Outdoor Comparison of Cup Anemometers
(Abweichendes Verhalten von Schalensternanemometern im Freifeld)

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1 INTRODUCTION
Within the ongoing project “Identification of Variables for Site Calibration and Power Curve Assessment in Complex Terrain” (SiteParIden, contract: JOR3-CT98-0257), which is co-funded by the European Commission, cup anemometers of different type are compared in the open. The aim of these investigations is to study how far cup anemometers are influenced by the turbulence present in the atmosphere and how far terrain induced flow effects influence the anemometer measurements. For this purpose simultaneous wind speed measurements with different cup anemometers mounted in the same arrangement in the field are performed in flat terrain by DEWI and in complex terrain by the Netherlands Energy Research Foundation (ECN). The results from these measurements deviate far from the expectations. Even in flat terrain large deviations between wind speed measurements with different cup anemometers in the order of 2 % have been found. These findings are linked with significant consequences for wind turbine power performance tests as well as for site assessments.

2 METHODOLOGY
Two cup anemometers of different type have been mounted on a special test rig on top of a 8 m high met mast (see Fig. 1). The cup anemometers are separated by a distance of 2.4 m. A sonic anemometer is centred between the cup anemometers for measurements of turbulence characteristics. The whole test rig is aligned automatically perpendicular to the wind. Before anemometers of different type have been compared, detailed tests with two identical anemometers have been made in order to ensure that at the two anemometer positions the same wind regime is present. Furthermore, to avoid effects caused by different wind tunnel calibrations, all anemometers are calibrated in the same wind tunnel according to the latest standards [1], [2]. In flat terrain the experiments have been repeated in various heights up to 70 m above ground at different locations by using a simplified test rig (without ultra sonic anemometer, use of a very limited wind direction sector instead aligning the rig perpendicular to the wind). All cup anemometer comparisons are based on averages of the wind speed measurements over 10 minute intervals.

Fig. 1 Test rig for outdoor comparison of cup anemometers

DEWEK 2000 Tagungsband 107
3 EXPECTATIONS UNTIL 2000

In the last years wind speed measurements related to wind energy applications went through a long harmonisation process. In the beginning of the ninetieth large deviations between different wind tunnel calibration procedures have been identified as a severe problem in terms of wind turbine testing and site assessment. Meanwhile, a good comparability of wind tunnel calibrations is achieved by MEASNET [1]. But unfortunately still anemometer calibrations outside the MEASNET quality ensurance are used for wind speed measurements or power performance measurements which show unacceptable differences (Fig. 2). Furthermore, it is known that cup anemometers are influenced by the vertical flow component [2]. This effect is strongly dependent on the type of anemometer and in some cases also on the wind speed (Fig. 3).

Overall, the general expectation until the new millennium was that good quality cup anemometers would deviate insignificantly in flat terrain when they are calibrated in the same wind tunnel. In complex terrain with steep terrain slopes significant deviations were expected, because systematic vertical flow inclination can occur.

![Difference of Wind Tunnel Calibrations (1999)](image1)

**Fig. 2** Observed differences of wind tunnel calibrations in 1999.

4 RESULTS

The investigations have been initialised with measurements 8 m above ground. Contrary to all expectations cup anemometers of different type show large differences in wind speed measurements up to 4% even in flat terrain (Fig. 4). The experiments have been repeated at higher height levels above ground. Fig. 5 illustrates that at 30 m height the different cup anemometers are closer compared to 8 m height. However, even at 65 m height above ground an effect of about 2% in wind speed has been observed in flat terrain between the Thies 4.3303.22.000 and the Vector A100 anemometer (Fig. 6).

The same tendency in the deviations between cup anemometers has been found by ECN in complex terrain, where a Mierij anemometer has been used as reference.

![Difference in wind speed measurements of various cup anemometers compared to the Thies 4.3303.22.000 cup anemometer in flat terrain measured 8 m above ground.](image2)

**Fig. 4** Difference in wind speed measurements of various cup anemometers compared to the Thies 4.3303.22.000 cup anemometer in flat terrain measured 8 m above ground.

![Sensitivity of Cup Anemometers on Flow Inclination](image3)

**Fig. 3** Influence of vertically inclined air flow on two different cup anemometers as observed in a wind tunnel.

![Difference in wind speed measurements of various cup anemometers compared to the Thies 4.3303.22.000 cup anemometer in flat terrain measured 8 m and 30 m above ground.](image4)

**Fig. 5** Difference in wind speed measurements of various cup anemometers compared to the Thies 4.3303.22.000 cup anemometer in flat terrain measured 8 m and 30 m above ground.
Fig. 7 Difference in wind speed measurements between the Thies 4.3303.22.000 and the Vector A 100 cup anemometer observed at various sites in flat terrain in different heights above ground. The average turbulence intensity is displayed for each site.

5 ORIGIN OF THE EFFECT

The comparison between the Thies 4.3303.22.000 and the Risoe P2445b anemometer has been done using different types of output signals of the anemometers. The differences in wind speed measurements have been found to be independent of the electrical signal conditioning. Hence, the different aerodynamics of the anemometers must be responsible for the effect.

The data gained from comparisons between the Thies 4.3303.22.000 and the Vector A100 anemometer in flat terrain from different sites and heights above ground have been classified according to the turbulence intensity (Fig. 7). A strong tendency of the differences in wind speed measurements to increase with increasing turbulence intensity is seen. From this result it is clear, why different types of anemometers show differences in the open, although they are calibrated in the same wind tunnel.

In the wind tunnel a very low turbulence intensity is present, and the calibration is not representative for the outdoor wind regime.

It is not fully understood yet which turbulence characteristics mainly rule the differences in cup anemometer measurements.

However, there are indications, that the fluctuations of the vertical flow speed component due to turbulence play a major role. Some anemometers tend to measure more or less the horizontal flow component, while others tend to measure the complete wind speed vector, including the vertical flow component. Indeed such anemometers, which have the tendency to measure only the instantaneous horizontal flow component (Risoe P2445b) or even less than that (Vector A100), show in the outdoor anemometer comparison a smaller wind speed than the Thies 4.3303.22.000 anemometer, which is known to measure in tendency the full wind speed vector (compare Fig. 3 with Fig. 4 and Fig. 5). Furthermore, simulations of the effect of turbulent fluctuations of the vertical flow component predict differences in cup anemometer measurements up to 2 % [3], [4].

Another source for the differences in measurements with different types of cup anemometers is the fact that the acceleration of cup anemometers during increasing wind speeds is larger than the deceleration when the wind is decreasing. This true measurement error is known as overspeeding and is strongly dependent on the type of the cup anemometer, which is expressed in the so called distance constant. However, simulations of the overspeeding effect as well as experiments show that overspeeding plays a minor role. According to reference [2] the overspeeding effect is in the order of just 0.2 % in a conservative scenario with a turbulence intensity of 15 % and an anemometer with a large distance constant of 5 m.

An interesting result from the outdoor anemometer comparison so far is that the anemometers measuring the highest wind speeds, which are the Thies compact, the Friedrichs 4033.1100x and the Thies 4.3303.22.000, all have semispherical cups, while the anemometers measuring the lowest wind speeds (Vector A100, Risoe P2445b) have conical cups (Fig. 4). This fact supports well the thesis that the differences are to a large part originating from fluctuations of the vertical flow component, because the drag of the cups as well as the Bernoulli effect in respect to vertically oriented flow depends much on the cup’s shape. A further result is that the size of the cups or the whole rotating part of the anemometer seems to have no major influence. For instance, very small anemometers, like the Thies compact (diameter 165 mm), fall into the same group as the large Thies 4.3303.22.000 anemometer (diameter 315 mm) (Fig. 4).

6 CONSEQUENCES FOR THE WIND ENERGY MARKET

An example for the effect of different cup anemometers on power curve measurements is given in Fig. 8. Power curves of a large wind turbine have been measured in flat terrain simultaneously with two anemometers, a Thies 4.3303.22.000 and a Vector A 100. The experiment has been repeated in complex terrain at an medium sized wind turbine. The effect of the type of anemometer on the meas-
Influence on Power Curve

![Influence on Power Curve](image)

Fig. 8 Differences of wind turbine power curves measured simultaneously with a Thies 4.3303.22.000 and a Vector A 100 cup anemometer in flat terrain and complex terrain.

The effect on the annual energy production calculated from the power curves is for a location with an annual average wind speed of 7 m/s in the order of 3% in flat terrain and about 6% in complex terrain (Fig. 9). The differences in AEP are increasing with decreasing annual average wind speed. Thus, especially at low wind sites, the use of wind energy is often linked to high financial risks anyway, the observed differences in wind speed measurements due to the different types of anemometers lead to severe additional uncertainties. The fatal aspect about this source of uncertainty is that it systematically goes in one direction, dependent on the type of anemometer in use. This in contrast to other uncertainty components like e.g. the effect of the terrain on wind turbine power performance measurements. In short, the present situation is completely unsatisfying for the wind industry, because the power performance of wind turbines can not be compared if measured with different anemometer types. Furthermore, measured power curves are useless for the prediction of the site specific energy production, when the type of anemometer in use for the power curve determination does not match the type of anemometer applied for the site assessment.

![Influence on Annual Energy Production (AEP)](image)

Fig. 9 Difference in the annual energy production (AEP) resulting from power curves measured simultaneously with a Thies 4.3303.22.000 and a Vector A 100 cup anemometer in flat terrain and complex terrain.

7 RECOMMENDATIONS

The observed differences in wind speed measurements due to the use of different types of cup anemometers lead to the following recommendations:

- The ideal solution for the problem would be the use of a unified cup anemometer for all wind energy related measurements. This path is followed by the project "Development of a Standardised Cup Anemometer Suited to Wind Energy Applications (CIASSCUP, JOR3-CT98-0263)", which is co-funded by the European Commission. However, first discussions between specialists give only poor hope of the feasibility of this solution in the near future.

- Standards and recommendations for wind turbine testing and wind energy related wind measurements [2], [5], [6], [7] must define the flow speed component to be measured. Related to this issue are requirements on the anemometer class to be used (see next point).

- Cup anemometers must be classified, e.g. according to results from investigations of their sensitivity on vertically inclined air flow or based on open field comparisons.

- Site assessments should be based on wind measurements with the same class of anemometers which have also been used for the determination of the power performance of the planned wind turbine type or vice versa. A fatal scenario is the determination of the wind potential on the bases of a fast anemometer (e.g. Thies or Friedrichs) combined with a power curve measured with a slow anemometer (e.g. Risoe P2445b or Vector A100).

- The development of a correction for measured wind turbine power curves from one anemometer class to the other is necessary in order to make power curves comparable. This is also needed for site assessments, because a match between the anemometer used for the wind potential prediction and the anemometer applied for the wind turbine power performance test will not always be possible.

- Further research is required regarding the question which turbulence parameters dominate the differences in cup anemometer measurements. This has to be answered for a proper classification of cup anemometers and for the development of an adequate correction of wind turbine power curves from one anemometer class to the other. The results presented here indicate that an anemometer correction must take the turbulence intensity into account. Key issue is, whether other site specific turbulence or flow characteristics, like e.g. the ratio between longitudinal and vertical turbulence, the turbulence length scale or the average flow inclination have to be taken into account.

- Some helpful steps should be taken immediately: In all power curve certificates and wind potential determinations a clear statement should be given regarding the used anemometer. Power performance guarantees should clearly state the anemometers for which the power curve is valid.
Furthermore, MEASNET offers the possibility for a quick agreement on a certain class of anemometers to be used within the MEASNET group. The expert group of the Technical Guideline for Wind Turbines [7] has already agreed on the determination of the full wind speed vector for wind turbine power performance measurements.

8 ACKNOWLEDGEMENTS
The work is partially supported by the European Commission under contract number JOR3-CT98-0257. Thanks belong also to the wind turbine manufacturers which have allowed to use the measurements performed at their wind turbines for this work.

9 REFERENCES