Helipod Measurements of Turbulent Energy and Aerosol Transport in the Lower Atmosphere – Benefits for the Wind Energy use in Wind Parks

J. Bange, T. Spieß, P. Vörsmann, Inst. for Aerospace Systems, TU Braunschweig
D. Nagel, U. Maixner, Inst. for Coastal Research, GKSS Research Centre Geesthacht

Abstract

Wind parks gain energy by interaction of the converters with the turbulent viscosity of the atmospheric flow. This turbulent flow contains besides kinetic energy also heat, humidity, and matter e.g. in form of aerosol. In off-shore installations sea-water aerosol causes damage in all parts of the power stations by erosion and corrosion. Forward scattering spectrometer probes (FSSP) mounted on the helicopter-borne turbulence probe Helipod are able to determine particle size distribution and concentration with high resolution and accuracy. Area-covering airborne measurements up-, mid, and down-stream of the installations quantify the aerosol loss within the wind park and are relevant for protection measures. The same flight strategy can quantify statistical and systematic errors of point measurements as performed for instant at the FINO1 research platform and enhance their area-representativeness. Such Helipod measurements were already performed in past field campaigns to verify or calibrate ground-based observations, remote sensing, and numerical atmospheric models. Similar Helipod flights near (off-shore) wind parks would improve the understanding of the atmospheric processes in the vicinity of the park and contribute to the reliability, stability, and life time of (future) installations.

1 Introduction

The use of wind energy in large wind parks is not only determined by mean wind yield and economically reasonable locations. Other important boundary conditions are the reduction of the wind yield due to rotor-blade icing and – important for future off-shore wind parks – damage to the wind converters due to sea-water aerosol. Atmospheric wind flow does not only transport matter like particles and droplets, but also turbulent energy in form of sensible heat H, latent heat E_L, mechanical momentum τ, and turbulent kinetic energy E_k. The content of matter and turbulent energy in the flow depends on low-troposphere parameters like surface roughness (sea waves, vegetation, etc.), spray, thermal stratification, mean wind vector, height above the surface, and others.

Some of these atmospheric boundary layer (ABL) quantities are already measured in or nearby wind parks. A good example is the recently raised FINO1 research platform in the German bight (NEUMANN et al. 2004). There are two main drawbacks of these ground-based measurement stations. To the author's knowledge, none of these stations observe all enlisted parameters with sufficient accuracy and temporal resolution. Also, these point measurements are not representative for entire regions or even three-dimensional flow volumes. But wind parks of noticeable size interact with the ABL flow on spatial length scales between a metre and several kilometres in addition to a wide time range. Recent investigations (KANDA et al. 2004; UHLENBROCK et al. 2004) demonstrated that mast and tower measurements at several altitudes as well as remote sensing (RADAR, SODAR, LIDAR) do not provide area representative observations of the ABL flow. This is especially valid for convective situations as usual above the sea. However, point measurements can become area-representative (BEYRICH et al. 2002a) after the comparison (calibration) with measurements that covered the area of interest in various conditions of the ABL.

The necessary in-situ and area-representative measurements are usually performed with low-flying research aircraft since satellite observations do not satisfy the accuracy requirements to date. Probably the world's most accurate and flexibly applicable airborne measurement system is the helicopter-borne turbulence probe Helipod. The application of such a system upstream, within, and downstream of a wind park would not only serve the tasks mentioned above. The entire interaction of a wind park with the ABL flow with all consequences to structures in the downstream region can be investigated during limited experimental case studies. Such new data will support the save, economical, and ecological operation of wind parks especially off-shore.

2 The Helipod

2.1 Measurement Technique

The Helipod is a unique meteorological measurement system, initially funded by the German government (BMBF) in 1994. The autonomously operating sensor package can be carried below almost any helicopter attached to rope of 15 m length (Fig. 1). At a typical air speed of 40 ms^{-1} the Helipod is outside the downwash area of the rotor blades. The Helipod itself is a container of about 5 m in length, 0.5 m in diameter, and 250 kg in weight (Fig. 2). It carries its own navigation systems, power supply, board computer, data storage, and fast responding sensor equipment. The system was especially designed for in-situ measurements of the turbulent fluctuations of wind, temperature, humidity, and the associated turbulent fluxes (e.g., BANGE et al. 2002; BANGE and ROTH 1999). In 2004 the Helipod was modernised and received a new board computer, cameras, and sensors for CO_2 and aerosol measurements.

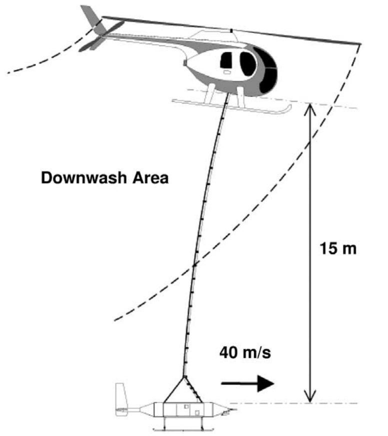

Fig. 1: The principle of the Helipod-flight: At a true airspeed of 40 ms^{-1} the system is out of the downwash area.

The modernised Helipod measures each meteorological parameter with at least two different types of instruments at a recording rate of 500 Hz which is equivalent to one measurement point every 8 cm. In addition the earth-surface temperature (visible and infra-red cameras), CO_2, and aerosols (see below) are measured. Due to its small fuselage and the absence of wings and propulsion, Helipod's influence on the atmosphere is small compared to an aeroplane. As a helicopter payload the Helipod is no subject to approval (e.g. aeronautical authorities) and is in general allowed to perform low-level flights at less altitude than aeroplanes.

The Helipod is demountable and can be transported in boxes around the world on a ship or by commercial aircraft. This makes missions in tropical areas or polar regions feasible. The system participated in several arctic expeditions since 1995. These missions, a speciality of the Helipod, were started from the helicopter deck aboard a research sea vessel e.g. the 'Polarstern' (Fig. 3).

The entire Helipod system is under the control of a single board computer with commercial industry components, temperature proofed to -30°C (PowerPC, MEN Company, Nürnberg, Germany). A real-time LINUX operating system controls the commercial input-/output modules. The choice of usual components saved money and will make future updates easier. The board computer communicates with 32 differential A/D-channels, the inertial navigation system, 8 GPS receivers and antennas for complete attitude alignment, and the flash-storage.

The aerosol measurements are realised with two external standard aviation pods which can be mounted on each side of the Helipod on demand. These pods include FSSP (Forward Scattering Spectrometer Probes) manufactured by the company PMS (Particle Measurement Systems, Boulder, USA) for the measurement of microphysical properties of small particles in the size range from 0.3 to 49 micron. The principle of operation of those probes was described in detail by BAUMGARDNER et al. (1992) and DYE und BAUMGARDNER (1984). The probes can easily be replaced by similar probes extending the size range up to 6.4 mm. The main advantage of this kind of probes in comparison to widely used in-housing aerosol counters is the measurement in the nearly undisturbed air.

These high sensitive optical probes have been designed especially for the use in aircraft to determine particle size distribution and concentration. Other parameters of interest, e.g. the volume distribution or effective radius, can be derived. The measurement principle is based on the scattered light produced by single aerosol particles moving through the laser beam in the sample volume. The amount of scattered light is a measure for particle size. In the given size range the probes must be able to detect scattered light in an order of more than 6 magnitudes. A world-wide new calibration technique has been developed at GKSS Research

Fig. 2: The Helipod ready for take-off during the LITFASS-2003 field campaign.

Centre Geesthacht. In addition manifold modifications have been done to the original PMS probes to improve measurement accuracy and system reliability and to guarantee the high accuracy of all determined parameters. A special data acquisition system samples single particles with 50 Hz which is equivalent to a spatial resolution of 80 cm. A sampling with 100 Hz is under development and will be carried out in spring 2005.

2.2 Field Experiments of the Past

Since its construction in 1994 the Helipod participated in several large meteorological field campaigns. The most important ship-borne campaigns were performed aboard the research vessel 'Polarstern' of the Alfred-Wegener Institute of Bremerhaven. During the ARK XI, XII, and XIX missions the Helipod completed about 60 hours of flight measurements above sea ice and open arctic sea water. Some goals of these campaigns were the observation of internal ABL near the ice edges, convection above polynyas and leads, and the stably stratified ABL (SBL) containing very small scaled turbulence over sea ice.

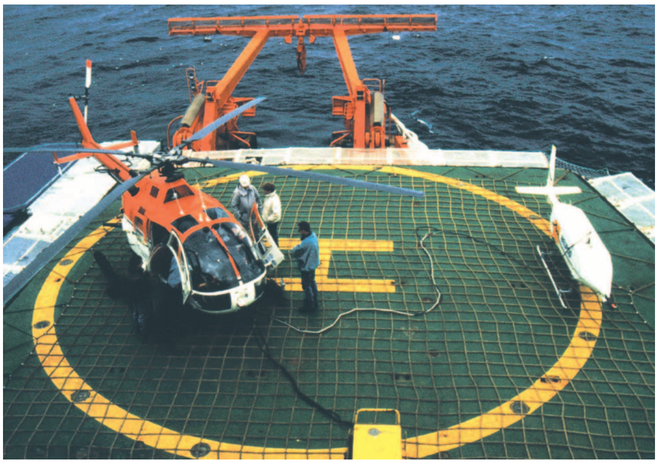

Fig. 3: Start preparation of the Helipod on the helicopter deck of the research vessel 'Polarstern'.

Most of the measurement flights above land surface were performed in the LITFASS area (BEYRICH et al. 2002b) between 1998 and 2003 (in total 110 measurement flight hours). The campaigns were completed within the framework of LITFASS and the German climate research (DEKLIM) and atmosphere research (AFO-2000) programs. The experiments included the work of about 20 different research groups who contributed with various experimental instruments and numerical models. Some of the flight goals were the initialisation and verification of numerical models of the atmosphere, the development of an averaging strategy for ground-based meteorological measurements, the verification of the involved remote sensing systems (RADAR, SODAR, LIDAR), turbulent fluxes, structures, statistics, and spectra, to name a few. The thinnest combined humidity and temperature layers ever observed were detected by the Helipod (SPIESS et al. 2004a). In a SBL the Helipod measured vertical temperature and humidity changes of remarkable 0.3 Kelvin per metre and 0.8 $g \cdot kg^{-1}$ per metre mixing ratio, respectively, beating its own record of 1995 (MUSCHINSKI and WODE 1998).

During LITFASS-2003 for the first time ever military jets of the German Airforce contributed to a meteorological field campaign. Helipod flights were used to calibrate large infra-red maps yield from Tornado reconnaissance flights over the LITFASS area (BANGE et al. 2004a). The Helipod joined also the field campaign PHELIX in a coastal region of California / USA (about 40 flight hours), a field campaign in the Baltic Sea (BALTEX), and some smaller experiments.

In-situ measurements with PMS probes of microphysical parameters not only of aerosol but also of clouds and precipitation have already been performed by GKSS since the late 80th. Members of the team participated in many national and international research projects. Based on the newly developed calibration technique they have worked for NASA and ESA and have been in demand for numerous field projects in the Arctic, the USA, Canada, Japan and several European countries.

3 Wind Park Experiments

After its modernisation (SPIESS et al. 2004b) the Helipod is ready for new ABL experiments. In addition to fundamental meteorological research it is intended to use the Helipod for wind energy applications. The new equipment with fast and accurate aerosol sensors suggests the investigation of convective and turbulent transport of matter and the interaction with wind parks. In the following some investigation goals are suggested. Generally, the measurements have to be performed at several altitudes within an area of several kilometres in diameter around a wind park. Various ABL conditions like thermal stratification, sea waves, wind direction and speed, etc. have to be studied. The content of turbulent energy in an atmospheric flow can be quantified by the variances of the air temperature T

$$\sigma_T^2 = \overline{T'^2} = \overline{\left(T - \overline{T}\right)^2},$$

and of the humidity q, and by the turbulent kinetic energy

$$E_k = \frac{\rho}{2} \cdot \overline{(u'^2 + v'^2 + w'^2)},$$

with air density ρ, and the three-dimensional wind components u, v, and w. The prime denotes the turbulent fluctuations, the over-bar the average over typically some kilometres. The vertical turbulent transport of the momentum, the sensible and latent heat are defined by the covariance with the vertical wind fluctuations w', i. e.

$$H = \rho c_p \overline{w'T'},$$

with the air heat capacity c_p at constant pressure. The atmospheric turbulence and its transport covers length scales from one millimetre up to several hundred metres, and time scales from some milliseconds to about one minute. The measurement of turbulent energy (H, E_L, τ, E_k) up- and downstream of the wind park quantifies the total loss and production of turbulence in the park at all relevant length scales. Low-level flights within the wind park quantify the effect of front-row wind converters on back-row installations. Prospectively, the results help with the planning of future wind parks (maximum lateral depth, optimum spacing between converters) by delivering high resolution input data for corresponding simulation software.

The transport of sea-water aerosol to wind parks at different low altitudes and under various conditions has effect on the life span of converter components. Due to their sub-micron scale aerosols mainly contribute to erosion processes in all parts of the power station. Beside the total quantity of aerosol losses in an off-shore park, the distribution of aerosol sizes is relevant for protection measures. The aerosol is transported by turbulent and convective structures from the sea spray into the ABL. The influence of the thermal stratification, sensible and latent heat fluxes, momentum flux, and turbulent kinetic energy of the ABL flow on the aerosol formation and transport above sea is an important topic and not much investigated up to now.

Due to comprehensible reason, it is not possible to investigate the lower atmosphere with research aircraft in icing conditions. But the Helipod is equipped with aerosol probes that target the small pre-condensation particles which may contribute to the formation of super-cooled droplets in fog and precipitation and therefore to icing. Thus a suited field experiment focuses on the ABL conditions before icing occurs. Beside air humidity, aerosol sizes, and above mentioned ABL parameters the heating and cooling of the air flow at the height of the converter rotors due to turbulent sensible and latent heat fluxes are of great interest. A cooperative investigation is flight experiments in comparison with tower measurements as e.g. performed at the

FINO1 research platform. Such measurement flights with respect to the tower have two main goals:

1. The identification and quantification of systematic tower measurement errors at different levels. For instance NEUMANN et al. (2004) report disturbing effects of the tower and platform structures on the tower measurements.
2. The representativeness of tower measurements for a large area such an off-shore wind park. The problem of non-representative tower measurements especially in a convective ABL (as usual above the sea) was also investigated using high-resolving numerical simulations (KANDA et al. 2004; UHLENBROCK et al. 2004). Under stable stratification the dependence on the measurement location is even larger.

The Helipod was already deployed in several field experiments especially in LITFASS in order to provide area-representative data. These data were used to develop averaging-strategies for ground-based measurements (BANGE et al. 2004b; SPIESS et al. 2004c), for remote sensing verification, and for the initialisation of numerical models of the atmosphere. Similar data could seriously contribute to a better understanding of meteorological and chemical processes in the surrounding of wind power fields and could help to increase station reliability and power production stability as well as wind turbine life time.

4. References

Bange, J., F. Beyrich, D. A. M. Engelbart, 2002: Airborne Measurements of Turbulent Fluxes during LITFASS-98: A Case Study about Method and Significance. *Theor. Appl. Climatol.*, **73**, 35–51.

Bange, J., R. Roth, 1999: Helicopter-Borne Flux Measurements in the Nocturnal Boundary Layer Over Land -a Case Study. *Boundary-Layer Meteorol.*, **92**, 295–325.

Bange, J., S. Wilken, T. Spieß, P. Zittel, 2004a: Calibrated Surface Temperature Maps of Heterogeneous Terrain Derived from Helipod and German Air Force Tornado Flights during LITFASS-2003. In: *4th Study Conference on BALTEX*, Bornholm, Denmark, S. 39–40, 39-40.

Bange, J., P. Zittel, T. Spieß, J. Uhlenbrock, 2004b: A New Method for the Determination of Area-Averaged Turbulent Surface Fluxes from Low-Level Flights Using Inverse Models. *Boundary-Layer Meteorol.*, submitted.

Baumgardner, D., J. E. Dye, B. W. Gandrud, 1992: Interpretation of Measurements made by the Forward Scattering Spectrometer Probe (FSSP-300) during the Airborne Arctic Stratospheric Expedition. *J. Geophys. Res.*, **97, D8**, 8035 – 8046.

Beyrich, F., F. Berger, H. de Bruin, T. Foken, W. Kohsiek, S. Richter, U. Weisensee, 2002a: Experimental Determination of Turbulent Fluxes over the Heterogeneous LITFASS Area -Selected Results from the LITFASS-98 experiment. *Theor. Appl. Climatol.*, **73**, 19–34.

Beyrich, F., H.-J. Herzog, J. Neisser, 2002b: The LITFASS Project of DWD and the LITFASS-98 Experiment: The Project Strategy and the Experimental Setup. *Theor. Appl. Climatol.*, **73**, 3–18.

Dye, J. E., D. Baumgardner, 1984: Evaluation of the Forward Scattering Spectrometer Probe. Part I: Electronic and Optical Studies. *J. Atm. Ocean. Tech.*, **1**, 329 – 344.

Kanda, M., A. Inagaki, M. O. Letzel, S. Raasch, T. Watanabe, 2004: LES Study of the Energy Imbalance Problem with Eddy Covariance Fluxes. *Boundary-Layer Meteorol.*, **110**, 381–404.

Muschinski, A., C. Wode, 1998: First In-Situ Evidence for Co-Existing Sub-Meter Temperature and Humidity Sheets in the Lower Free Troposphere. *J. Atmos. Sci.*, **55**, 2893–2906.

Neumann, T., K. Nolopp, K. Herklotz, 2004: First Operating Experience with the FINO1 Research Platform in the North Sea. *DEWI Magazin*, **24**, 27–34.

Spieß, T., P. Zittel, J. Bange, 2004a: Analysis of Flat Convection during the Morning Boundary Layer Transition using Airborne Measurements. In: *16th Symposium on Boundary Layers and Turbulence*, AMS, Portland/Maine, USA, P4.17, 9 pp.

Spieß, T., P. Zittel, J. Bange, 2004b: The Helicopter-Borne Turbulence Probe Helipod -Considerations and Improvement. In: *4th Annual Meeting of the European Meteorological Society*, EMS, Nice, France.

Spieß, T., P. Zittel, J. Bange, 2004c: The Role of the Helicopter-Borne Turbulence Probe Helipod in Joint Field Campaigns. In: *AMS: Eighth Symposium on Integrated Observing and Assimilation Systems for Atmosphere, Oceans, and Land Surface*, AMS, Seattle, USA, P7.6, 6 pp.

Uhlenbrock, J., S. Raasch, B. Hennemuth, P. Zittel, W. Meijninger, 2004: Effects of Land Surface Heterogeneities on the Boundary Layer Structure and Turbulence During LITFASS-2003: Large-Eddy Simulations in Comparison with Turbulence Measurements. In: *16th Symposium on Boundary Layers and Turbulence*, AMS, Portland/Maine, USA, 9.3.