Atmos. Meas. Tech. Discuss., 2, 1143–1160, 2009
www.atmos-meas-tech-discuss.net/2/1143/2009/

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Design and performance of an automatic regenerating adsorption aerosol dryer for continuous operation at monitoring sites

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Received: 9 April 2009 – Accepted: 10 April 2009 – Published: 23 April 2009

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Sizes of aerosol particles depend on the relative humidity of their carrier gas. Most monitoring networks require therefore that the aerosol is dried to a relative humidity below 50% RH to ensure comparability of measurements at different sites. Commercially available aerosol dryers are often not suitable for this purpose at remote monitoring sites. Adsorption dryers need to be regenerated frequently and maintenance-free single column Nafion dryers are not designed for high aerosol flow rates. We therefore developed an automatic regenerating adsorption aerosol dryer with a design flow rate of 1 m^3/h. Particle transmission efficiency of this dryer has been determined during a 3 weeks experiment. The lower 50% cut-off was found to be below 3 nm at the design flow rate of the instrument. Measured transmission efficiencies are in good agreement with theoretical calculations. One drier has been successfully deployed in the Amazonas river basin. From this monitoring site, we present data from the first 6 months of measurements (February 2008–August 2008). Apart from one unscheduled service, this dryer did not require any maintenance during this time period. The average relative humidity of the dried aerosol was 27.1+/−7.5% RH compared to an average ambient relative humidity of nearly 80% and temperatures around 30°C. This initial deployment demonstrated that these dryers are well suitable for continuous operation at remote monitoring sites under adverse ambient conditions.

1 Introduction

Diameters of aerosol particles, and thereby their physical and optical properties, depend on the relative humidity of the carrier gas (e.g. Mozurkewich, 1986; Ten Brink et al., 2000; Wex et al., 2006). To investigate aerosol effects on climate it would be desirable to measure physical and optical properties at ambient relative humidity. This would either require to avoid any temperature (and thereby relative humidity) change during the transport from ambient air to the measurement volume or the reconditioning of the aerosol to ambient relative humidity prior to the measurement. The latter approach has been implemented in research grade instruments like the Hygroscopicity Tandem Differential Mobility Analyzer (HTDMA) but most commercially available instruments used at monitoring sites are not designed to preserve atmospheric humidity conditions (e.g. due to internal heating by electronic components). In many instruments, the reduction of relative humidity is even desired to avoid condensation of water vapour on internal surfaces. Consequently intercomparison of aerosol parameters from different measurement sites under different humidity conditions was difficult in the past.

With the establishment of major measurement networks like the Global Atmosphere Watch (GAW) program of the World Meteorological Organization (WMO) or the European Supersites for Atmospheric Aerosol Research (EUSAAR) and many others this problem needed to be solved. Because aerosol growth starts typically above a relative humidity of 50% RH a common approach is to measure the aerosol below this threshold level (Baltensperger et al., 2003). The philosophy is therefore to conduct the measurements at low relative humidity conditions to be comparable between different sampling sites. Especially under warm and humid conditions active drying of the aerosol is necessary to achieve this goal.

Currently three methods are used to condition the aerosol to the required relative humidity.

A first approach is to heat the aerosol. Aerosol temperature must, however, be kept low because e.g. up to 20% of ammonium nitrate evaporate from the aerosol within 5 s at a temperature of 42°C (Bergin et al., 1997). Losses at 50°C were observed comparing filter based measurements with TEOM derived mass concentrations (Cyrys et al., 2001; Charron et al., 2004). This method of aerosol drying is therefore primarily suitable for cold and dry regions, where mild heating at 30°C is sufficient to condition the aerosol to the required relative humidity.

Presently, semi-permeable tubes (Nafion®, Wilmington, DE) are used for aerosol drying. Because of the small diameter of commercially available single Nafion tubes these dryers are only suitable for aerosol flow rates up to 2 l/min. They should not be used at higher flow rates to avoid turbulent deposition of particles in the dryer. Commercially available bundles of 50–100 single tubes, capable of handling higher flow rates, are designed to dry gases. Used for aerosol drying, these dryers suffer from impaction losses on the faceplate of the bundles, and a pressure drop of several 10th of hPa depending on the flow rate.

Diffusion dryers using chemical adsorbents such as Silica gel are designed with respect to minimization of aerosol losses at high flow rates. In these dryer, the chemical adsorbent needs to be exchanged and regenerated on a regular basis. This is, however, often not feasible at remote monitoring sites that are not permanently manned.

We therefore developed an automatically regenerating chemical adsorption dryer for long-term measurements of aerosol properties. Here, we present the design and performance of this automated aerosol diffusion dryer.

2 Design and operation of the automated aerosol diffusion dryer

The aerosol dryer is housed in a separate shelter which can be deployed on the roof of a measurement laboratory (Fig. 1). This shelter may either be air conditioned or kept at laboratory temperature by active ventilation from the laboratory. All parts of the dryer in contact with the aerosols are made of stainless steel to reduce losses of small particles due to image forces. All aerosol ducts are optimized for minimal losses at an aerosol flow rate of 1 m^3/h. For this purpose, 3/4" tubing with minimal bends is used for aerosol ducts outside the actual dryer columns. A scheme of the dryer is shown in Fig. 2. The whole assembly consisting of the dryer and the shelter weighs about 160 kg.

Aerosol enters the shelter through a commercially available PM_{10} inlet. Subsequently, it is fed to one of two parallel stainless steel columns with an inner diameter of 70 mm and a total length of 800 mm. Each of these columns if filled with approximately 11 kg of Silica gel and houses seven aerosol ducts made of stainless steel mesh with an inner diameter of 10 mm. In operation, one of these columns is used for aerosol drying, while the other column is regenerated at ambient pressureby dry air supplied from compressed air with a very low dew point temperature. For this purpose, each column can be shut on top and bottom by motor actuated ball valves Bv1 or Bv2 (EKN 3/4 -020-L020, Bahr GmbH, Dattenberg, Germany). These ball valves feature a straight 3/4" bore to minimize aerosol losses. During regeneration, the dry air is flushed through the column separated from the atmosphere using the magnetic valves V1/2 or V3/4, respectively (type 6013, Christian Bürkert GmbH & Co. KG, Ingelfingen, Germany).

For our employment, we use a scroll compressor with active water removal (Mark 3 OFMS 2SD, MET Technology Ltd, Stockport, Great Britain) providing up to 14.4 m^3/h of dry air for the regeneration of the Silica gel. The dew point temperature of the air is additionally reduced by an automatic adsorption dryer (DAZ5, Boge Int. GmbH, Bielefeld, Germany).

Temperature and relative humidity of the dried aerosol, the currently regenerating column, and the shelter are constantly measured by 3 RH/T sensors (HIH-4602-C, HyCal Sensing Products, El Monte, CA) using a National Instruments data acquisition board type USB-6009 (National Instruments, Austin, TX). Analog output signals from this board are used to drive the actuators of the valves. Operation of the aerosol dryer is controlled by a custom made LabView program (LabView 8.5, National Instruments, Austin, TX). A flow diagram of the control program is shown in Fig. 3.

This program initiates a column switch, if the set-point for the aerosol humidity is exceeded and the last change of the columns has been longer ago than the set minimum time (This time has been implemented to avoid extensive switching of the columns). When a column change is initiated magnetic feed valves for the dry air are closed first. Then both magnetic exhaust valves are opened to avoid any pressure change in the aerosol line after the dryer. In the next step, the ball valves of the freshly regenerated column are opened. Only after these ball valves are fully open the ball valves of the used column are closed, its magnetic exhaust valve is opened and the feed valve is opened starting the regeneration process. This sequence minimizes dilution effects during column change and avoids pressure fluctuations, which would cause unwanted peaks in filter based aerosol measurements.

Temperature and humidity measured by all sensors are logged every 10 min along with information on the column in use. An additional record is written after each column change.

3 Performance

3.1 Aerosol losses in the dryer

A major concern in the design of an aerosol dryer is minimization of aerosol losses in the system. The design of this dryer has been optimized towards this goal. We measured particle losses under ambient conditions during a 3 weeks field campaign in Melpitz, Germany. During this campaign, we attached a vertical 3/4” inlet tube and the aerosol dryer to the same Twin DMPS system (Birmilli et al., 1999) measuring the number size distribution in the size range from 3 to 800 nm. Both inlets were equipped with commercially available PM_{10} sampling heads and operated at an aerosol flow rate of 1 m^3/h. Automatic ball valves were used to switch between both inlets after each 10 min measurement of one number size distribution.

Three week average raw particle number size distributions measured during this experiment with and without aerosol dryer are shown in Fig. 4. The blue represent the average raw concentrations per size channel without aerosol dryer, the green triangles represent the respective measurements with the aerosol dryer. Errors bars shown in this figure are Poisson errors due to counting statistics.

Figure 5 presents the transmission efficiency of the aerosol dryer derived from these number size distributions. Here, the black dots represent the actual measurements along with their Poisson error. The additional red curve shows the calculated transmission efficiency including diffusion, sedimentation and impaction losses calculated using Paul Baron’s Aerocalc. Both, measured and calculated transmissions are in good agreement for the flow rate of 1 m^3/h (R^2=0.96) used in this experiment.

We found a transmission efficiency of 72% for 3 nm particles increasing to 92% for

10 nm particles. The lower 50% penetration diameter was below at 3 nm. Losses of particles larger than 800 nm could not be determined experimentally in this experiment. Calculated losses for larger particles in the dryer suggest an upper 50% penetration diameter of 6000 nm.

Based on this experiment, we calculated transmission efficiencies for different aerosol flow rates. The lowest usable flow rate with a penetration efficiency of 50% for 3 nm particles was found to be 5 l/min. Lower flow rates can only be used if nano-particles are not measured using this dryer. With increasing aerosol flow rate, the lower penetration diameter shifts towards smaller particles. Note, however, that drying performance will decrease with increased aerosol flow rates.

3.2 Drying performance

So far seven dryers of this type are deployed world-wide. One of the most challenging sites for such an instrument is located in the rainforest of the Amazonas river basin about 50 km off the city of Manaus. Typical monthly average temperatures at this site range from 24 to 33°C with a daily average relative humidity of up to 90%.

The first dryer was installed at this site in the context of the European Integrated project on Aerosol Cloud Climate and Air Quality Interactions (EUCAARI). The average ambient temperature from February 2008 through August 2008 was 30.3+/−2.3°C with a relative humidity of 78.5+/−3.9%. Note that the actual relative humidity of the ambient aerosol was even higher because the "ambient" humidity sensor is mounted inside the shelter of the dryer. There exhaust air from the regeneration process of the columns is used to lower the humidity inside the shelter in order to protect the electronics of the system from water condensation.

During the experiment, the average relative humidity of the dried aerosol was 27.1+/−7.5%. The time series of the dried aerosol (red) and of the humidity inside the shelter (orange) during this experiment is shown in Fig. 7. Missing data in March 2008 were due to a compressor failure caused by overheating. To avoid such failures the compressor housing has been modified and can now be actively ventilated. A closer look at the time series of relative humidity (Fig. 8) with target aerosol humidity set to 30% reveals that in the beginning the dryer was operating close to its design limits. The columns were switched every 60 min (set minimum time). This time was, however, not sufficient to finish the drying process of the regenerating column. Nevertheless, aerosol humidity stayed well below 50% throughout the whole time period. To avoid operation of the dyer close to the limits of the dryer the set-point for the target humidity was increased to 40% and minimum time between column changes was increased to 120 min allowing for better drying of the columns during regeneration. After these changes, the dryer performed adequately and we did not encounter further problems with its drying capacity.

All other aerosol dryers, deployed in less challenging environments, have performed as well or better. There was no scheduled maintenance during the time period of 6 months. Some unscheduled repair and modification was, however, necessary because of the overheating of the compressor.

4 Summary and conclusions

We designed a new automatic dryer and showed a satisfying performance under adverse environmental conditions. The relative humidity of the aerosol at the most challenging site never exceeded design values. Operational parameters of the system needed, however, to be set according to site requirements. Routine maintenance of the system requires however little effort, which makes these aerosol inlet dryers suitable to be operated at remote continuous monitoring sites.

Aerosol losses in the system were measured using atmospheric aerosol. Observed transmission efficiencies agree well with theoretical calculated values. Operated at the design flow rate aerosol penetration efficiency reaches approximately 100% in the size range from 20 nm to 800 nm. The lower 50% penetration diameter was below 3 nm at the design flow rate of 1 m^3/h, while the calculated upper one is around 6000 nm.

Due to its dimensions, this aerosol dryer may not be suitable for all remote measurement sites. The shelter needs to be placed on a flat roof capable of carrying the weight of both the instrument and an operator. Furthermore, a compressor for the regenerating air needs sufficient three phase power supply. If these requirements for a deployment can be met, installation of such a dryer system will improve the comparability of measurements in an aerosol network.

Acknowledgements. The authors wish to thank all operators of the dryers at the sites for their contributions. We wish to acknowledge the skills of the mechanics in our mechanical workshop who helped to build the dryers.

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Fig. 1. Aerosol dryer deployed at Elandsfontein, RSA.

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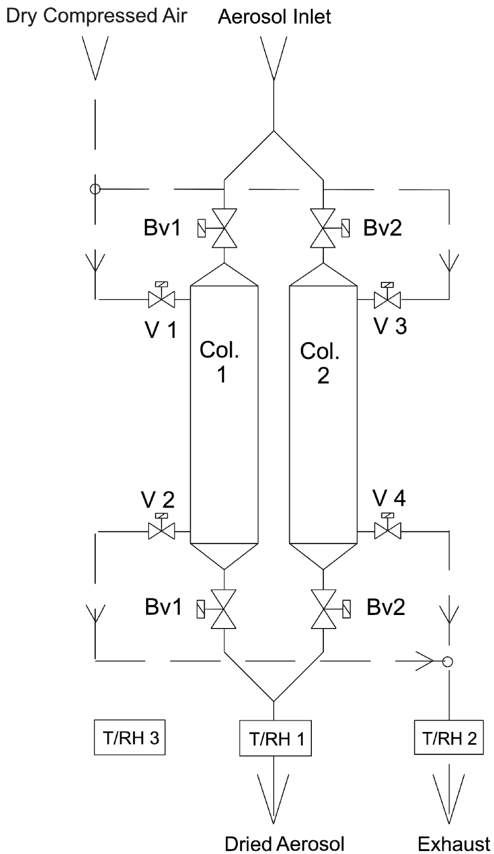

Fig. 2. Schematical view of the aerosol dryer.

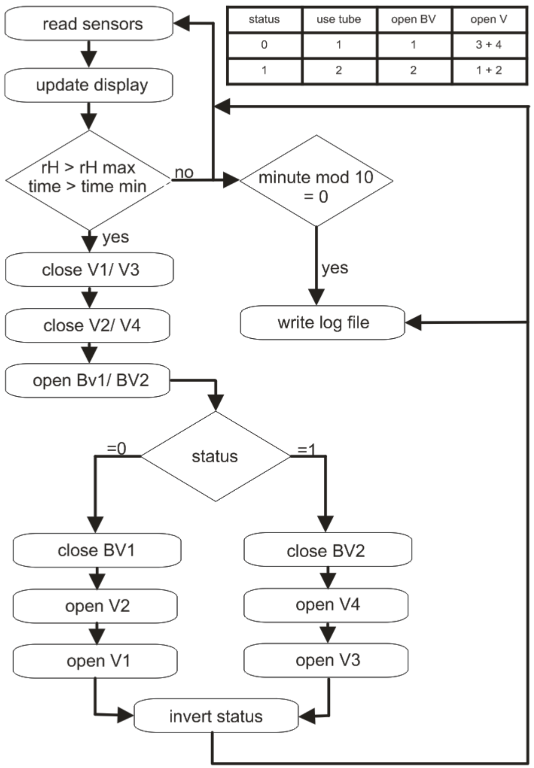

Fig. 3. Flow diagram of the control program for the dryer.

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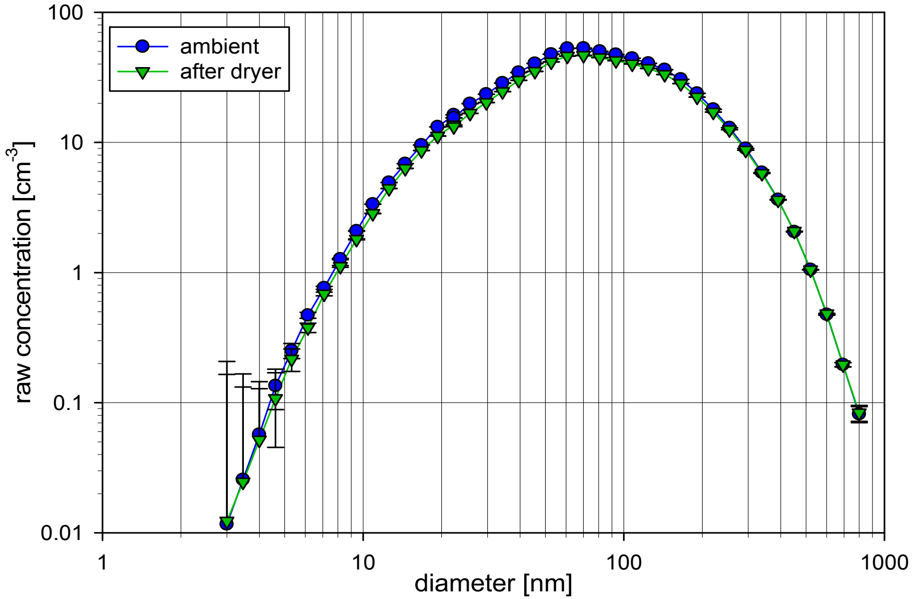

Fig. 4. Average size distribution during field intercomparison.

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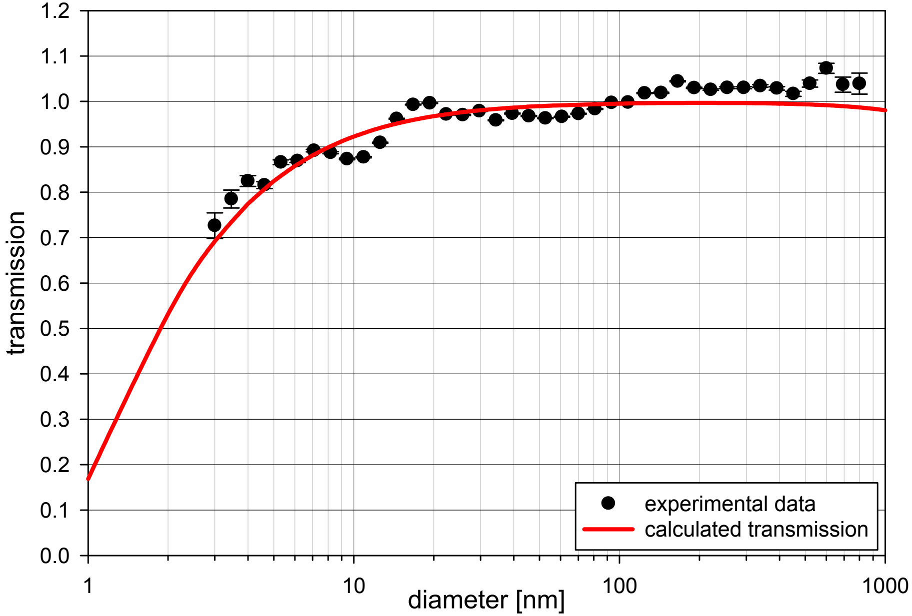

Fig. 5. Size dependent transmission of the aerosol dryer (measured and calculated) at 16.7 l/min.

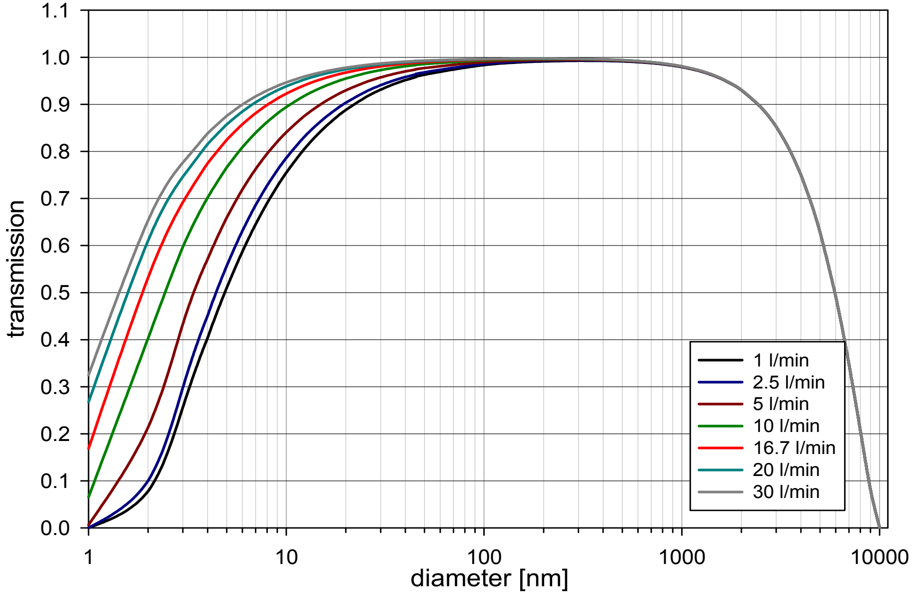

Fig. 6. Size dependent transmission of the dryer, calculated curves for air flow rates from 1 to 30 l/min.

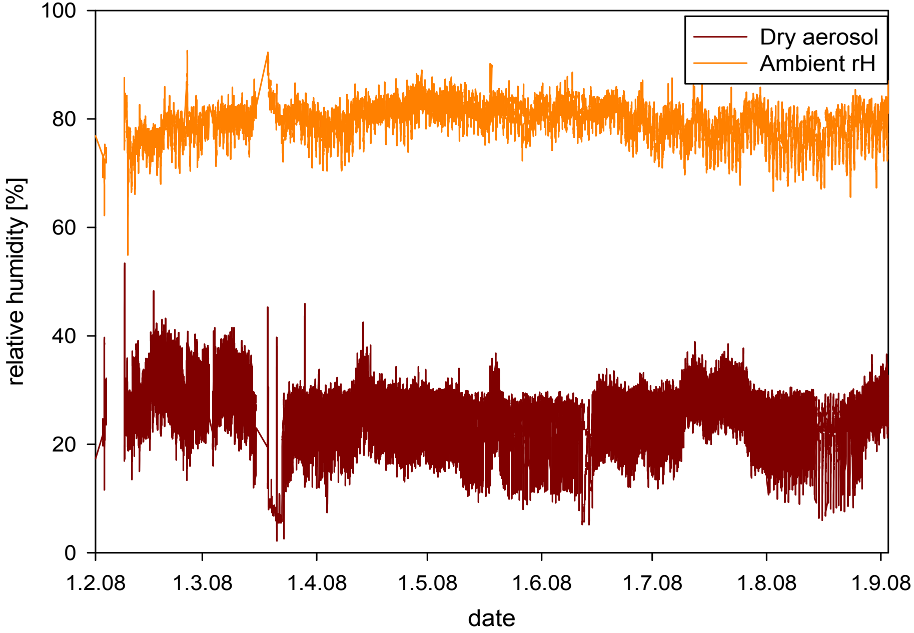

Fig. 7. Dryer performance at Manaus station.

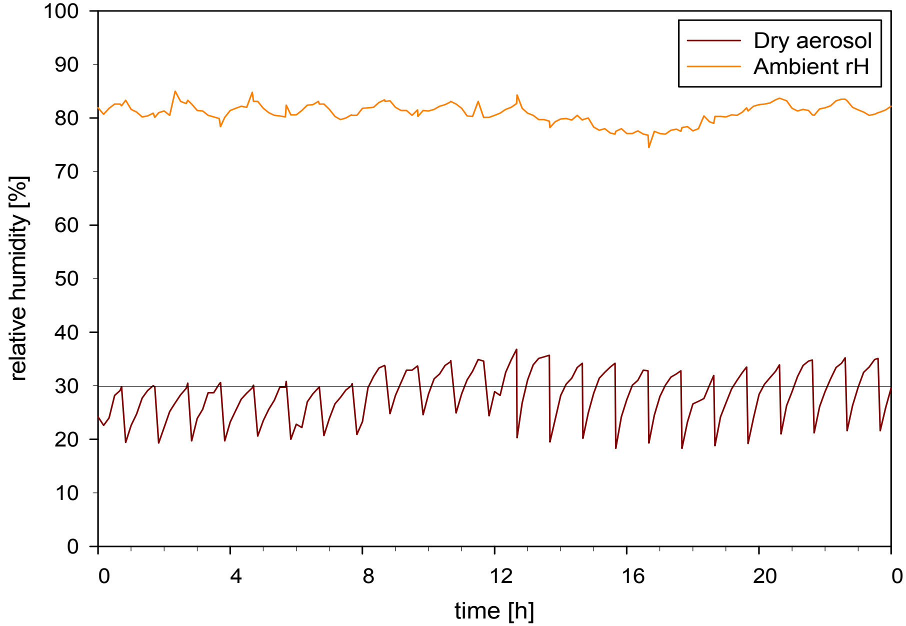

Fig. 8. Diurnal variation of ambient and aerosol humidity in the Amazonas basin (Example 13 April 2008 with dryer at design limits around noon).