different ambient conditions (different air flow viscous forces).

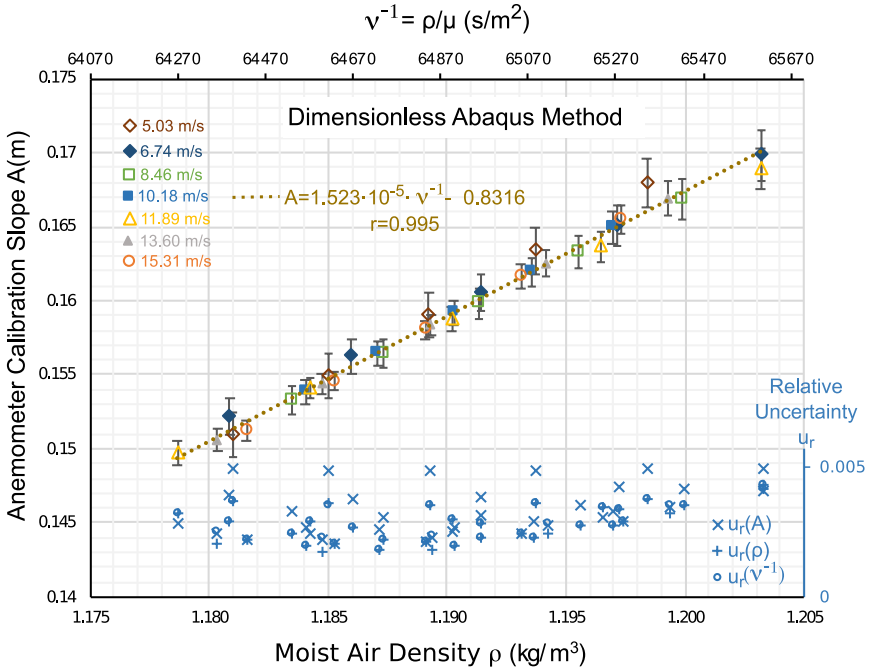

Fig. 7. Moist air density versus anemometer calibration line slope: Dimensionless abacus method. Bars represent a 95% confidence level.

Relative uncertainties are compared in Fig. 8.a. It is noteworthy the low and almost constant values provided by Dimensionless Abacus Method compared with Direct Method. Fig. 8.b classifies the relative uncertainties using the Dimensionless Abacus Method respect to wind speed. A reduction in relative uncertainty $u(A)/A$ is observed as the wind speed increases, this is a consequence of the manometer uncertainty, which growths as wind velocity decreases.

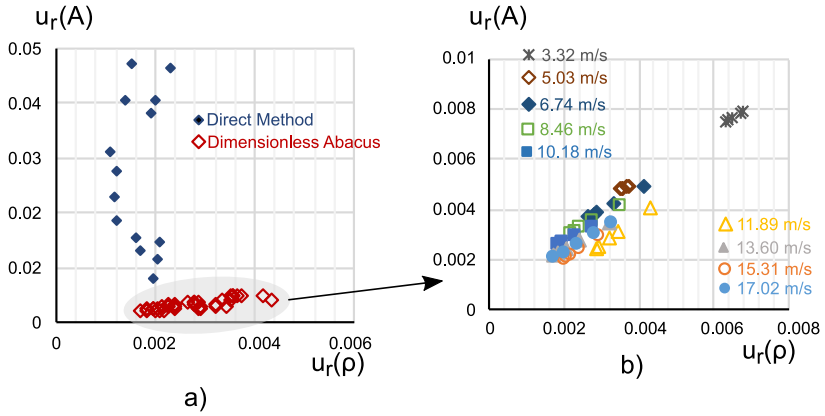

Fig. 8. Relative uncertainty of anemometer calibration line slope: a) Dimensionless Abacus Method versus Direct Method, b) Dimensionless Abacus Method values at tested wind speeds.

Note that, with the exception of V=3.32 m/s, the values represented in Fig. 7-8 lay within the wind speed range recommended by the annex F of the IEC international standard [11]. This range is stablished between 4 m/s and 16 m/s. According to the tests accomplished, the uncertainty is high for $V < 4$ m/s, and the linear Eq. (17) changes for $V > 16$ m/s.

3.2. The hyperbolic paraboloid surface.

The Eq. (17), obtained using the Dimensionless Abacus Method, helps to estimate A respect to ρ and therefore, the anemometer calibration Eq. (1) can be rewritten for $V \in [4\text{ m/s}, 15.3\text{ m/s}]$ as follows:

$$V = (c \cdot \rho - d) \cdot f_r + B\,, \qquad (18)$$

Eq. (18) is a hyperbolic-paraboloid surface: a doubly ruled surface, since it satisfies the conditions described for those quadratic surfaces [26]. According to Fig. 9, air density and rotation frequency isolines are the hyperbolic paraboloid surface rulings. In order to see the differences between the hyperbolic-paraboloid surface and the planar surface obtained by applying the IEC anemometry method [11], both surfaces have been extrapolated outside the measured density range (it is considered a mean density value during the calibration process equal to 1.1863 kg/m^3). When the anemometer is used in field application where the air density differs from that at the calibration laboratory, the measurement provided by the anemometer varies. The IEC method does not take into consideration this fact.

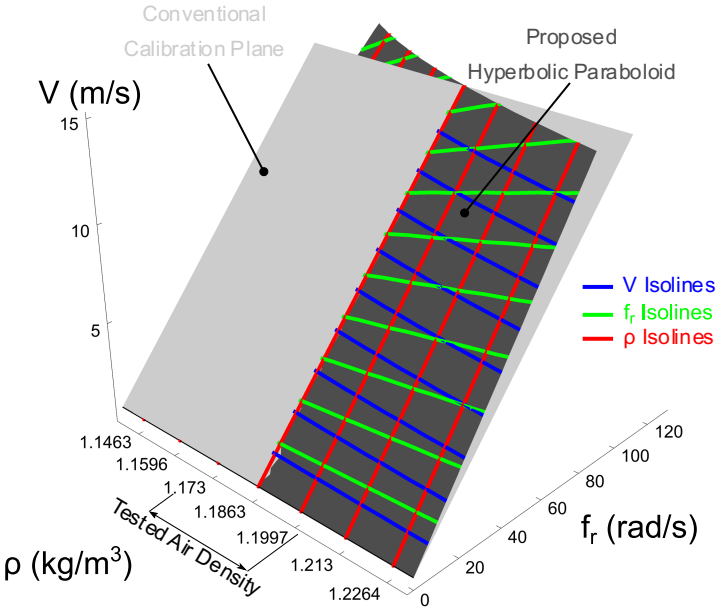

Fig. 9. Moist air density effect on an Auriol IAN cup anemometer. Calibration surfaces: Plane from the IEC anemometry method [11] and Hyperbolic Paraboloid from the Dimensionless Abacus Method.

Above V = 15 m/s the system does not behave as the ruled surface described by Eq. (18). A nonlinear response appears, which depends on the moist air density. It is noteworthy that, for air density measurements upper than 1.1863 kg/m^3, rotation frequency growths more slowly than if the air density is lower than 1.1863 kg/m^3.

Fig. 10 shows the ρ and f_r ruling lines as well as V isocurves (parabolas) in the $V(\rho, f_r)$ projected views. Note how the surface rulings evolve to curvilinear paths above 15 m/s (Fig. 10 a and b). Moreover, the curvature is concave for high moist air density values, and convex for low moist air density values. This effect of air density (or kinematic viscosity) could explains the underspeed or overspeed of cup anemometers observed in some field measurements, such as those highlighted by Kristensen [27,28], although this author relates this behaviour to the effect of air turbulence.

According to Fig. 10.b, the slope of the rotation frequency iso-curves, up to V=15 m/s, is a measure of how the wind speed changes ΔV due to air density variation $\Delta\rho$ during the IEC calibration process:

$$\frac{\Delta V}{\Delta \rho} = \mathrm{c} \cdot f_{\mathrm{r}}^{*}, \qquad (19)$$

Eq. (19) depends on the anemometer and provides the slope of the rotation frequency iso-curves respect to: the cup anemometer rotation frequency considering the air density at the calibration laboratory f_r^*, and the "cup-anemometer air density sensibility" parameter c (Eq. (17)). For example, an Auriol IAN anemometer has a c = 0.8315 m^4/kg, if f_r^* = 80 rad/s, then a density variation of $\Delta\rho$ = 0.013 kg/m^3 with respect to air density during the calibration process leads to ΔV = 0.86 m/s, which will grow proportionally with the increments of air density.

Finally, Fig. 11 portrays the wind tunnel experimental data, the hyperboloid paraboloid surface and the IEC calibration line. The proposed Dimensionless Abacus model has a maximum absolute error of 0.4 m/s while the IEC calibration line has a maximum absolute error of 0.9 m/s.

In order to consider the influence of air density on wind speed measurements, the IEC linear regression [11] can be corrected by means of Eq. (19). On the other hand, the hyperboloid paraboloid surface considers the ambient conditions, thus wind speed estimation does not need additional corrections. In this regard, and according to Fig. 12, if $\rho > \rho_c$, where ρ_c is the air density at the calibration laboratory and ρ is the air density in a specific location, then the wind speed model obtained from the Direct Method provides values below the actual measurements, while if $\rho < \rho_c$ the Direct Method regression curve is above the real measurements. The hyperbolic parabolic regression does not need correction in any case.

The abacus showed in Fig. 6 and Eqs. (13), (15) point out that air-cup friction produces the aforementioned deviations. Hence, instead of air density, the kinematic viscosity is the most important ambient parameter. It is adequate the use of the moist air kinematic viscosity for wide ranges of temperature and density, such as those considered in Annex I of the IEC standard [11]: from 0.9 to 1.35 kg / m^3 (classifications A, B, C and D). For these cases, it is not possible to establish an equivalence between the air density and the inverse of the kinematic viscosity. Therefore, according to Fig. 7, Eqs. (17)-(19) should be rewritten respect to the inverse of the moist air kinematic viscosity as follows:

$$A = e \cdot {}^{1}/_{\nu} - d, \qquad (20)$$

$$V = \left(e \cdot {}^{1}/_{\nu} - \mathrm{d}\right) \cdot f_{\mathrm{r}} + \mathrm{B}, \qquad (21)$$

$$\frac{\Delta V}{\Delta(1/\nu)} = e \cdot f_{\nu}^{*}, \qquad (22)$$

the parameter e is the "cup-anemometer air kinematic viscosity sensibility", and f_ν^* is the equivalent rotation frequency when in-field air kinematic viscosity is equal to that of the calibration laboratory.

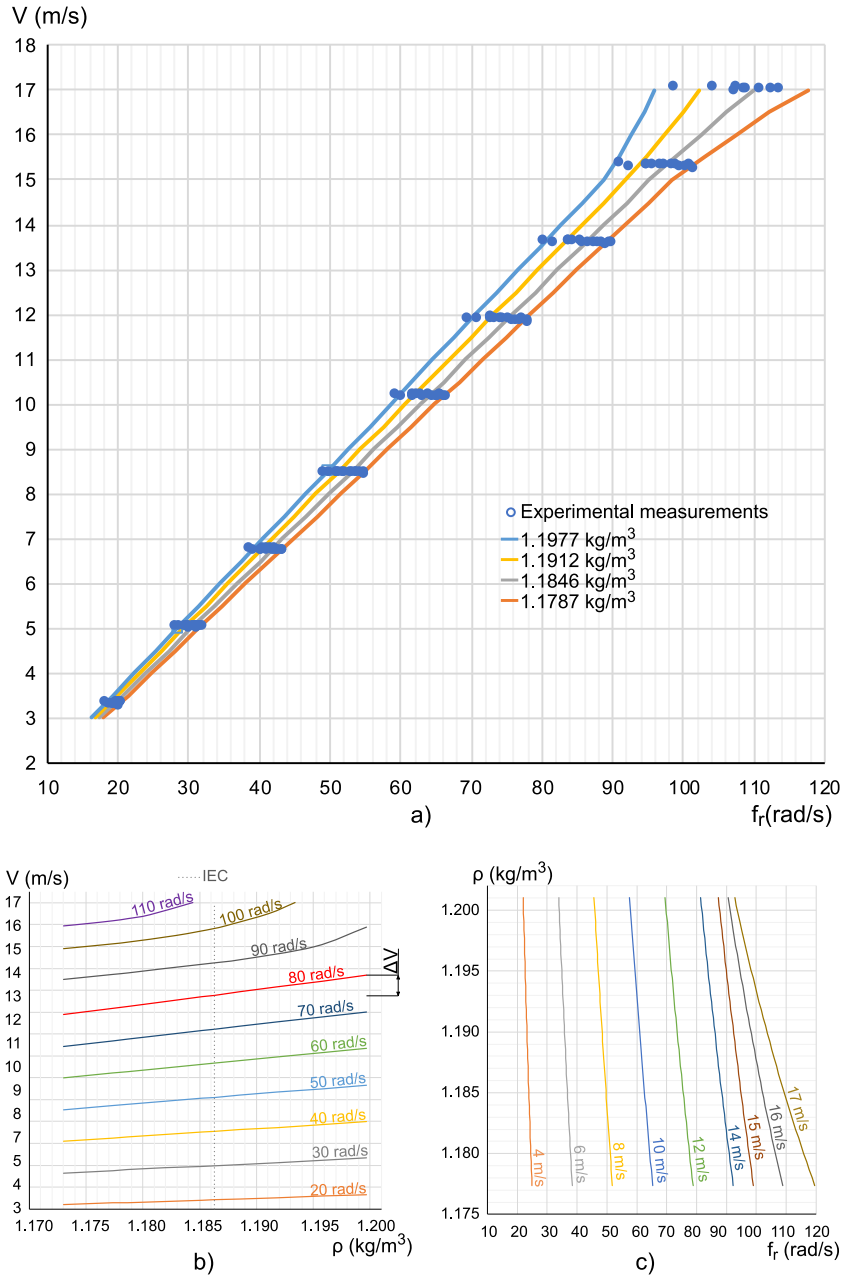

Fig. 10. Projected views of the Auriol IAN calibration surface. a) Front view, b) Top view, c) Side view.

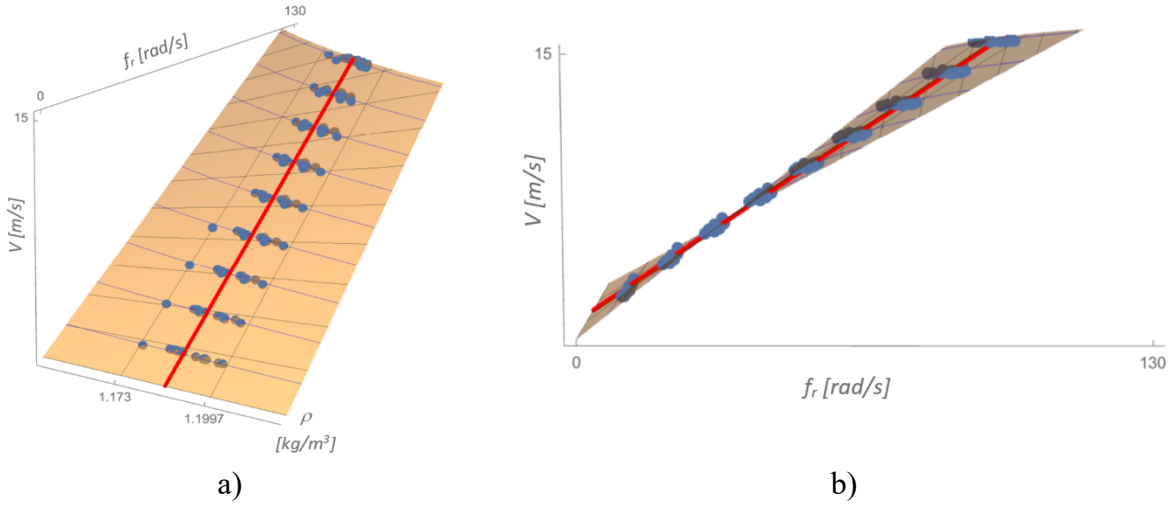

Fig. 11. Two views of the experimental observations fitting: the surface is the hyperbolic paraboloid that take into account ambient conditions, and the highlighted line is obtained from the IEC anemometry method [11].

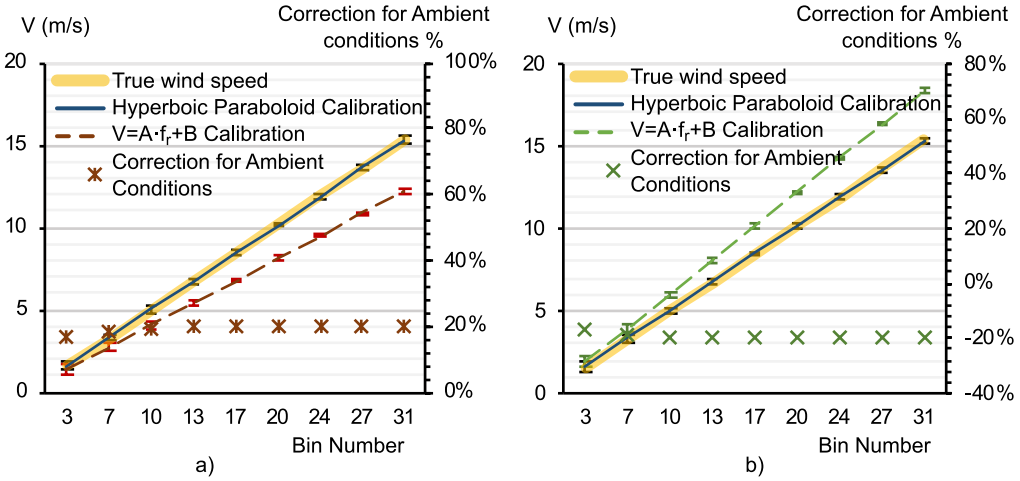

Fig. 12. Example of Direct Method and Dimensionless Abacus Method regressions models for an Auriol IAN cup anemometer. a) $\rho_c = 1.1863$ kg/m^3, $\rho = 1.225$ kg/m^3, b) $\rho_c = 1.1863$ kg/m^3, $\rho = 1.1476$ kg/m^3.

3.3. Annual Energy Production.

Annual Energy Production AEP, which depends on the turbine power curve and the wind speed probability distribution during a year, is key to study turbines performance.

The power curve relates wind speed and output power. According to the bin method described in the IEC 61400-12-1 international standard [1], an average value of wind speed and power corresponds to a specific bin (wind speed V_i- electrical power P_i) of the power curve. This method does not consider the influence of density variations between field and calibration laboratory on power curves.

A study case is presented to understand the role of the aforementioned density variations in power curves definition. In this case, the power data and wind speed measures provided in page 67 of the IEC 61400-12-1 standard [1] are used considering that wind speed was obtained by means of the analysed Auriol anemometer. Fig. 13 shows the resulting power curves. If the in-field air density ρ is greater than that at the calibration laboratory ρ_c, then the corrected power curve is beneath the power curve provided by the bin method (Fig. 13.a) and, on the contrary, when $\rho_c > \rho$ the bin method curve is beneath the corrected power curve (Fig. 13.b). Note that, even small density variations (±0.04 kg/m^3 in Fig. 13) lead to significant differences on the power curves (up to 20% of relative error, see Fig. 13). Actually, kinematic viscosity is the responsible of the cup anemometer rotation speed variations and therefore, it should be the parameter for correcting the power curve. Nevertheless, as it was previously discussed, for small density variations there is a direct relationship between density and the inverse of the kinematic viscosity so that density can be used instead of viscosity to correct the power curve.

According to the observed results in Fig. 13, power curves should be corrected in order to compare the turbine performance at different locations with different densities. This correction involves applying Eq. 19, which depends on the anemometer used; for the studied Auriol anemometer the value of c coefficient is shown in Fig. 7.

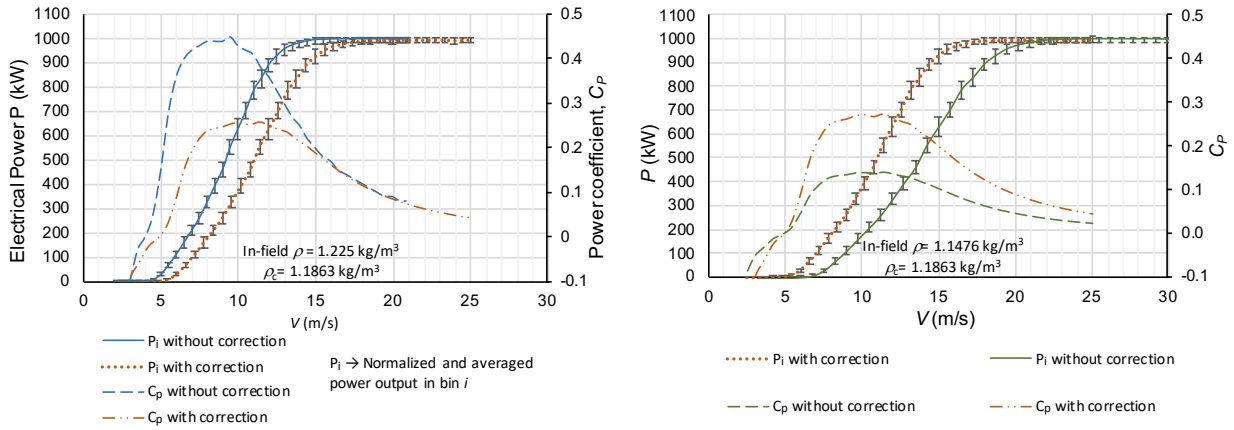

Fig. 13. Study case: power curves and power coefficient C_P curves. a) $\rho > \rho_c$ b) $\rho_c > \rho$. Confidence intervals with a coverage factor of one.

In addition to the power curve, it is necessary a wind speed probability distribution for AEP estimation. This probability distribution is also affected by the ambient conditions. The same method previously discussed can be applied to correct this distribution considering the density of a specific place and the used cup anemometer.

For the study case under consideration, Fig. 14 shows the resulting wind speed Weibull cumulative distribution $F(V_i)$ and its probability distribution with and without density corrections at two locations with different air densities. For a place with $\rho > \rho_c$,

the viscous effects slow down the anemometer's rotational speed respect to the rotation speed observed during calibration. This means that the frequency assigned to a wind speed without density correction should be assigned to a higher wind speed. On the contrary, in locations with lower density, the viscous effects are reduced, which increases the anemometer's rotational speed and therefore, the wind speed value provided by the anemometer is higher than the actual one. Fig. 14 also portrays the wind speed frequencies with and without correction. The mode values of the wind speed frequency curves comply with the abovementioned observations: higher mode value for the corrected curve at places with air density greater than the calibration one (Fig. 14.a) and vice versa. Recall that in this study case there are small density variations, otherwise viscosity should be considered instead of density.

It is worth to note that it is impossible to make rigorous comparisons between wind frequency curves of two different sites without accomplishing corrections for ambient conditions. The average annual wind speed (or the Weibull scale factor) should be corrected upwards at those places with air density above the calibration one (typically coastal locations), and otherwise it should be corrected downwards (typically interior or mountainous locations).

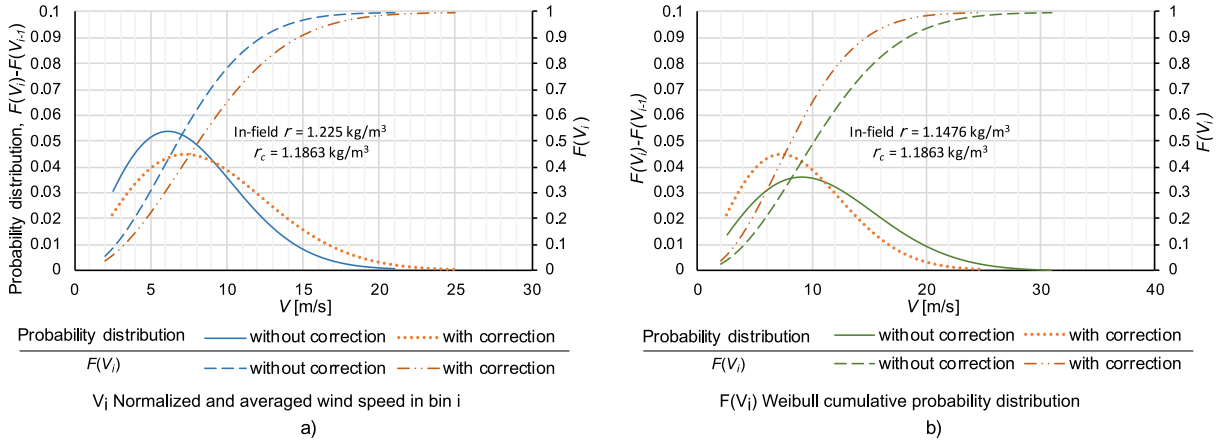

Fig. 14. Study case: Weibull cumulative probability distribution and wind speed frequency distribution: a) $\rho > \rho_c$ b) $\rho_c > \rho$

Finally, according to the international standard IEC 61400-12-1 [1], specific AEP is calculated as the product of power curve and the wind speed frequency distribution at a specific site, while generic AEP is obtained by multiplying measured power curve by a set of reference distributions for wind speed frequency. Each reference distribution has a mean value of wind speed measured at hub height. Fig. 15 shows specific and generic AEP measured using the power curves and the frequency distributions shown in Figs. 13-14. Generic AEP is typically used for design optimization of wind turbines [29] and specific AEP is used for determining the optimal location among several proposed places for the installation of a wind turbine [30].

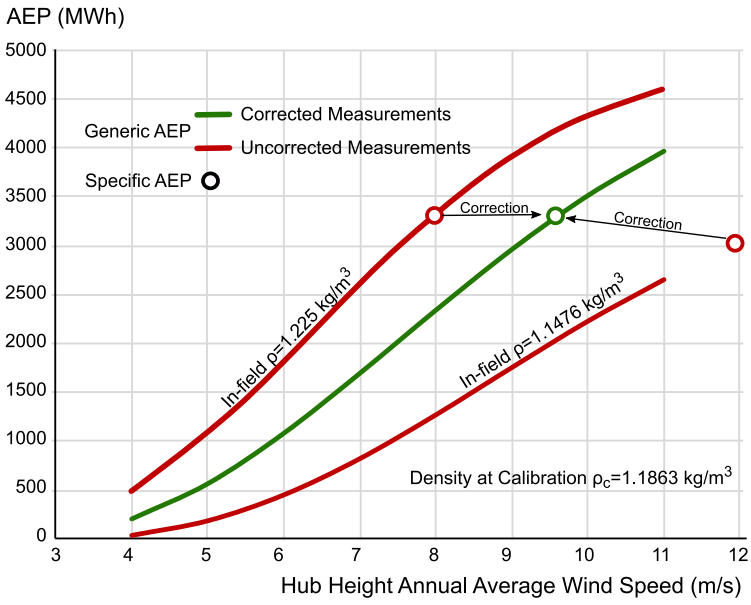

Fig. 15. Example of specific and generic AEP using an Auriol IAN cup anemometer, ρ_c= 1.1863 kg/m^3.

Regarding generic AEP, it is observed that the values at sites with $\rho > \rho_c$ should be corrected downward; whereas when the generic AEP is calculated in locations with $\rho < \rho_c$, the generic AEP should be corrected upwards. Therefore, when calculating estimations of generic AEP, the effect of the variation in ambient conditions between the measuring location and the calibration laboratory of the anemometer must be considered. The effect of air density can be corrected by means of Eq. (19). Nevertheless, if the variation range of density is significant, the correction should be based on the kinematic viscosity, as it is stated in Eq. (22).

As explained above, the specific AEP for a particular location can be calculated from the mean power curve and the wind speed specific frequency curve. If both curves are measured at the same time and using the same anemometer, the resulting value of the specific AEP does not require a correction of the effect of air density during the calibration procedure (see Fig. 15). This is because the correction affects both curves in an inversely proportional way, which leads the result of the multiplication to remain

unaffected. The problem arises from the fact that is necessary to measure the wind turbine power curve at its final location, or at a near one. Nevertheless, the research literature shows that the same anemometer is rarely used, due to the manufacturer power curve is used [30] or wind speeds are obtained from wind resource maps [31,32].

The proposed correction procedure allows to study the wind energy potential of a wind turbine before installing it in a specific location. The idea is to correct a known power curve of the wind turbine considering the variation of air density between a specific place where the turbine could be installed and the calibration laboratory.

4. Conclusions

This work provides an explanation for those cases where a cup-anemometer has different rotation frequencies for the same wind speed. According to a set of experimental measurements conducted in a wind tunnel, we concluded that the main cause of the abovementioned variations are the kinematic viscosity variations or, equivalently, the density variations when a constant dynamic viscosity can be assumed. Moreover, we verified that the experimental observations fit adequately to a hyperbolic paraboloid surface, which relates wind speed, rotation frequency and density.

The proposed relation leads to more accurate wind speed measurements. Hence, it helps to improve the AEP estimations by reducing the error linked to the cup-anemometers calibration procedure. On the other hand, in view of the presented results, for those that prefer a conventional calibration (which is accomplished considering a constant density), we described a procedure to correct in-field wind speed measurements according the specific density conditions.

Respect to the observations that foster this work, even for a low-density variation of 0.0267 kg/m^3, we noted differences up to 20 rd/s for a constant wind speed of 17 m/s as we showed in Figure 4. A linear regression between the slopes A of V-f_f calibration curves for different densities failed due to great dispersion of (ρ, A) data (Figure 5).

In order to overcome the above drawback, we discovered that representing the information in a TSR^{-1} vs Re diagram, it is possible to estimate the calibration slope coefficient with a relative uncertainty lower than 0.005, as a linear function of the density or the kinematic viscosity. The resulting relation among wind speed, rotation frequency and density is a type of ruled surface (a hyperbolic paraboloid surface). This surface, fitted using our experimental data, has a maximum absolute error of 0.4 m/s while the conventional calibration line has a maximum absolute error of 0.9 m/s. Experimental results show that, when field air density varies ±0.01 kg/m^3 from that at the calibration laboratory, the error in wind speed provided by the cup anemometer is about ±5%. The conventional calibration can be improved by correcting the measure with $\pm\Delta V$ that depends on the air density and the coefficient c (cup-anemometer air density sensibility) of the hyperbolic paraboloid surface (Eq. 19).

Regarding wind turbine power curves, if in-field measurements of wind speed with a cup-anemometer are not corrected, a 50% variation in the power coefficient C_P is observed when the same wind turbine is tested at several locations whose air density slightly differs from that at the calibration laboratory. Therefore, wind power curves for the same turbine differs significantly depending on the location where the observations are made. If the correction procedure proposed in the present study is applied, the estimated value of wind turbine power decreases as in-field air density increases respect to that of the calibration laboratory, and vice versa. Therefore, the proposed procedure provides the same power curves for a particular cup-anemometer regardless of the location where measurements are performed.

Additionally, using the power data and wind speed measures provided by the IEC 61400-12-1 standard for a 1 MW wind turbine, we computed the AEP with and without applying the developed equation for cup anemometers. The results of this computation showed for example, overestimations of 1000 MWh/year for an annual mean wind speed of 10 m/s measured at hub height in a location where air density is about 0.04 kg/m^3 higher than that at the calibration laboratory, and underestimations about 1250 MWh/year when density is 0.04 kg/m^3 lower. The error of the estimation is even greater for lower wind speeds.

Just in case of determining the power curve and the wind speed specific frequency at the same location and with the same anemometer, specific AEP estimations don't require anemometer correction. Therefore, this case is feasible only when measuring an existing wind turbine.

Finally, the following bullets summarize the main findings of this work:

- The rotation frequency variations for constant wind speeds in cup-anemometers are due to kinematic viscosity variations.
- A hyperbolic paraboloid surface that relates wind speed, rotation frequency and kinematic viscosity provides a more accurate wind speed estimation than a linear regression between wind speed and rotation frequency at constant density.
- The accuracy of cup anemometers would improve significantly by considering the calibration error and, consequently, wind speed measurements would lead to more accurate AEP estimations."

The novelty and interest of the summarizing findings are that they quantitatively explain the observed rotation frequency variations in a cup anemometer respect to ambient conditions. The proposed approach would improve the reproducibility of the measurements provided by cup anemometers, which would increase the reliability of these devices when they are used to perform power curves, statistical studies regarding wind speed and estimations of AEP.

Since the proposed approach has been done using wind tunnel measurements and a specific anemometer, future works that would help to support the presented results could be to perform in field measurements with different anemometers, or do the cup-anemometer calibration in a wind tunnel that allows large variations in air density. For this last case, the wind tunnels must allow a regulation of air pressure, so that it can be slightly modified respect to the ambient pressure.

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