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Temperature and pressure effects on the response behavior of anemometers

Temperatur- und Druckeinflüsse auf das Antwortverhalten von Anemometern

Abstract: Cup anemometers are within the most used wind speed sensors for the wind energy industry. Wind tunnel calibrations under controlled conditions are required, but during operation uncontrolled environmental conditions occur. This is accounted for in the IEC 61400-50-1:2022 international wind measurements standard, which specifies sensor classification based on their response to external conditions, due to the influence parameters turbulence, air temperature, density, and upflow angle. Temperature and density effects are not covered appropriately in the IEC 61400-50-1:2022, since it assumes that air temperature only influences the bearing friction of a cup anemometer. No guidance is provided on evaluating variations in density, which depends on temperature and pressure. To investigate this, two cup anemometers are measured in Deutsche WindGuard's Climatic Wind Tunnel, where density is changed by varying pressure and temperature independently. The results show that the sensor's response to temperature can have other effects than an increase in ball bearing friction. Using pressure or temperature to modify density can even cause opposing results. Hence, varying temperatures and pressures independently is crucial to characterize a sensor's response. The results correspond to cup anemometers, but the methodology is applicable on all sensors.

Keywords: anemometer; calibration; classification; IEC 61400-12-1; IEC 61400-50-1; wind sensor; wind tunnel

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Zusammenfassung: Schalensternanemometer gehören zu den am häufigsten verwendeten Windgeschwindigkeitssensoren in der Windenergieindustrie. Windkanalkalibrierungen unter kontrollierten Bedingungen sind erforderlich, während des Betriebs treten dennoch unkontrollierte Umweltbedingungen auf. Diese Problematik wird in der internationalen Norm IEC 61400-50-1:2022 berücksichtigt, die eine Klassifizierung der Sensoren auf der Grundlage ihrer Reaktion auf äußere Bedingungen durch die Einflussparameter Turbulenz, Lufttemperatur, Dichte und Anströmwinkel festlegt. Temperatur- und Dichteeffekte werden in der IEC 61400-50-1:2022 nicht angemessen berücksichtigt, da davon ausgegangen wird, dass die Lufttemperatur nur die Lagerreibung eines Schalensternanemometers beeinflusst. Zudem wird keine weitere Beschreibung zur Bewertung von Änderungen in der Dichte gegeben, die von Temperatur und Druck abhängt. Um dies zu untersuchen, werden Messungen mit zwei Schalensternanemometern im Klimawindkanal von Deutsche WindGuard durchgeführt, in dem die Dichte durch unabhängige Variation von Druck und Temperatur verändert wird. Die Ergebnisse zeigen, dass das Antwortverhalten des Sensors auf die Temperatur andere Auswirkungen haben kann als eine Erhöhung der Kugellagerreibung. Die Verwendung von Druck oder Temperatur zur Veränderung der Dichte kann sogar zu gegensätzlichen Ergebnissen führen. Daher ist die unabhängige Variation von Temperatur und Druck entscheidend für die Charakterisierung des Antwortverhaltens eines Sensors. Die Ergebnisse beziehen sich auf Schalensternanemometer, aber die Methodik ist auf alle Sensoren anwendbar.

Schlagwörter: Anemometer; Windsensor; Klassifizierung; Kalibrierung; Windtunnel; IEC 61400-12-1; IEC 61400-50-1

1 Introduction

Anemometers have been used for over 550 years [1], permitting a quantification of the local wind speed and the development of associated technology. They have developed from relatively simple devices into very reliable sensors, based on a variety of working principles (mechanical, ultrasonic, thermoelectric, optical) [2]. The one thing they have in common, as with most measurement instruments, is that they require regular calibrations for traceability of the measurements.

Anemometer calibrations for the wind energy industry – independent of the anemometer type – are most often performed in atmospheric wind tunnels, at a constant, prevailing air temperature and atmospheric pressure, in a range that is within the wind tunnel's accredited performance envelope. This calibration is the basis for using the sensor data for a wide range of applications, such as wind speed measurements for meteorological purposes, on meteorological masts for wind resource assessment regarding the energy yield potential of wind farms, and for wind turbine control. As the environmental conditions can influence the performance of the anemometer, it is necessary to consider the anemometer's class when choosing the appropriate sensor for the considered application.

Anemometers are assigned into different accuracy classes, according to a classification schema given in the standard IEC 61400-50-1 [3]. The IEC 61400-50-1 standard is part of a structural revision, and the technical content of this document could previously be found in IEC 61400-12-1:2017 [4] and IEC 61400-12-2:2013 [5]. As the IEC 61400-50-1 was published recently in 2022, the previous standards are still widely used. According to the standard, air temperature and air density, are two of the influence parameters which have to be investigated during the anemometer classification. The classes cover different operational ranges of these influence parameters, of which this study focuses on air temperature and the air density.

Regarding cup anemometers, it is assumed in the standard IEC 61400-50-1 that a change in air temperature only influences the bearing friction, with one of the causes being the ball bearing's lubricating oil's viscosity variation. The assumption is that, at a constant wind speed, higher air temperatures decrease the friction and therefore increase the rotational speed of the cups and vice versa. However, the standard IEC 61400-50-1 does not provide specific guidance on how to evaluate a variation in air density.

According to the ideal gas law [6], the density ρ is a function of the absolute pressure p, the specific gas constant R_{specific}, and the absolute Temperature T:

$$\rho = \frac{p}{R_{\text{specific}} \cdot T}.$$

Therefore, to change the density of the air, the air temperature T and the air pressure p can be altered, individually or simultaneously. If the temperature is used as a parameter for changing the air density, it is difficult or even impossible to distinguish between the influence of a changing air temperature, and the influence a changing density can cause on the sensor's response behavior. Only when the two parameters air temperature T and air pressure p are varied independently, the interpretation of the respective dependency is unambiguous.

In atmospheric wind tunnels, the pressure cannot be directly set, and the temperature is not always controlled. As a result, the impact of these environmental conditions cannot be investigated outside the available operating conditions of the employed wind tunnel. In order to investigate the effects of air temperature and air pressure on the anemometer response, the company Deutsche WindGuard developed its Climatic Wind Tunnel, a Göttinger type closed-return, hermetic wind tunnel, with the capability to independently vary the wind tunnel pressure and temperature, covering the range of pressures and temperatures, and therefore densities, to which sensors can be exposed to on Earth. Regarding the application of anemometers on wind turbines, this covers altitudes from sea level to approximately 5000 m above sea level.

The aim of the present article is to describe a measurement methodology for the temperature- and pressure-dependent calibration of cup, propeller and sonic anemometers in the climatic wind tunnel of the company Deutsche WindGuard, while the experiments here are focused on cup anemometers as an example. The calibration result is the indicated air velocity of the anemometer at different temperatures and/or different air pressures. The calibration results can be used to estimate the uncertainty for wind sensors operating at very low or high temperatures and/or at high altitudes (lower temperatures combined with lower density). The results also prove to be essential for the classification of anemometers according to IEC [3].

In Section 2, previous investigations of the influence of a changing air temperature on the bearing friction of cup anemometers are presented. In Section 3, a technical description of the climatic wind tunnel is given, followed by the anemometer calibration procedure for varying air temperatures and air pressures with the associated uncertainty calculation in Sections 4 and 5. Example results are presented for two different, commonly used and similarly shaped cup anemometers with a frequency output in Section 6.

2 Previous investigations of temperature-induced effects on the anemometer response

Previous investigations of temperature-induced effects on air velocity measurements with cup anemometers were performed by flywheel experiments in a climate chamber [7, 8]. Figure 1 illustrates the experimental set-up for studying bearing friction in a climate chamber using the flywheel method. This method consists of substituting the anemometer's rotor for a flywheel of known characteristics. The flywheel is driven by an external motor until a desired rotational speed is reached, the motor is decoupled, and the rotational speed is measured constantly during specific phases of the rotational speed decay. To evaluate the temperature influence, the measurement is performed at different temperatures.

The procedure assumes that the air resistance of the rotating disk is known. A drag coefficient determined in 1934 by W. G. Cochran [9] is still used. Purucker [8] studied the effects of using different disks and different values of disk roughness. The results showed the possibility of high deviations if the disk roughness is not properly defined.

A similar but alternative procedure previously used during the classification of anemometers. To calculate the influence of varying air pressures and air temperatures [10]. A foil heater was used to solely increase the temperature of the bearing shaft, see Figure 2. To reduce the temperature of the bearing shaft, a cooling device was constructed, see Figure 3.

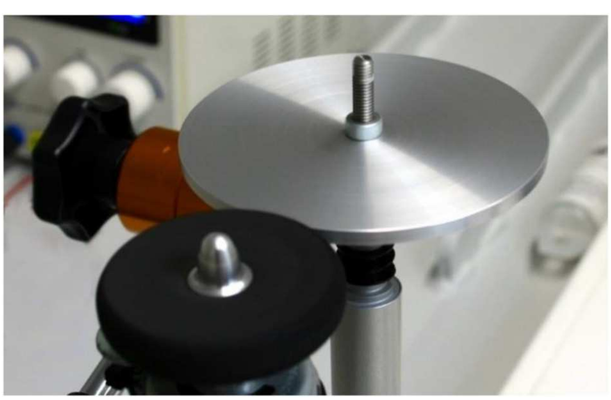

Figure 1: Experimental set-up for a flywheel test in a climate chamber at Deutsche WindGuard facilities. The flywheel ($D = 86$ mm) substitutes the anemometer's rotor. During the flywheel speed-up, the drive wheel (black) is in contact with the flywheel.

Figure 2: Externally heated anemometer in the test section. Experimental set-up for producing hot temperatures through a foil heater mounted locally on the anemometer'. The wind is from right to left. For viewing clarity, the necessary thermal insulation is not shown [10].

Both methods are based on the idealized assumption that a change in air temperature only affects bearing friction. Other possible temperature-induced effects, such as distortion of the rotor, dimensional changes and/or changes in the aerodynamic properties, are not considered. Wind tunnel tests with changing air temperature, on the other

Figure 3: Externally cooled anemometer in the test section. Experimental set-up for producing cold temperatures through the cooling device. The wind is from right to left, and the cup anemometer's housing is surrounded by two cooling devices. For viewing clarity, the necessary thermal insulation is not shown [10].

hand, also assess these effects and should therefore assess the anemometer performance in a more realistic way.

3 The climatic wind tunnel

The climatic wind tunnel of Deutsche WindGuard Wind Tunnel Services (DWG WTS) is a hermetic, closed-return wind tunnel with a closed test section. The wind tunnel is characterized by a low turbulence (<0.5 %), homogeneous flow. The wind tunnel was specifically designed for testing sensors at different air pressures and air temperatures.

3.1 Design considerations

The range for the ambient conditions of interest are specified in the IEC 61400-50-1 [3]. Based on this, the following design requirements were specified:

- Air velocity range in the empty test section: 0–16 m/s
- Air temperature range: −20 °C – +40 °C
- Air pressure: 600 hPa – 1100 hPa
- Resulting air density range @ 10 °C: 0.9 kg/m^3 – 1.35 kg/m^3

Based on these criteria and constraints, a closed-return, closed test section configuration was chosen. The test section has a length of 0.8 m and a cross-sectional area of 0.5 m × 0.5 m. This provides an acceptable blockage ratio for the intended anemometer testing at different air densities. Keeping the volume of the wind tunnel relatively low is beneficial to reduce pressurization times. The nozzle has a contraction ratio of 3.3:1.

Figure 4 shows a photo of the climatic wind tunnel at the DWG headquarters in Varel, Germany.

Figure 4: Photo of the climatic wind tunnel of DWG WTS. The 0.5 m × 0.5 m × 0.8 m test section with two windows, is located after the nozzle. Flow is from right to left.

The wind tunnel is a hermetically sealed sheet metal construction which allows the internal air pressure to be varied. In addition, the entire wind tunnel is placed in an insulated and temperature-controlled chamber.

Calculations were performed in order to determine the size and location of each wind tunnel component, the pressure variation and the air velocity in different sections of the tunnel. These calculations were based on experience and well proven values for diffuser angles, contraction ratios and pressure drop coefficients. In order to achieve a high-quality flow, the settling chamber contains an arrangement of five screens and a honeycomb flow straightener. A single fan unit was selected to compensate the pressure loss and produce the desired air velocity at the test section.

Figure 5 illustrates the air density range which can be set in the climatic wind tunnel, with the range of possible air temperatures and pressures on the X and Y axis correspondingly.

3.2 Instrumentation

Two pitot static tubes are installed in the test section near the nozzle exit, from which independent pressure sensors measure the dynamic pressure. The static pressure port is also used to measure the barometric pressure inside the wind tunnel. Together with a temperature and humidity sensor located downwind of the test section, the reference air velocity is calculated. Furthermore, the air temperature inside the temperature-controlled room is also monitored.

The pressure and temperature sensing electronics are located in a temperature-controlled chamber, outside the test section. Only the sensing element of the pressure and humidity sensor, as well as the pitot tubes are exposed to the changing conditions.

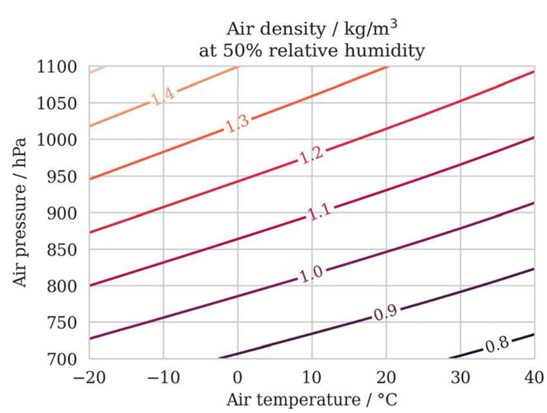

Figure 5: Isopycnic (constant density) lines, as a function of air temperatures and air pressures.

4 Calibration procedure

In a first step, the test item is calibrated under normal ambient conditions in the accredited, reference wind tunnel WK2. This wind tunnel has the lowest uncertainty of Deutche WindGuard's 8 wind tunnels. A Laser Doppler Anemometer (LDA) from the German National Metrology Institute (Pysikalisch-Teschnische Bundesanstalt, PTB) is used to establish the traceability. The LDA and associated hardware is regularly calibrated at the PTB facilities in Braunschweig.

After the sensor's initial calibration in WK2, a transfer measurement in the climatic wind tunnel is performed at nearly identical ambient temperature and pressure conditions. The anemometer itself is used as a transfer standard and a transfer factor between wind tunnels is calculated for that specific sensor.

During the calibration in the climatic wind tunnel, the anemometer output is measured for air velocities between 4 m/s and 15.5 m/s. For each measurement point, sufficient time is allowed to establish stable flow conditions. After the settling time, the air velocity is kept constant for a sampling interval of at least 30 s. The sampling frequency is at least 4 Hz. To cover rising and falling air velocities, the following sequence is chosen: 4 m/s, 8 m/s, 12 m/s, 15.5 m/s, 14 m/s, 10 m/s, 6 m/s.

4.1 Calibration procedure for varying air temperatures (constant pressure)

After determining the transfer factor for the anemometer being tested, the air temperature is lowered to −20 °C and a calibration run is performed. The air temperature is then increased in 5 °C steps up to the maximum air temperature of 40 °C while keeping the air pressure constant. At each temperature, the calibration is performed as described above. To reduce the effect of random measurement errors, the minimum duration of the sampling interval is 30 s. For each calibration run, a linear regression analysis is performed on the anemometer's output, resulting in a calibration function with slope and offset as a function of wind speed, for a given air temperature.

4.2 Calibration procedure for varying air pressures (constant temperature)

The calibration procedure for varying air pressure is similar to that for varying temperature. After the measurement to determine the transfer factor, the air pressure is increased in 50 hPa steps from 700 hPa to 1100 hPa. To cover an air density range of approximately 0.8 kg/m^3 to 1.4 kg/m^3. As a reference, please note that the standard atmospheric density at sea level is defined as 1.225 kg/m^3.

The measurements for different air pressures are performed at a fixed air temperature of 10 °C. For each variable ambient pressure calibration run, a linear regression analysis is performed, resulting in a calibration function with slope and offset for each particular ambient air pressure.

It is possible to perform measurements at any combination of pressure and temperature within the operational envelope listed in Section 3.

5 Measurement uncertainty

The measurement uncertainty for the procedure described in Section 4 is a combination of the measurement uncertainty obtained from the calibration of the anemometer in the reference wind tunnel and the uncertainty components related to the calibration in the climatic wind tunnel.

The measurement uncertainty component given by the calibration in the reference wind tunnel is a combination of the accredited calibration measurement capability and sensor related uncertainty components such as the resolution and repeatability. The measurement uncertainty for this type of sensor is in the order of 0.5 % ($k = 2$).

The additional uncertainty components associated with the measurement in the climatic wind tunnel consist of the flow quality, the ambient conditions, repeatability, as well as further uncertainty components due to non-linearity, resolution and reproducibility. Since a wind tunnel calibration factor in form of the transfer factor is determined for each test item, blockage effects are accounted for and not further considered.

The results presented below show relative changes for varying air temperatures and air pressures, where the main uncertainty components are related to repeatability and reproducibility. Systematic errors such as drift, nonlinearity and flow quality don't influence the calculated ratio and don't have to be considered.

Taking into consideration both the sensor uncertainty and a statistical analysis of the additional uncertainty components, the calculated measurement uncertainty for the ratio $k_{(\mathrm{T,p})}$ is 0.012 ($k = 2$).

6 Results

To illustrate the influence of air temperature and air pressure, calibration results are presented in this section.

Two commonly used and similarly shaped cup anemometers (A and B) with a frequency output from two different manufacturers are tested. Both anemometers have ball bearings supporting the spindle. To compare the results, the ratio

$$k_{(\mathrm{T,p})} = \frac{f_{(\mathrm{T,p})}/v_{(\mathrm{T,p})}}{f_{(20\ ^{\circ}\mathrm{C},1000\ \mathrm{hPa})}/v_{(20\ ^{\circ}\mathrm{C},1000\ \mathrm{hPa})}}$$

Between the anemometer output $f_{(\mathrm{T,p})}$ at varying ambient conditions and the output $f_{(20\ ^{\circ}\mathrm{C},1000\ \mathrm{hPa})}$ at standard condition (approx. 20 °C and 1000 hPa) normalized each to the reference air velocity v is calculated.

6.1 Varying air temperatures (constant pressure)

In Figure 6 the ratio for different air temperatures is illustrated.

The dashed lines with a triangle show the results for anemometer A at different air velocities, the solid lines with a circle show the results for anemometer B. The influence of varying temperature is noticeably different for both anemometers. Anemometer A has a decreasing ratio for decreasing temperatures, whereas anemometer B has the opposite behavior. Furthermore, the influence of varying the air temperature is relatively more significant at lower air velocities. The proportion of frictional losses due to the bearings becomes smaller relative to the available aerodynamic torque as the air speed increases. Therefore, for anemometer A, bearing friction seems to be the main driver for the change in anemometer output with varying air speed and varying air temperature. However, Anemometer B shows the opposite behavior, suggesting that change in bearing friction for this type of anemometer is not the main driver for the change in sensor output at different air temperatures.

If the basic calibration function established at 20 °C is applied and the measured effects are not considered, anemometer A would underestimate the air velocity at low temperatures by up to over 5 %. Anemometer B, on the other hand, would slightly overestimate the air velocity at low temperatures by up to 1 %. Air temperatures above 20 °C would lead to opposing results, but of reduced scale. The influence of this effect is more pronounced on anemometer B, that would result in a slightly underestimated air velocity of 0.5 %.

6.2 Varying air pressures/air densities (constant temperature)

In Figure 7 the ratio for different air densities and air velocities is illustrated. The different air densities are obtained by varying the air pressure at a constant air temperature of 10 °C. Density is calculated using an equation given in the IEC 61400-50-1 standard [3].

The dashed lines with a triangle show the results for anemometer A and the lines with a circle show the results for anemometer B. The ratio is calculated by normalizing to the results to the response at 1000 hPa, which corresponds to an air density of approximately 1.23 kg/m^3. The influence of varying density is similar for both

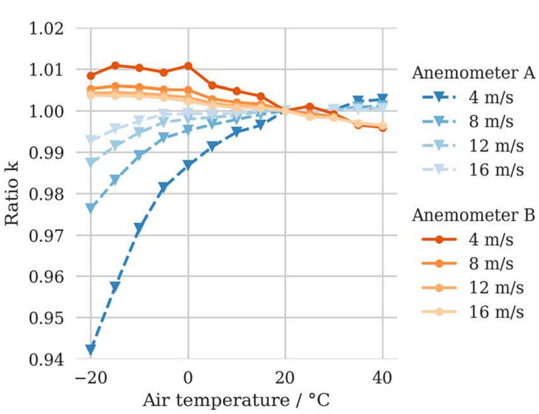

Figure 6: Ratio k for anemometer A and B at varying air temperatures and air velocities and at a constant air pressure of about 1000 hPa.

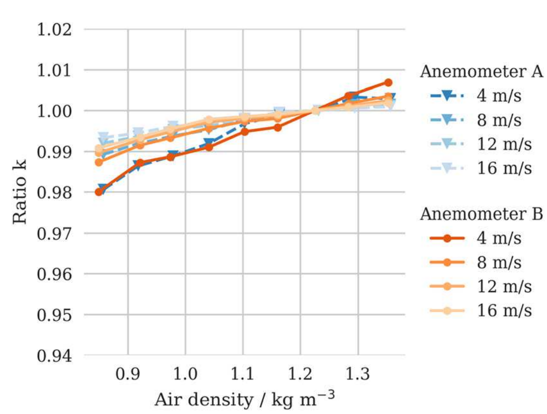

Figure 7: Ratio k for anemometer A and B at varying air density and air velocities and at a constant air temperature of about 10 °C.

anemometers. Both anemometers have a decreasing ratio with decreasing pressure. If the basic calibration function established at 1000 hPa is used, both anemometers would underestimate/overestimate the air velocity at lower/higher air densities. The influence of up to 2 % is stronger at lower air velocities and low pressures. The higher pressures would cause an up to 0.6 % overestimation of the wind speed.

To visualize the variation of density, due to pressure and temperature in the atmosphere, Figure 8 shows the ranges of pressure and density as a function of height above sea level. The barometric formula according to [11], under the assumption of a temperature drop of 6.5 K/km, permits calculating the barometric pressure and/or density in relation to the altitude above sea level, which is calculated with the standard atmosphere at sea level of 1013.25 hPa, 288.15 K and a density of 1.225 kg/m^3.

A pressure of about 950 hPa corresponding to 1.16 kg/m^3 in Figure 7, and correlates to an altitude of about 500 m. Starting at moderate altitudes of about 500 m, the pressure difference influences the performance of the anemometers. To the authors knowledge, the wind turbine operating at the highest altitude was installed in 2021, in Cuomei County, Tibet, with a hub height of 5150 m above sea level [12] (indicated by the red vertical line in Figure 8), corresponding to an approximate barometric pressure to less than 600 hPa. As for anemometer A both low temperatures and low pressures cause an underestimation of the wind speed, both effects would occur simultaneously. For anemometer B the effects of temperature and pressure reduce the magnitude of the difference. Note that this specific operational point has not been measured here, but it is well within the capabilities of the equipment.

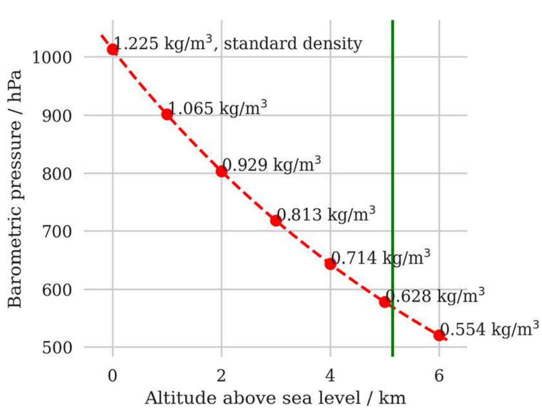

Figure 8: Density, indicated with a red dashed line, plotted against altitude above sea level, with indication of the associated barometric pressure. As an upper-limit reference, the wind turbine currently operating at the highest altitude (since 2021, in Tibet [12]) is indicated by a green line.

7 Conclusions

The experimental results show a distinct influence of varying air temperature and air pressure on the performance of cup anemometers, which is of particular interest for the wind energy industry. For the two sensors tested, the influence is more pronounced at low air velocities. While the results and trends for varying air pressure are similar between the anemometers tested, the results for varying air temperature differ. This demonstrates that a change in air temperature can have effects other than just an increase in ball bearing friction. Therefore, it is not sufficient to evaluate the influence of varying temperature exclusively with the flywheel method. Tests in which the entire anemometer in its normal operational condition is exposed to different temperatures are recommended.

The results show that the sensor's response is not only dependent on temperature and density, and the importance of considering air pressure, rather than the pressure- and temperature-dependent air density, as a primary influencing variable on cup anemometer measurements for classification purposes. Furthermore, since the air density depends on air temperature and air pressure, the influence of the air density and air temperature on cup anemometer measurements can be very different. Neither of these aspects is covered in IEC 61400-50-1 [3].

When using cup anemometers in subarctic climate regions or at higher altitudes, results based solely on a standard calibration may result in an under- or overestimation of the wind speed. The magnitude can be in the order of several percent in wind speed. Since the power generated by a wind turbine is proportional to the third power of the wind speed, this leads to a correspondingly larger error in the power output calculation. Additionally, the use of anemometers to control wind turbines in these regions may result in a delayed start of power generation, especially since the influence of air pressure and temperature is greatest at low wind speeds.

It is important to note that the magnitudes of the measured deviations are by no means representative for all sensors measured by the authors.

As outlook, a correction procedure to adjust the indicated wind speed based on measured operating conditions seems feasible. The correction algorithm may be developed considering air pressure, air temperature and wind speed, parameters that are readily available at most weather stations. This correction function has to be developed individually for each type of anemometer. Further discussion is needed on how to assess the impact of the air pressure and air temperature correction on the associated uncertainty due to the anemometer class number according to [3], and to analyze the underlying cause of the results presented in this study.

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