ON THE COLLECTION EFFICIENCY OF A ROTATING ARM COLLECTOR AND ITS APPLICABILITY TO CLOUD- AND FOGWATER SAMPLING

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Abstract—A Rotating Arm Collector (RAC) belonging to the class of (virtual) wide stream impactors is designed and operated to sample cloud or fog droplets. The applicability of RACs to sample atmospheric aerosol particles or fog/cloud droplets larger than about 5 μm is demonstrated by discussing their working principle in detail and comparing their sampling characteristics with impactors requiring an inlet. The specific properties of the flow past the sampling units of RACs, especially the variation of the flow velocity along the sampling area results in a dependence of the collection efficiency on the distance to the axis of rotation. This is remarkable when operating a RAC to collect cloud or fog droplets, because drops flow together after sampling. A method is developed which determines the overall collection efficiency of the sampling units experimentally. The resulting collection efficiency curve is compared with simplified theoretical evaluations of the collection efficiency of flat plates (Langmuir and Blodgett, *Collected Work of Irving Langmuir* 10, pp. 348–393. Pergamon Press, Oxford, 1946) and the collection efficiency of the gutter-formed sampling areas used in this study (Lesnic *et al.*, *J. Aerosol Sci.* **24**, 163–180, 1993). The agreement between experiment and theory is good, showing that the main characteristics of wide stream impaction are not affected by the complex flow field past the sampling units of the RAC and thus the simplified theory is an acceptable approach to describe the real sampling conditions.

1. INTRODUCTION

In the last decades plants, soils and consequently waters were affected by the deposition of fog and cloud droplets containing noxious chemical substances and therefore many studies on the chemical composition of cloud- and fogwater have been performed. The appropriate sampling of the droplets in fog or clouds is a basic requirement for a meaningful interpretation of the subsequent chemical analysis. Various types of fogwater samplers have been used, for example jet impactors, active and passive string collectors and Rotating Arm Collectors (RACs).

RACs were operated both for the sampling of atmospheric aerosol particles (Jaenicke and Junge, 1967; Noll, 1970; Jaenicke and Matthias, 1988) and fog or cloud droplets (Mack and Pillie, 1975; Jacob *et al.*, 1984; Schmitt, 1986; Krämer *et al.*, 1991). Based on the principle of inertial impaction, they are known to be particularly applicable to sample particles or droplets larger than 5 μm radius (Garland and Nicholson, 1991) without the problems typical for impactors that require an inlet, like jet impactors. Nevertheless, they are often criticized (Collet *et al.*, 1990) because the only gradually increase of the collection efficiency for smaller particles or with regard to their mechanical stability. To clarify again the applicability of RACs, especially to the sampling of droplets, their working principle will be discussed here in detail and compared with that of jet impactors.

The theoretical treatment of the collection efficiency of RACs is difficult and therefore up to now insufficient. Several properties of the flow past the sampling units are difficult to describe theoretically, for example the calculations of Langmuir and Blodgett (1946) and Lesnic *et al.* (1993) are restricted to two-dimensions but the sampling properties of a RAC change in the third dimension, i.e. along the plane of the sampling area.

When a RAC is operated to sample cloud- or fogwater, the drops flow together after sampling and therefore only the overall collection efficiency over the whole sampling area is relevant. The overall collection efficiency of a RAC designed and operated to sample cloud- or fogwater is determined in this study experimentally to find out if the simplified theoretical calculations mentioned above are applicable to Rotating Arm Fogwater Collectors.

2. APPLICABILITY OF THE RAC TO SAMPLE CLOUD- OR FOGWATER

2.1. *Requirements on a fogwater collector*

Fogwater samplers should sample only the droplets and not the aerosol particles not activated to drops (interstitial aerosol particles), thus they must have the appropriate size cut. Even if only a fraction of the interstitial particles are sampled, the chemical composition of the bulk sample of drops can be strongly influenced. Therefore, the size cut should be adjusted according to the droplet spectrum in the air. Figure 1 (curve 2) shows a model simulation of a typical droplet spectrum of fog formed over a rural area (Bott, 1991). Measurements of Garland (1971), Jiusto and Lala (1983), Jacob et al. (1984) and Borrmann and Jaenicke (1993) correspond with these calculations. The size of the droplets varies between 5 and 20 μm radius with a maximum at 12 μm. If a bulk sample of droplets is required, the collector should sample ideally all the drops contained in the spectrum. In other words:

• a fogwater sampler should have a steep collection efficiency curve,
• no losses or overloading of drops should occur during sampling,
• once sampled, the drops should be transmitted rapidly into a closed vessel so that evaporation or condensation of the sampled drops is avoided,
• the flow rate of the sampler should be known.

Because of the low concentration of droplets in the atmosphere, a high flow rate is a desirable but not a necessary requirement for a fogwater collector. If a collector fulfils all other demands, several samplers can be used to obtain a sufficient amount of cloud- or fogwater for the subsequent chemical analysis. The survey of the conditions on fogwater collectors is in accordance with Enderle and Jaeschke (1991).

In the present study a Rotating Arm Collector (RAC) was chosen as fogwater collector and in the next section its applicability to droplet sampling is described.

2.2. *Working principle of the RAC*

The arm of the collector consists of a rod with a revolving sampling unit at each end and the rod is fixed on the axis of a motor. Rotation of the arm causes a flow to the sampling units, which are composed of a gutter-shaped sampling area and a bottle (see Fig. 2). The system is mounted on a 2 m high three-legged stand and permanently faces the wind by the use of a weather vane.

Since inside the gutter there is no exit for the flow, the sampling area can be considered as a virtual impaction plate (see Fig. 3). Droplets in the oncoming flow with high enough
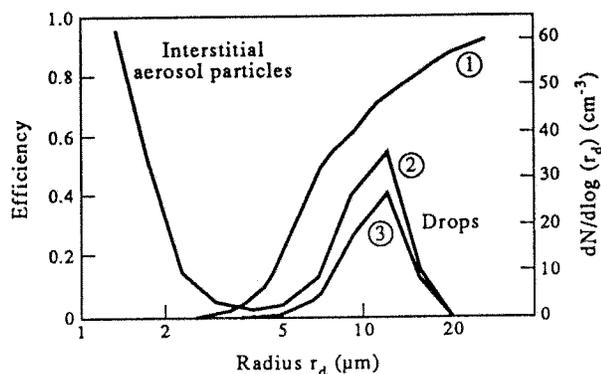

Fig. 1. Typical spectrum of fog droplets and the desired collection efficiency curve of the RAC. Curve 1 (left scale): collection efficiency of a flat plate, $r_{50} \sim 7$ μm, calculated by Langmuir and Blodgett (1946); Curve 2 (right scale): droplet spectrum calculated by Bott (1991); Curve 3 (right scale): sampled drops (from 1 and 2); r_d: droplet radius.

inertia penetrate into the gutter. Once in the gutter most of the drops glide into the bottles very quickly due to the centrifugal force while some droplets leave the gutter again as shown by Lesnic *et al.* (1993).

The RAC faces the wind and its sampling units are revolving as the direction and velocity of the flow $\vec{u}$ to the sampling units depends not only on the flow $\vec{v}$ caused by the rotation of the rod, but also on the wind $\vec{w}$ in the atmosphere (Jaenicke, 1964; Jaenicke and Junge, 1967). In Fig. 4a the relation between $\vec{u}$, $\vec{v}$ and $\vec{w}$ is demonstrated and it is important to note that the velocity of the rotational flow $|\vec{v}|$ varies along the sampling area. In the following a cross-section of the sampling area (Fig. 4b), where $|\vec{v}|$ is constant, is considered in order to simplify matters. It is seen that the angle α of the flow $\vec{u}$ to the sampling areas varies with the actual wind $\vec{w}$. This can cause errors in the concentration of the sampled droplets comparable to the aspiration errors of an inlet of a jet impactor (see section 3.1.1).

Facing the RAC into the wind keeps the direction of the actual wind $\vec{w}$ perpendicular to the plane of rotation of the RAC. The angle α is then dependent only on the varying wind velocity $|\vec{w}|$ as the direction of $\vec{w}$ and both the direction and the velocity of the flow $\vec{u}$ are constant. Revolving the sampling area so that the flow $\vec{u}$ is perpendicular to it gives the optimal sampling conditions. According to Fig. 4b the angle α can be determined along with $\tan \alpha = \dfrac{|\vec{w}|}{|\vec{v}|}$, so that

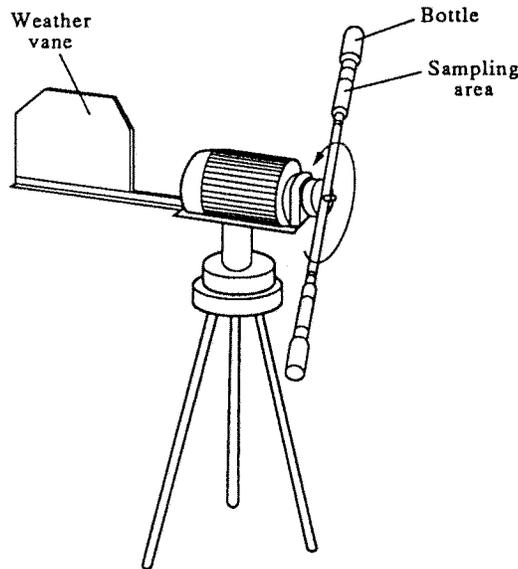$$\alpha = \arctan \frac{|\vec{w}|}{|\vec{v}|} . \tag{1}$$

Weather vane

Bottle

Sampling area

Fig. 2. Schematic diagram of the RAC.

Free flow

Gutter

Virtual impaction plate
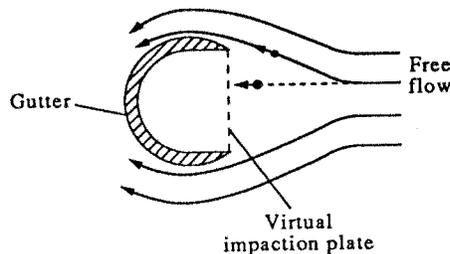
Fig. 3. Streamlines and particle trajectories past a cross-section of the sampling area.
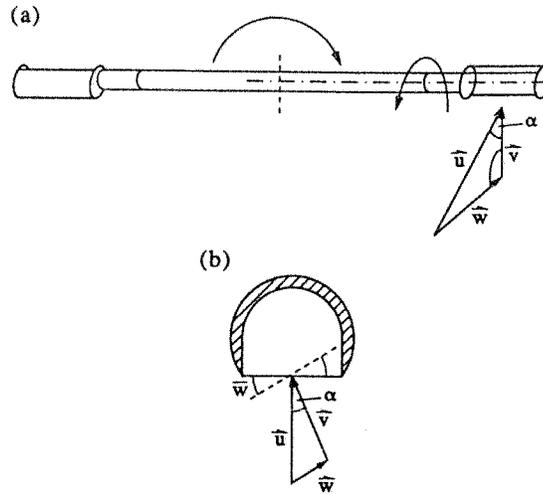
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Fig. 4. Adjustment of the angle of the sampling units to the actual wind ($\vec{w}$: wind in the atmosphere; $\vec{v}$: flow caused by the rotation of the rod; $\vec{u}$: flow to the sampling unit). (a) Perspective view; (b) cross-sectional view.
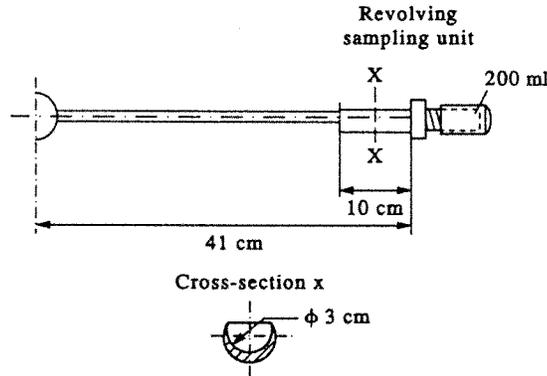

Fig. 5. Dimensions of the RAC.

The varying wind velocity $|\vec{w}|$ influences not only the direction but also the velocity of the flow $\vec{u}$ to the sampling area as

$$|\vec{u}| = \sqrt{|\vec{v}|^2 + |\vec{w}|^2}. \tag{2}$$

Therefore the collection efficiency and the flow rate of the RAC varies with the actual wind velocity $|\vec{w}|$. However, Jaenicke (1964) showed that these variations are negligible for wind speeds $|\vec{w}|$ smaller than about $5\,\mathrm{m\,s^{-1}}(\rightarrow|\vec{u}|\approx|\vec{v}|)$, which are frequently observed in fog. Nevertheless, the variation of the angle α is not negligible in this range of speeds.

It should be noted that, regarding the three-dimensional sampling area, the angle α varies along the sampling area together with $|\vec{v}|$.

Under field conditions the angle α was adjusted to the speed $|\vec{v}|$ in the middle of the sampling area and to the average wind speed $\overline{|\vec{w}|}$ based on the hour before the measurement took place and were adjusted hourly during the sampling period.

2.3. Technical data of the RAC

To determine the RAC parameters necessary to obtain the desired size cut between the interstitial aerosol particles and the droplets, a theoretically-calculated collection efficiency curve for a flat plate with a cut-off radius (r_{50}: this is the size of the particles where 50%

of them are sampled) at about 7 μm (Langmuir and Blodgett, 1946; see Fig. 1, curve 1) is used.

The Stokes number, a parameter which describes the inertia of a particle, is defined as:

$$\mathrm{Stk} = \frac{2r_p^2 \rho_p |\vec{u}|}{9\eta r_k}, \tag{3}$$

where r_p is the radius of the particle; ρ_p is the density of the particle; η is the viscosity of the air; r_k is the characteristic width of the sampling area.

From Fig. 1 it is seen that the cut-off Stokes number is 0.79 and the RAC is designed in order to obtain this cut-off as follows (see Fig. 5):

length of the arm (without bottle):	41 cm
length of the sampling area:	10 cm
width of the sampling area:	3 cm
sampling area:	$b = 30$ cm^2
frequency of revolution ω:	variable, up to 10 s^{-1}
flow speed:	$|\vec{u}| = 2 \cdot \pi \cdot R \cdot \omega$
	(R: distance to the axis)
flow rate (per bottle):	$q = b \cdot |\vec{u}|$.

For a frequency of revolution $\omega = 8$ s^{-1} ($\rightarrow |\vec{u}| = 18.1$ m s^{-1} at $R = 36$ cm) and a droplet density $\rho_d = 1.0$ g cm^{-3} the cut-off radius of the RAC becomes 7.3 μm and the flow rate yields about 390 m^3 h^{-1} for the two gutters (in fog with a typical liquid water content of 0.1 g m^{-3} about 40 ml h^{-1} fogwater is sampled, and this is sufficient for chemical analysis). Under these conditions the centrifugal force is almost 100 times the force of gravity and the Reynolds number of the flow, defined as $\mathrm{Re} = 2r_k \rho_{air} |\vec{u}|/\eta$, is about 36,000. Note, these values are valid only in the middle of the sampling area and they, together with the flow velocity $|\vec{u}|$, vary along the gutter.

2.4. Discussion of the sampling characteristics of the RAC

The RAC belongs to the (virtual) wide stream impactors (see Fig. 3), where particles or drops are impacted at an obstacle in a free stream (Fuchs, 1964). Their collection properties are different from jet impactors, where the particle loaded air stream is led into an inlet and subsequently through a nozzle in front of an impaction plate. Figure 6 shows schematically the collection efficiency curves of widestream and jet impactors. For small particles the collection efficiency of widestream impactors is less steep than that of jet impactors and thus their size cut is more poorly defined. This is caused by the less strong curvature of the streamlines in front of an impaction plate in a free stream compared to those of the jet produced by the nozzle. For large particles, the collection efficiency of widestream impactors predominates over the jet impactors because the problem to sample the large particles with an inlet is avoided (see section 3.1.1).

Therefore, no losses or overloading of large particles (or drops) occurs during sampling. Additionally, the particles (drops) are transmitted very quickly into a vessel so that no condensation or evaporation or uptake of trace gases from the ambient air takes place and, moreover, high flow rates are easy to obtain. Thus, the RAC is particularly suitable to sample low concentrations of large particles and cloud/fog droplets with radii larger than about 5 μm. In addition, a RAC is easy to handle and is not noisy and mechanical problems, such as instability, were not observed up to a frequency of revolution of 10 s^{-1}. Altogether it can be stated that the RAC fulfils most of the requirements on a fogwater sampler quite well. It is noted that, if smaller drops should be sampled in clouds or fog, then isokinetically operated jet impactors should be used.
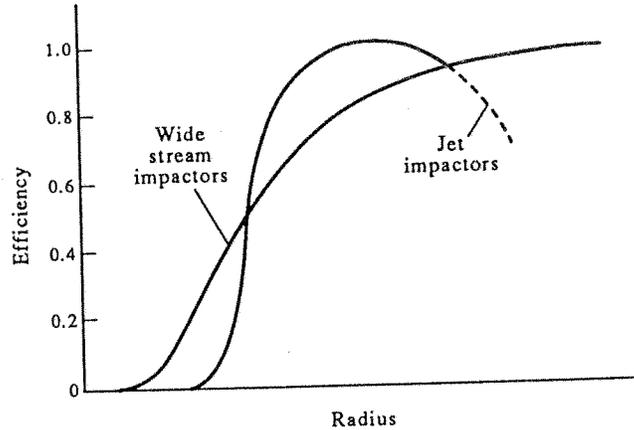
Fig. 6. Schematic collection efficiency curves of widestream and jet impactors.

Notwithstanding the above comments, some points should be critically mentioned:

(i) Because the collection efficiency curve of the RAC only increases gradually some of the small droplets are not sampled and this is illustrated in Fig. 1, where the desired collection efficiency curve of the RAC (Langmuir and Blodgett, 1946) is shown (curve 1). Curve 3 represents the part of the drop spectrum (curve 2) sampled with this collection efficiency curve. However, most of the droplet mass is sampled and it should be noted that some loss of droplets is unavoidable, no matter what kind of sampler is used.

(ii) The calculation of the flow rate is based on the sampling area of the gutter, but the real sampling cross-section is somewhat smaller ($\approx 85\text{--}90\%$ of the gutter-sampling area). To obtain knowledge about the accuracy of the real sampling area the limiting trajectory of the largest particle to be sampled should be known.

(iii) There are some aspects that may influence the overall, three-dimensional collection efficiency of the RAC which have up to now not been included in the theoretically calculated collection efficiency curves. As already mentioned, the collection efficiency curve of the RAC varies along the sampling area together with the speed of the flow $|\vec{u}|$ ($\approx \pm 15\%$ related to the middle of the sampling area). The angle α varies in the same way and is therefore adjustable only at one cross-section and the rotation of the arm produces a radial component to the flow $\vec{u}$. Further, in the rear of each sampling unit the flow is highly turbulent and the turbulence behind one sampling unit could influence the collection efficiency of the other.

Especially for fogwater samplers, where the sampled droplets flow together, it should be known if these properties of the flow influence the overall collection efficiency and if theoretically-calculated collection efficiency curves are applicable. The overall collection efficiency curve of the RAC is determined experimentally in this study and is compared with simplified two-dimensional theory as mentioned in sections 1 and 3.2. The calibration method and the results are presented in section 3.

3. OVERALL COLLECTION EFFICIENCY OF THE RAC

3.1. Calibration method

To determine the collection efficiency curve of the RAC experimentally, atmospheric aerosol particles were sampled simultaneously with the RAC and a Filter Holder (FH, for a detailed description see section 3.1.1). The pore size of the filter applied in this study ($r = 4.0\ \mu m$) is below the estimated cut-off of the RAC ($r_{50} \approx 7.0\ \mu m$). Therefore, the filter samples particles with $r_p > 4\ \mu m$ with an efficiency of 100%. Proceeding from the assumption that the collection efficiency of the sampling head of the FH is also 100%, the collection

efficiency curve of the RAC can be calculated from the particle number size distributions of both the FH- and the RAC-samples as follows:

$$E(r_p) = \frac{C_{RAC}(r_p)}{C_{FH}(r_p)}, \qquad (4)$$

where

$E(r_p)$ is the collection efficiency of the RAC for particles with radius r_p
$C_{RAC}(r_p)$ is the concentration of particles with radius r_p sampled with the RAC
$C_{FH}(r_p)$ is the concentration of particles with radius r_p sampled with the FH.

To meet this assumption as good as possible the FH has to be designed and operated very carefully, and this is described in section 3.1.1. The method to determine the particle number size distributions is described in section 3.1.2.

The method to calibrate the RAC in free air has some disadvantages such as not well-defined flow conditions (flow velocity is not constant) and aerosol (the particle density is not constant). A calibration in a wind tunnel with defined particles, which would have been preferable, was not possible because the typical diameter of a wind tunnel (80 cm) is much smaller than the diameter of the arm of the RAC (120 cm). However, the experimental calibration was performed mainly to determine if there are substantial discrepancies with the simplified theoretical calculations so that the uncertainties caused by the method can be accepted.

3.1.1. *The Filter Holder.* Figure 7 shows schematically the FH. The working principle is that particles within the free air stream are sucked in an inlet by means of a pump and subsequently to the filter, where they are separated from the flow. For a detailed discussion of the sampling characteristics of inlets a broad literature is available, for example Hinds (1982), and comprehensive studies by Vincent (1989) and Hangal and Willeke (1990). Here, only the most important problems occurring during the sampling of particles with an inlet will be discussed to show that the assumption to use the FH as an 'absolute' instrument is sufficiently fulfilled.

(i) *Aspiration*

The inlet must face the wind (isoaxial sampling) and the velocity in the inlet must be equal to the velocity in the free stream (isokinetical sampling). Otherwise the streamlines of the flow in front of the inlet would be distorted and particles with sufficient inertia would not follow them, which would lead to losses or overloading of particles in the flow into the inlet. These two size dependent effects are summarized under the definition *aspiration*. Therefore,

- the FH is mounted on a weather vane (→isoaxial sampling)
- the aperture of the inlet is adjusted to the actual mean wind speed (→isokinetic sampling).
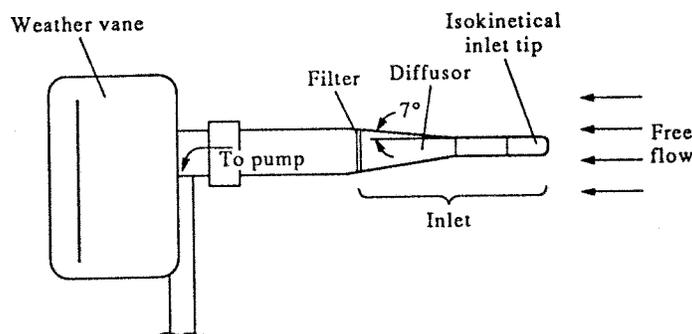
Fig. 7. Schematic diagram of the Filter Holder (FH).

The size of the aperture of the inlet is determined by the velocity of the flow inside by $d = 2\sqrt{\dfrac{q}{\pi \cdot v}}$ (d is the diameter of the inlet, q is the flow (suction) rate and v is the velocity inside the inlet).

Several isokinetical inlet tips for different velocities v were used. Under field conditions the inlet tips are adjusted hourly during the sampling period according to the average wind velocity $|\vec{w}|$ in the atmosphere. Because the inlet tip can guarantee isokinetical sampling only for the average wind speed then

- samples are taken in meteorological situations with small fluctuations of the wind velocity.

(ii) Rebounce

Particles following the streamlines to the FH can hit the edge of the inlet (because it has a certain thickness) and rebounce back into the free air stream or into the flow into the inlet. To avoid particle losses or overloading due to rebounce then

- the inlet of the FH is thin walled and sharp edged.

(iii) Transmission

Once having entered the inlet, the particles can be lost on their way to the filter for several reasons:

(a) If the inlet is too long, they can sediment due to gravity.

(b) A boundary layer develops in the inlet whose thickness depends on the Reynolds number of the flow and particles which enter the boundary layer immediately impact on the wall. Therefore, the diameter of the inlet should be large compared to the boundary layer thickness.

(c) When the diameter of the inlet broadens, eddies can develop behind the bend if its angle exceeds a certain value. Those eddies transport particles to the wall.

The term *transmission* covers all these size dependent mechanisms. In order to minimize losses due to transmission then

- the inlet of the FH is kept short
- the flowrate is kept small ($\approx 4 \text{ m}^3 \text{ h}^{-1}$) and the samples are taken at low wind velocities ($\approx 3 \text{ m s}^{-1}$) ($\rightarrow$large aperture)
- the angle of the inlet diffusor is small (7°, after Bohl (1982)).

3.1.2. *Analysis of the RAC- and FH-samples.* The particle number size distribution of both the RAC and the FH samples were determined with a Coulter Counter (Type: Coulter Multisizer (CM)). Coulter Counters have been used over several decades to measure size distributions of insoluble particles in liquid suspensions and for a detailed description see for example Kinsman (1979) or Hinds (1982). To determine the number size distribution of the samples of the FH and the RAC with the CM, the particles have to be suspended in an electrolyte (working fluid of the CM) which meets the following requirements:

- the particle covered filter (material: cellulose nitrate) is dissolved
- the particles are not dissolved or broken up (i.e. for agglomerates)
- a limiting electrical conductivity (10 mS cm^{-1}) is exceeded.

These conditions are met by a solution containing 50% methanol and 50% methyl acetate as solvent with 4% LiCl in solution. Methyl acetate dissolves the filter in fragments much smaller than its pore size. Methanol is needed to solve sufficient LiCl to exceed the limiting electrical conductivity. These substances do not dissolve natural aerosol particles to a great extent (4% of a particle is soluble in methanol (Winkler, 1974); methyl acetate

does not have an effect on the particles (Sartorius GmbH, 1988)). Furthermore, it is considered likely that changes in the particle size distribution due to the break-up of agglomerated atmospheric aerosol particles during the CM analysis will be small. Thus, the sizes of the particles are approximately preserved when suspending them in the electrolyte.

The particles of the FH-samples are suspended in the electrolyte by dissolving the filter. The inlet of the FH is rinsed with the electrolyte to remove particles that may have impacted on the wall. To suspend the particles sampled in the bottles of the RAC, the gutter is rinsed with electrolyte so that it runs in the bottle.

3.2. Discussion of the collection efficiency of the RAC

During the calibration measurements the RAC was operated at a frequency of revolution of $\omega = 6 \, \text{s}^{-1}$. Thus, the speed in the middle of the sampling area is $|\vec{u}| = 13.6 \, \text{m s}^{-1}$ and the theoretical cut-off radius becomes 6.9 μm for an average particle density of $\rho_p = 1.5 \, \text{g cm}^{-3}$.

The calculation of the errors in measurement include errors due to aspiration at the inlet of the FH. The formula of Belyaev and Levin (1974), which is one of the best approaches (Zhang and Liu, 1989) to calculate aspiration errors for isoaxial sampling, is given by

$$A(r_p) = 1 - \left(\frac{U_0}{U} - 1 \right) \cdot \left(1 - \frac{1}{1 + \left(2 + 0.62 \frac{U}{U_0} \right) \cdot \text{Stk}} \right), \tag{5}$$

where

$A(r_p)$ is the aspiration efficiency due to non-isokinetical sampling
U_0 is the velocity in the inlet
U is the velocity of the free stream.

The maximum and minimum wind speeds during the calibration measurements are employed to calculate the maximum errors of the collection efficiencies.

Figure 8 shows the experimentally-determined overall collection efficiencies for the RAC and two theoretically calculated collection efficiency curves. The theoretical curves are related to the (two-dimensional) conditions in the middle of the gutter. One is calculated by Langmuir and Blodgett (1946) for flat plates, the other was recently calculated by Lesnic et al. (1993) for the gutter-formed sampling areas used in this study. They are based on potential flow perpendicular to the sampling area, therefore the radial flow component and the turbulence in the rear of each sampling unit is not considered.

Taking into account the simplifications of the theory and the uncertainties of the calibration measurements, theory and experiment can be regarded as nearly corresponding over quite a large range of conditions. Thus, it can be concluded that the influence of the effects concerning the overall, three-dimensional collection efficiency of the RAC (pointed out in section 2.4) on the sampling behaviour of the RAC are not large. The variation of the collection efficiencies along the gutter balances on average. The turbulence in the rear of one sampling area does not disturb the sampling characteristics of the other to a high degree. The component of velocity radial to the flow $|\vec{u}|$ may have caused the somewhat low collection efficiencies at Stokes numbers between 0.7 and 1.0. In the range Stk = 0.25–0.4 the experimentally-determined collection efficiencies exceed the theoretically-calculated. Until now no explanation could be found for this effect. The high collection efficiencies at Stokes numbers larger than 2.0 are connected with large errors. This is due to aspiration at the inlet of the FH, even when operating it very carefully. Thus, in this size range the collection efficiencies could be overestimated slightly. In addition, this effect again demonstrates the problematical nature of leading large particles into an inlet.

Altogether, the results of the experimentally-determined and theoretically-calculated collection efficiencies of the RAC allow the assumption that the application of the simplified theory is an acceptable approach to describe the real sampling conditions used here.
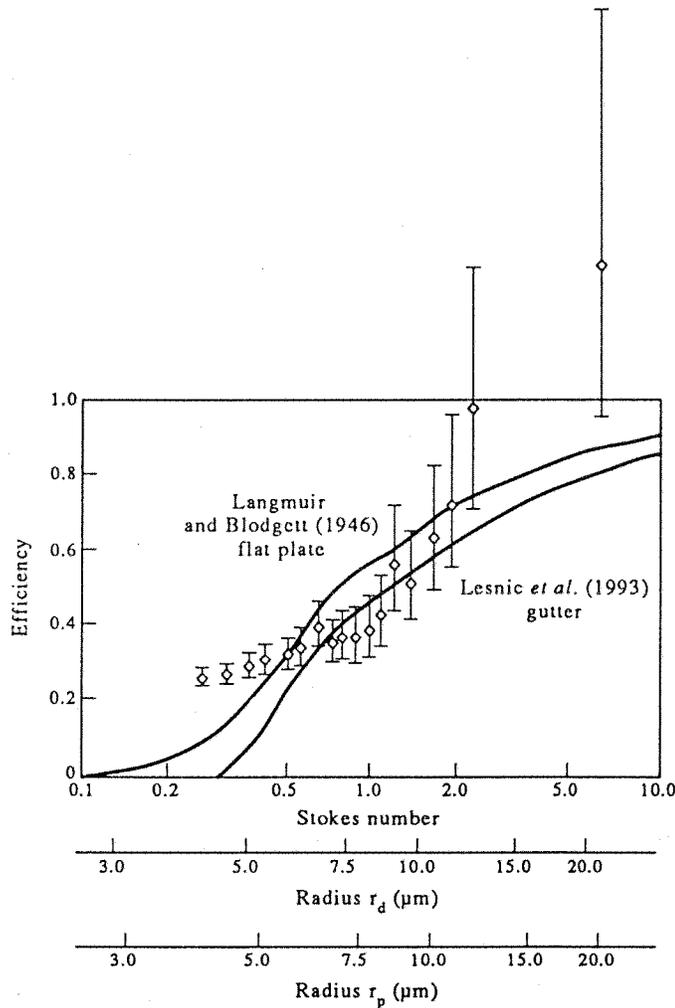
Fig. 8. Experimental and theoretical collection efficiency curves of the RAC (r_p is related to $|\bar{u}| = 13.57$ m s^{-1} and $\rho_p = 1.5$ g cm^{-3}, r_d to $|\bar{u}| = 18.1.0$ m s^{-1} and $\rho_d = 1.0$ g cm^{-3}) as a function of Stokes number, respectively drop/particle size.

A generalization of this assertion is not allowed because the flow conditions, especially for higher frequencies of revolution, can be different to those investigated in this study.

Figure 9 shows again the experimentally-determined collection efficiencies of the RAC together with those of a RAC operated as a fogwater sampler by Jacob et al. (1984) (some calibration points are taken from Fig. 5 of Jacob et al. (1984)). The characteristic dimensions of the RAC used by Jacob et al. (1984) are different from the RAC used in this study, for a detailed description, see Jacob et al. (1984). Two important differences between the two samplers are:

(a) The RAC of Jacob et al. (1984) is not facing the wind and the sampling units are fixed. This means the flow is not perpendicular to the sampling areas.

(b) The frequency of revolution of the RAC used by Jacob et al. (1984) is about 28 s^{-1}, whereas in the present case it does not exceed 10 s^{-1}.

Although the two RACs sample droplets in the same size range, their overall collection efficiencies differ considerably with regard to the Stokes number (see also Lesnic et al., 1993). Because the theoretical calculations (Lesnic et al., 1993) are in good agreement with the experimentally-determined efficiencies of the RAC used in this study, this difference is probably caused by flow characteristics of the RAC used by Jacob et al. (1984) not included in the theory. It is supposed that the main reason for this behaviour is that the turbulence in
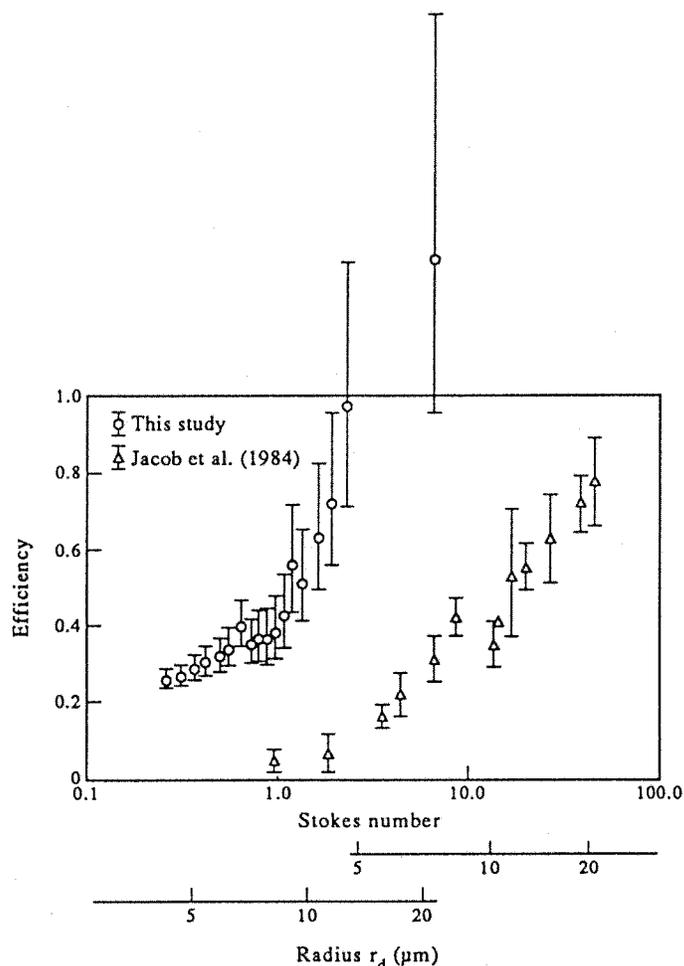
Fig. 9. Collection efficiencies of two RACs (this study and Jacob et al., 1984) as a function of Stokes number, respectively drop size.

the rear of one sampling unit influences the sampling characteristic of the other at this high frequency of revolution. The misalignment of the sampling units to the flow is probably of minor significance.

4. SUMMARY

Comparison of the sampling characteristics of wide stream impactors and those requiring an inlet shows that both are affected by errors when sampling droplets or particles over a large size range. The size cut of wide stream impactors is poorly defined and thus the appropriate sampling of smaller particles is not guaranteed, while losses or overloading of large particles can occur when leading them into an inlet. Therefore,

• RACs (belonging to the (virtual) wide stream impactors) are suitable to sample coarse atmospheric aerosol particles and cloud or fog droplets larger than about 5 μm radius.

The collection efficiency of RACs is influenced by the flow produced by the rotation of the sampling units. The flow velocity and direction varies along the sampling area, a flow component parallel to the sampling area exists and the flow in the rear of the sampling units is turbulent due to its high velocity. In addition, the shape of the sampling area also influences the collection efficiency.

When operating a RAC to sample fog- or cloudwater, the droplets join after sampling so that a correction of the concentrations for different drop sizes is not possible during the subsequent analysis.

Thus, the overall, three-dimensional collection efficiency of a RAC with gutter-shaped sampling areas, designed to sample cloud or fog droplets, is investigated experimentally. The experimentally-determined collection efficiencies are compared with those theoretically calculated for the two-dimensional flow conditions appropriate in the middle of the sampling area of the RAC (for flat plates by Langmuir and Blodgett (1946) and for the gutter by Lesnic et al. (1993)). The theoretical calculations do not include the turbulence in the rear of each sampling area and the flow component parallel to them. Nevertheless, the agreement between experiment and theory is good and therefore it is concluded that

- the specific properties of the flow past the sampling areas of a RAC do not conceal the typical sampling characteristics of wide stream impactors and hence simplified theory is an acceptable approach to describe the real sampling conditions.

REFERENCES

Belyaev, S. P. and Levin, L. M. (1974) Techniques for collection of representative aerosol samples. *J. Aerosol Sci.* **5,** 713–720.
Bohl, W. (1982) *Technische Strömungslehre*, pp. 112–113. Vogel-Verlag.
Borrmann, S. and Jaenicke, R. (1993) Application of microholography for ground-based in situ measurements in stratus cloud layers. *J. Atmos. Oceanic Technol.* **10,** 277–293.
Bott, A. (1991) On the influence of the physico-chemical properties of aerosols on the life cycle of radiation fogs. *Bound.-Layer Met.* **56,** 1–31.
Collet Jr, J. L., Daube Jr, B. C., Munger, J. W. and Hoffmann, M. R. (1990) A comparison of two cloudwater/fogwater collectors: the rotating arm collector and the Caltech active strand cloudwater collector. *Atmos. Envir.* **24A,** 1685–1692.
Enderle, K. H. and Jaeschke, W. (1991) Chemie und Mikrophysik des Nebels. *Ber.-Zentr. Umweltforschung* **13.** ZUF-Verlag, Frankfurt/M.
Fuchs, N. A. (1964) *The Mechanics of Aerosols.* Pergamon Press, Oxford.
Garland, J. A. (1971) Some fog droplet size distributions obtained by an impaction method. *Quart. Jl R. met. Soc.* **97,** 483–494.
Garland, J. A. and Nicholson, K. W. (1991) A review of methods for sampling large airborne particles and associated radioactivity. *J. Aerosol Sci.* **22,** 479–499.
Hangal, S. and Willeke, K. (1990) Overall efficiency of tubular inlet sampling at 0–90 degrees from horizontal aerosol flows. *Atmos Envir* **24A,** 2379–2386.
Hinds, W. C. (1982) *Aerosol Technology: Properties, Behaviour and Measurement of Fine Particles.* Wiley, New York.
Jacob, D. J., Wang, R.-F. T. and Flagan, R. C. (1984) Fogwater collector design and characterization. *Envir. Sci. Technol.* **18,** 827–833.
Jaenicke, R. (1964) Die obere Grenzgröße des natürlichen Aerosols. Masters Thesis. Joh. Gutenberg-University, Mainz.
Jaenicke, R. and Junge, C. (1967) Studien zur oberen Grenzgröße des natürlichen Aerosols. *Beitr. Phys. Atmos.* **40,** 129–143.
Jaenicke, R. and Matthias, S. (1988) The primary biogenic fraction of the atmospheric aerosol. In *Aerosol and Climate* (Edited by Hobbs, P. V. and McCormick, M. P.), pp. 31–38. Depag.
Jiusto, J. E. and Lala, G. G. (1983) Radiation fog field programs—recent studies. ASRC-Suny, Pub. No. 869.
Kinsman, S. (1979) Aerosol particle measurement using the electrical resistance principle. In *Aerosol Measurements* (Edited by Lundgren, D. A. *et al.*), pp. 650–654. Univ. Press of Florida.
Krämer, M., Schütz, L., Svenningsson, B. and Wiedensohler, A. (1991) Number size distribution of insoluble atmospheric aerosol particles in fog/cloud-water. *J. Aerosol Sci.* **22,** S525–S528.
Langmuir, J. and Blodgett, K. (1946) Mathematical investigation of water droplet trajectories. In *Collected Work of Irving Langmuir* **10,** pp. 348–393. Pergamon Press, Oxford.
Lesnic, D., Elliott, L. and Ingham, D. B. (1993) A mathematical model for predicting the collection efficiency of the Rotating-Arm-Collector. *J. Aerosol Sci.,* **24,** 163–180.
Mack, E. and Pillie, R. (1975) Fog water collector. U.S. Patent 388 9532.
Noll, K. (1970) A rotatry impactor for sampling giant particles in the atmosphere. *Atmos. Envir.* **4,** 9–19.
Sartorius GmbH (1988) Private communication.
Schmitt, G. (1986) The temporal distribution of trace element concentration in fogwater during individual fog events. In *Atmospheric Pollutants in Forest Areas* (Edited by Georgii, H.-W.), pp. 129–141. Reidel, Dordrecht.
Vincent, J. H. (1989) *Aerosol Sampling: Science and Practice.* Wiley, New York.
Winkler, P. (1974) Die relative Zusammensetzung des atmosphärischen Aerosols in Stoffgruppen. *Meteorol. Rdsch.* **27,** 129–136.
Zhang, Z. Q. and Liu, B. Y. H. (1989) On the empirical fitting equations for aspiration coefficients for thin walled sampling probes. *J. Aerosol Sci.* **20,** 713–720.