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Technical note: Dimensioning IRGA gas sampling system: laboratory and field experiments

M. Aubinet[1], L. Joly[2], D. Loustau[3], A. De Ligne[1], H. Chopin[1], J. Cousin[2], N. Chauvin[2], T. Decarpenterie[2], and P. Gross[4]

[1]University of Liege, Gembloux Agro-Bio Tech, Dept. of Biosystem Engineering (BIOSE), Ecosystems – Atmosphere Exchanges, Liege, Belgium
[2]University of Reims, Groupe de Spectrométrie Moléculaire et Atmosphérique, Reims, France
[3]INRA, UMR ISPA, Villenave d'Ornon, 33140, France
[4]INRA, UMR EEF, Champenoux, 54280, France

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Correspondence to: M. Aubinet (marc.aubinet@ulg.ac.be)

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Abstract

Both laboratory and field experiments were carried out in order to define suitable configuration ranges for the gas sampling systems (GSS) of infrared gas analyzers (IRGA) used in eddy covariance measurements.

In the laboratory, an original dynamic calibration bench was developed in order to test the frequency attenuation and pressure drop generated by filters. In the field, IRGAs equipped with different filters or different rain cups were installed and run and the real frequency response of the complete set-up was tested.

The main results are that:

- Filters may have a strong impact on the pressure drop in the GSS and this impact increases with flow rate.
- On the contrary, no impact of the tested filters on cut off frequency was found, GSS with and without filters presenting similar cut off frequencies.
- The main limiting factor of cut off frequency in the field was found to be the rain cup design. In addition, the impact of this design on pressure drop was also found noteworthy.

1 Introduction

The use of the eddy covariance technique to study gas exchange between ecosystems and the atmosphere has greatly developed these last decades (Baldocchi, 2014) and does not limit to CO_2 and H_2O exchanges but expands to more and more trace gases like methane, N_2O or VOC. Several networks using eddy covariance with the aim to characterize ecosystem functioning across a spectrum of pedoclimatic conditions have been implemented (Valentini et al., 2000; Baldocchi, 2001; Ciais et al., 2010). However, to work accordingly, they require a high level of standardization of equipment and measurement procedures. In the case of eddy covariance, standardization concerns

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the infra-red gas analyzer (IRGA) and sonic choice, their positioning and, as far as closed or semi-closed IRGAs are concerned, the gas sampling system (GSS), which carries air from the sampling point to the infrared gas analyzer (IRGA). The GSS has to meet several constraints, among which are protecting the IRGA against dust and rain, minimizing high frequency attenuation of concentration fluctuations and keeping pressure drop in the measurement cell in an acceptable range. Rain cup, filter, tube and pump are key elements of this system and need proper dimensioning. This paper describes experiments that were carried out in the frame of the ICOS project with the aim to establish the protocol for IRGA installation and, especially GSS dimension optimization. Both laboratory and field experiments were carried out in order to define suitable configuration ranges.

In the laboratory, a dynamic calibration bench was developed that generated different flow rates and concentration fluctuation frequencies in order to test the frequency response of some filters and to measure the pressure drop they generated. In the field, three identical IRGA equipped with different GSS were installed and run at a grassland site and the real frequency response of the complete set-up was tested. This paper summarizes these experiments and provides recommendations for GSS dimensioning.

2 Theory

In addition to the necessity to keep the cell clean, the main constraints on the GSS are the needs to maintain the pressure drop inside the chamber above a critical threshold (depending on IRGA type) and the concentration fluctuation frequencies as high as possible. In turbulent conditions, the constraint on pressure drop in a linear tube is expressed by the Darcy–Weisbach equation (a.o. Sayers, 1992; Massel, 1999):

$$\Delta p = \frac{8\rho Q^2 \lambda L}{\pi^2 d^5}, \tag{1}$$

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where ρ is the air density, Q is the flow rate, λ is the friction factor and L and d are the tube length and diameter. The friction factor may be described by several equations (see, a.o., Sayers, 1992). However, as is does not play a critical role in this problem, it may be considered here as a constant with a conservative value of 0.047. However, Eq. (1) only applies to a linear tube and does not take turns, diameter changes or porous media crossings that are frequent in GSS, due to the presence of filters or rain cups. Complementary experiments are thus necessary in order to evaluate the exact pressure drop exerted by a GSS.

The effect of tubing on concentration fluctuation damping at high frequency has been studied by several researchers, including Leuning and King (1992), Leuning and Judd (1996) and Massman and Ibrom (2008). In the case of turbulent flow, the Leuning and King function modified by Massman and Ibrom (2008) is:

$$\left(\frac{32 \ln 2\, Q^2}{\left(160\, Re^{-\frac{1}{8}} + 2666\, Re^{\frac{29}{40}}\right) \pi^2 d^5 L} \right) < f_{co}^2. \tag{2}$$

This equation cannot be solved explicitly in terms of volume flow as the Reynolds number is a function of Q. However, in the range of interest, the Massman and Ibrom factor at the numerator may be very well (less than 1 % difference for $2000 < Re < 9000$) approximated by:

$$160\, Re^{-\frac{1}{8}} + 2666\, Re^{\frac{29}{40}} \approx 293\, Re^{-0.185}, \tag{3}$$

so that the conditions on minimal flow may be rewritten, in turbulent conditions:

$$Q > 9.11\, d^{2.37} L^{0.458} \nu^{0.085} f_{co}^{0.916}. \tag{4}$$

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3 Material and methods

3.1 Laboratory experiment

3.1.1 Gas sampling system and pressure drop measurements

A dynamic calibration bench was developed at the "Groupe de Spectrométrie Moléculaire et Atmosphérique" (GSMA) to investigate experimentally the pressure drop and the concentration fluctuation attenuation caused by different filters without a rain cup. For these experiments, the flow rate in the GSS was generated by a pump (KNF, N 026.1.2 AN.18, Village Neuf, France). The GSS was constituted, from upstream to downstream, by a filter, a 1 m length – 5.3 mm diameter tube, the IRGA (LI-7200, LI-COR, Lincoln, Nebraska), a mass flow controller (Vögtlin MC-50SLPM-D-I/5M-5IN Gaz, Aesch, Switzerland) driven by a computer, a buffer in order to dampen pump fluctuations and, finally, the pump. Concentrations measured by the IRGA were sampled at 20 Hz and the data were collected and stored on a computer. Experiments were repeated four times, one time without filter and three times with different filters: ACRO 50 1 µm (PALL, Port Washington, NY, USA), Swagelok FW 2 µm (Swagelok, Solon, OH, USA) and PALL Open Face filter holder with 2 µm membrane (PALL, Port Washington, NY, USA).

In each experiment, one filter was installed at the system inlet and the mass flow was varied step by step from 1 to 28 $L\,min^{-1}$. Chamber pressure measured by the analyzer was collected through the IRGA RS232 output and stored on the computer.

3.1.2 GSS frequency response

Concentration fluctuations at the GSS inlet were generated by diluting ambient air (with ambient CO_2 concentration) with dry, CO_2-free, air (Alphagaz 1 air, Air liquide, France). The GSS inlet was placed in a nozzle, fed by ambient air by a fan and in which CO_2-free air was injected intermittently through a chopper (Fig. 1). The intermittent mixing

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of ambient and CO_2-free air provoked CO_2 concentration fluctuations. The frequency of the fluctuations was adjusted by modulating the chopper rotational frequency. One measurement cycle lasted for 150 s (Fig. 2a) and consisted of 20 successive phases with an alternation of free CO_2 air injection or not. The injection modulation frequency was fixed to 1 Hz during the first injection phase and increased by 1 Hz between each successive injection phase (Fig. 2b) so that the investigated frequency range was 1 to 20 Hz with a 1 Hz resolution. For each filter, the cycle was repeated five times with different GSS flow rates, between 5 and 30 $L\,min^{-1}$.

Independence of free CO_2 air injection flow rate to chopper modulation frequency was checked during a previous validation phase so that the amplitude of concentration fluctuations could be considered as independent of injection modulation frequency.

An example of concentration measurement by the IRGA during one measurement cycle is illustrated on Fig. 2. As the concentration fluctuation amplitude in the nozzle was constant, the amplitude decrease with injection modulation frequency could only result from frequency attenuation by the GSS and the IRGA. System cut off frequency was then computed as the frequency at which the concentration fluctuation amplitude was divided by two (Fig. 2a).

3.2 Field experiment

3.2.1 Site and set up description

Site measurements were performed at the Dorinne (DTO) and Vielsalm (VTO) Terrestrial Observatories. The first is a grazed permanent grassland and the second is a mixed forest. As the site choice is not critical for the experiments, which concern mainly the IRGA set-up, site details are not given here. They can be found in Jérôme et al. (2014) for DTO and in Aubinet et al. (2001) for VTO. Both sites are equipped with an eddy covariance system and a micrometeorological station. From July to October 2013, we tested the impact of filters on pressure drop and cut-off frequency. In addition to the system in place, one sonic anemometer (Gill HS 50, Gill, Lymington,

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UK) and three additional IRGA (LI-COR-7200, LI-COR, Lincoln, NE) were installed at DTO. They were placed in order to minimize the distance between the IRGA sampling point and the sonic path volume. In practice, the horizontal and vertical separation distances between the sampling point and the sonic path volume were lower than 15 and 24 cm, respectively. In addition, the sonic anemometer boom and IRGA tubes were all oriented perpendicularly to the main wind direction. All three IRGA were equipped with a rain cup (LI-COR 9972-43) and a tube of same dimension (1 m length; 5.3 mm diameter). Different flow rates, filters and rain cup configurations were tested. They are summarised in Table 1. In October 2013 we tested the impact of rain cup design: one IRGA was maintained at the sites, fed by a 15 $L\,min^{-1}$ flow rate and equipped with the same tube, a Swagelok FW 2 µm filter and rain cups of different design. Especially, in addition to the original LI-COR rain cup, two home-made rain cups, one derived from the LI-9972-43 but without tube restriction (HM1) and one with a lateral insertion and a reduced volume (HM2) were tested as well as a simple stuffing gland. The new LI-COR 9972-72 (LI-COR, Lincoln, NE) was tested as soon as it had been provided, in April 2014. The system was identical to the preceding one but was installed at VTO.

3.2.2 Data treatment

Set up transfer functions of field data were computed as the ratio of CO_2 and temperature spectra. Spectra were computed on six successive half hours, free of spikes and of step changes (Vickers and Mahrt, 1997), satisfying stationarity criteria (Foken and Wichura, 1996) and for which sensible heat was larger than 25 $W\,m^{-2}$ and CO_2 fluxes were larger than 2 $\mu mol\,m^{-2}\,s^{-1}$. Computation was made using the EDDYFLUX Software (O. Kolle, Jena, Germany). The ratio of mean spectra was computed, giving an experimental transfer function. Cut-off frequencies (f_{co}) were then computed as a result of Gaussian relation fitting on the experimental transfer functions (δ):

$$\delta = \exp\left\{-\ln 2\,\frac{f^2}{f_{co}^2}\right\}, \tag{5}$$

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where f is the frequency.

4 Results

4.1 Laboratory measurements

4.1.1 Pressure drop

The response to flow rate of pressure drop across the tube and the filters (without rain cup) was measured in the laboratory (Fig. 3). In addition, the predicted pressure drop along the tube (Eq. 1) is presented by the continuous line. In each case, the pressure drop non linearly increased with mass flow. In the absence of a filter, the increase is described by the theoretical curve with a 5 % accuracy. In addition, the other curves show that the presence of a filter always enhances the pressure drop and that the filter impact increases with flow rate. At 10 L min^{-1}, it is about 0.3 kPa for the Swagelok PW2, 0.6 kPa for the PALL 2 µm and more than 5 kPa for the ACRO 50 1 µm. This shows that filters contribute significantly to the pressure drop in the GSS, and are in some cases the main cause of this drop. It also appears that the largest pressure drop was observed for the filter with lower pore size and smaller exchange surface.

4.1.2 Cut-off frequency

The response to flow rate of the cut-off frequency due the tube and the filters (without rain cup) was measured in the laboratory with the set-up described in Sect. 3.1.2 (Fig. 2). The results are given in Fig. 4. The continuous line represents the theoretical cut off frequency due to tube attenuation (Eq. 4), line path averaging (Moore, 1986) and sampling.

A fair agreement is found between observed and theoretical cut off frequencies. The latter are however systematically 1 Hz higher than the former, probably because the theoretical function does not take all the frequency attenuation causes into account.

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However, the most important point is that these frequencies do not differ significantly between GSS with and without filters and among GSS with different filters. This clearly suggests that, contrary to earlier guess (a.o., Aubinet et al., 2001), none of the tested filter had any effect on the system cut off frequency.

4.2 Field results

Results from the first campaign are summarized in Table 2. They clearly differed from laboratory results as GSS cut-off frequencies observed in the field were much (almost a decade in some cases) lower than in the lab. As the main difference between designs tested in the lab and in the field was the introduction of the rain cup in the latter, we conclude that the main cause of cut off frequency decrease should be due to the rain cup. This is confirmed by the experiments made with systems 2b and 2c, where the rain cup was replaced by a simple stuffing gland. In these conditions, cut off frequency reached about 8 Hz, which was comparable with lab observations.

The second field campaign was thus held in order to test different rain cup designs and evaluate their frequency response. Some transfer functions obtained during the experiment are shown on Fig. 5. All these functions were obtained with identical GSS (i.e., same tube, filter, flow rate, see Sect. 3.2.1), differing only by the rain cup design. It is clear that this characteristic is critical as resulting cut off frequencies varied from 1 to 6 Hz according to the rain cup design. The lower frequency corresponded to the original LI-COR rain cup design (LI-9972-43), the higher to the new design (LI-9972-72) and the intermediate to the home-made rain cups HM1 and HM2. It was also observed that the pressure drop created by a rain cup could differ strongly from one design to another. Observed pressure drop along the GSS were 3.3, 4.4, 2.6 and 2.0 kPa at 15 L min^{-1} for the LI-9972-43, HM1, HM2 and LI-9972-72 rain cup, respectively.

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5 Discussion and conclusions

5.1 Filter impact

The laboratory experiment suggested that filters may have a strong impact on the pressure drop in the GSS and that this impact increases with flow rate. The relative impact of filters and tubes depends on their respective dimensions (pore size, exchange surface). In some cases this impact may be not critical, for instance, when closed path analyzers are used with long tubes, when flow rates are limited or when constraints on chamber pressure are not too severe. In the specific case of the eddy covariance system recommended by the ICOS network, where the protocol recommended to maximize GSS cut off frequency and to limit IRGA chamber underpressure below 9 kPa (Aubinet et al., 2015), this impact is critical and some filters (i.e. PALL ACRO 50 1 µm) would appear impracticable.

Quite unexpectedly, no impact of the tested filters on cut off frequency was found. GSS with and without filters presented similar cut off frequencies. In addition no difference in cut off frequencies was found between filters characterized by different pore sizes (1 and 2 µm) or exchange surfaces. This study was however not exhaustive, all types of filters being not tested. As it will be suggested below, the introduction of large volumes in the GSS may have a critical impact on cut off frequency so that it is recommended to avoid filters with large exchange volumes.

We expect that filters with small pore size induce larger pressure drop. However, the use of a too large pore size would lead to insufficient chamber protection and premature dirtying or even destruction of the thermocouples that measure air temperature in the chamber of enclosed systems (LI-7200). A compromise is thus needed, which probably is probably site specific, depending on pollution level but also on pollen presence. At the field sites used in this study, filters with 5 µm pore size have been found to be insufficient, provoking chamber dirtying after a few days while 1 µm filters provoked a too large pressure drop. 2 µm pore size appeared as a good compromise, which

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could probably hold for many sites. This needs however to be checked individually at each site.

Practical considerations should also be taken into account when choosing a filter. Ease of use during maintenance is important: for example membrane change in filters with open face holders is challenging, especially in difficult conditions like tower tops under windy conditions. In addition, the use of metallic filters could lead to problems at night: they are more prone to night cooling and may appear more frequently blocked at sunset. They thus need heat protection and heating. Finally, filter duration is also an important criterion to consider in order to limit maintenance time and cost.

5.2 Rain cup impact

The comparison between laboratory and field experiments showed that, unexpectedly, the main limiting factor of cut off frequency was the rain cup design. This design also impacted significantly the pressure drop in the GSS. As it was not the aim of this paper to substitute to IRGA designers, no extensive research was made to optimize the rain cup design. However, the following points were raised after field tests:

- The rain cup volume should be as reduced as possible in order to avoid a cut off frequency reduction; a compromise should be found between rain cup volume and its ability to protect the GSS from rain.

- Turns and flow restriction (even of short length) have been found to create pressure drops in the system and should be avoided.

- Inadequate designs could favor inner circulation (eddies) in the rain cup which could provoke reduction in cut off frequencies (G. Burba, personal communication, 2014).

The new rain cup design proposed by LI-COR (LI-9972-72) was tested successfully in the field and provided satisfying cut off frequencies. Long term field studies in rainy conditions are now needed to test their efficiency for GSS rain protection.

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As soon as the filter and the rain cup have been optimized, spectral cut off frequencies up to 6 Hz can be reached. However, these values are much lower for cospectra (and thus eddy covariance fluxes). Indeed, if rain cup design and filter choice was optimized, the main limitation of the system cut off frequency remains the spatial separation between sonic path and IRGA inlet. Cospectral cut off frequencies larger than 3 Hz remain difficult to reach. This value is anyway sufficient to get defensible flux estimates at most sites.

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Table 1. Schedule of filter, flow rate and rain cup design use at the field site.

	Filter	Flow rate	Rain cup	Date
System 1:	ACRO 50 1 µm	6 slpm	LI 9972-43	5 Jul–2 Sep
System 2a	Swagelok 2 µm	15 slpm	LI 9972-43	5 Jul–2 Sep
System 2b	Swagelok 2 µm	15 slpm	Stuffing gland	2 Sep–26 Sep
System 2c	Swagelok 2 µm	20 slpm	Stuffing gland	26 Sep–9 Oct
System 3a	Savillex 2 µm	15 slpm	LI 9972-43	5 Jul–31 Jul
System 3b	PALL 2 µm	15 slpm	LI 9972-43	31 Jul–26 Aug
System 3c	PALL 3 µm	15 slpm	LI 9972-43	26 Aug–2 Sep

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Table 2. Averaged cut off frequencies measured on each system tested in the field between June and September 2013.

	Cut-off frequency [Hz]
System 1	0.75 ± 0.08
System 2a	1.36 ± 0.12
System 2b	8.0 ± 2.9
System 2c	7.87 ± 0.76
System 3a	0.62 ± 0.03
System 3b	0.89 ± 0.13
System 3c	0.76 ± 0.20

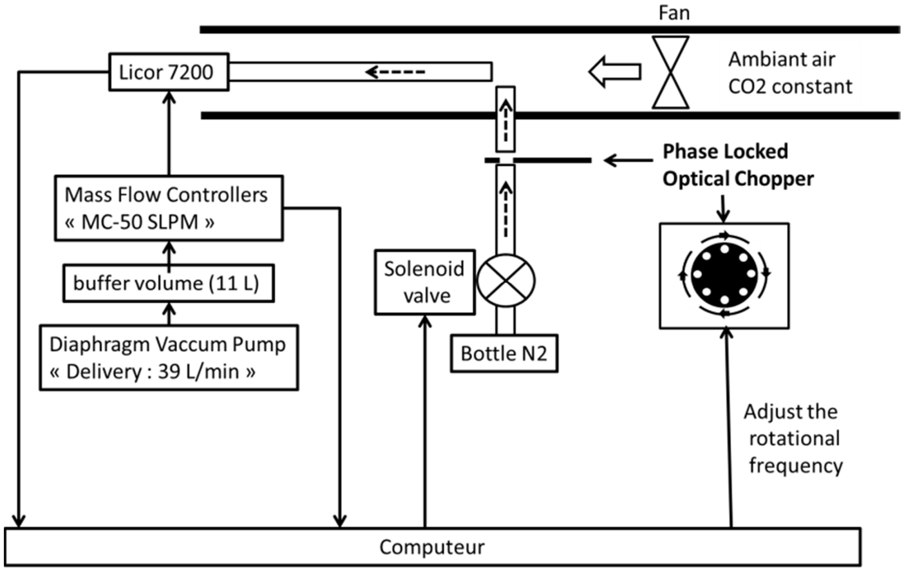

Figure 1. Calibration bench for cut off frequency determination.

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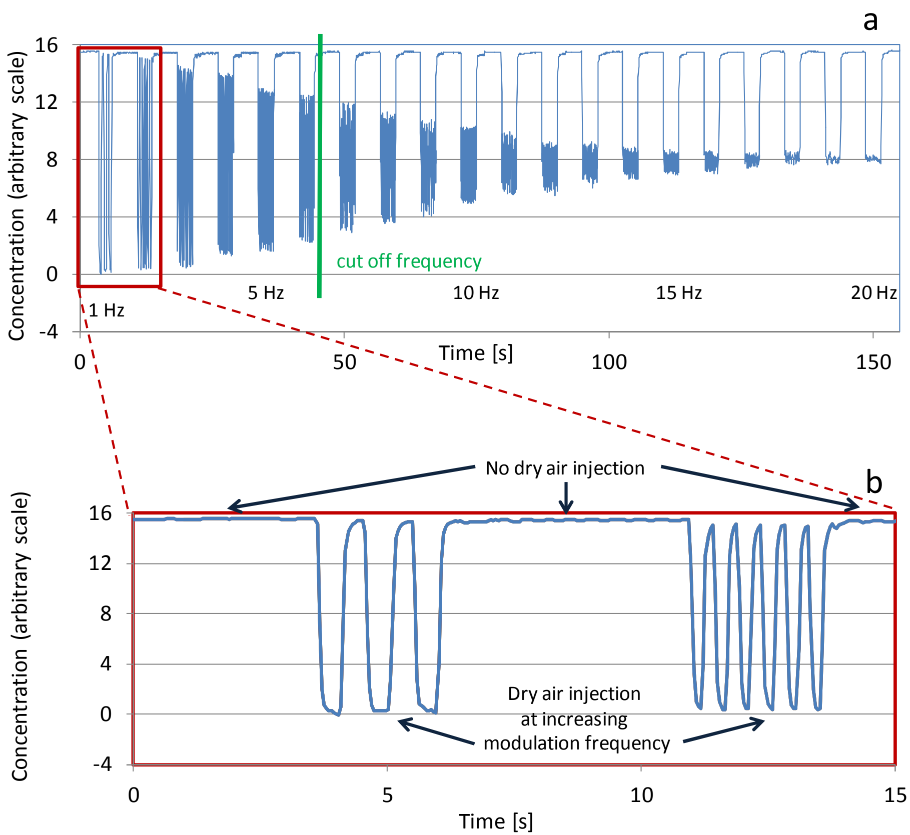

Figure 2. Recording of concentration measurements by the IRGA during one measurement cycle. **(a)** Representation of the whole cycle. **(b)** Focus on the first 15 s. For details, see text.

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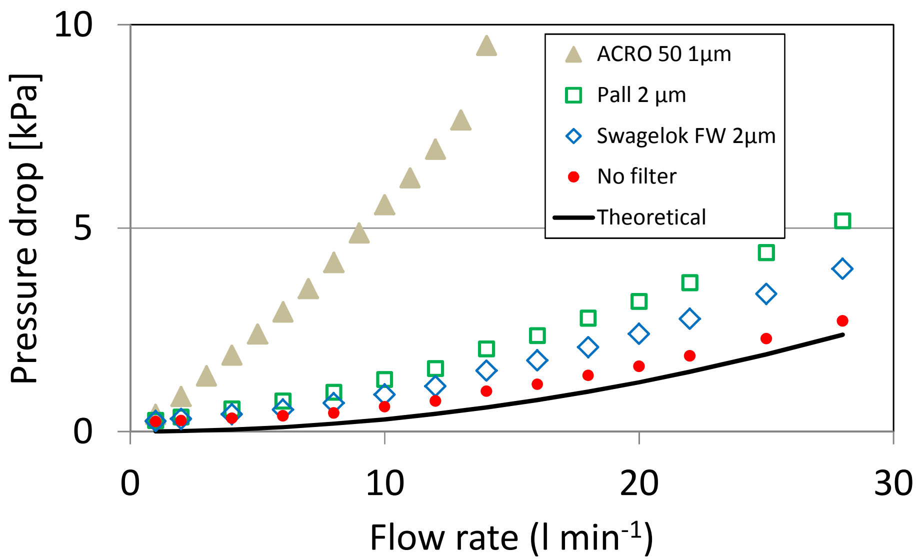

Figure 3. Pressure drop in the IRGA cell (kPa) in function of the flow rate ($L\,min^{-1}$) for different filters ACRO-50 (triangles), Pall 2 µm (crosses), Swagelok FW 2 µm (diamonds), and without any filter (asterisks). The theoretical curve (Eq. 1) is given by the continuous line.

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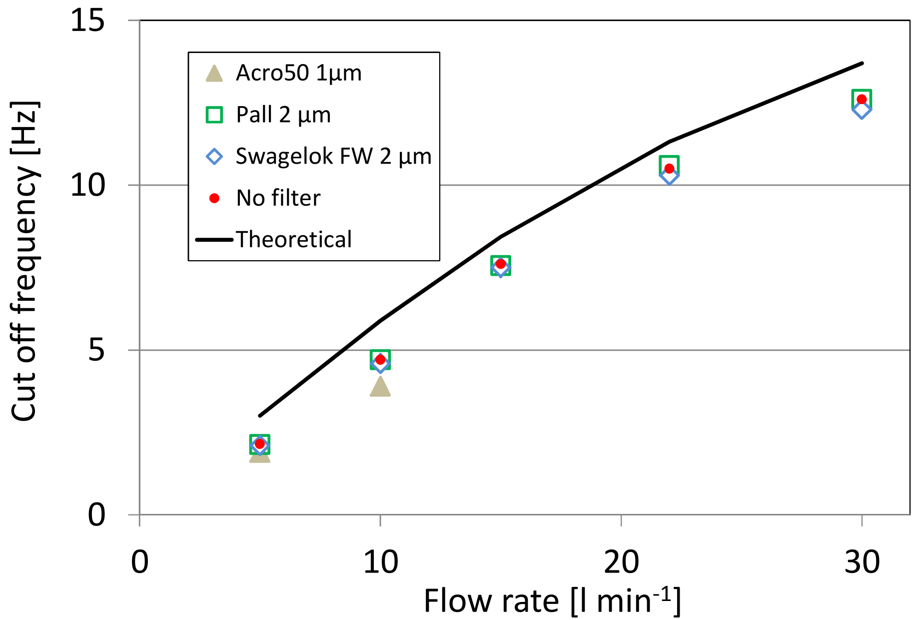

Figure 4. Cut-off frequencies [Hz] in function of the flow rate ($L\,min^{-1}$) for LI-7200 with ACRO-50 (grey triangle), Pall 2 µm (red circle), Swagelok FW 2 µm (blue losange), and without any filter (green square). Continuous line: theoretical estimate.

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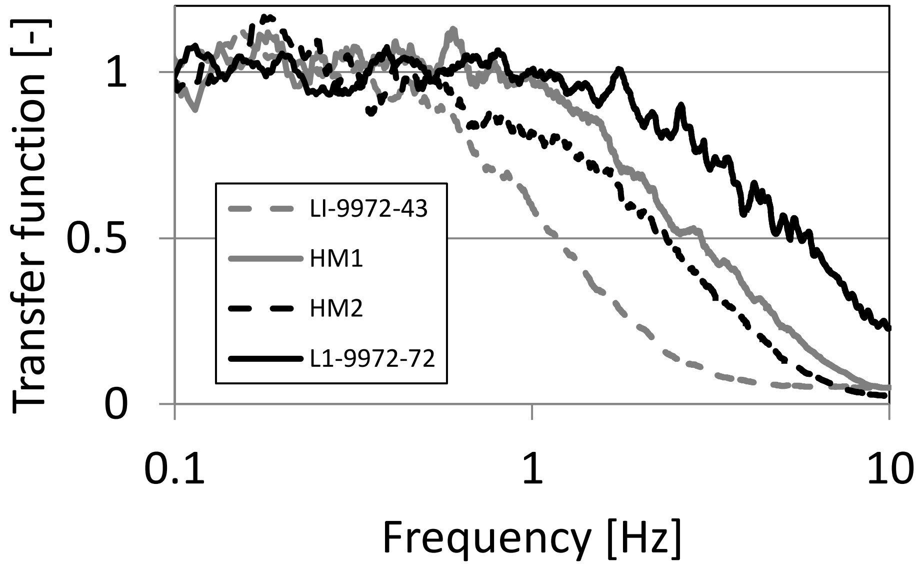

Figure 5. Transfer functions corresponding to different rain cup designs. Legend: dotted grey line: LI-9972-43; dotted black line: HM1; full grey line: HM2; full black line: LI-9972-72.

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