

Advancements in Instrumental Odour Monitoring System from Stationary Emission Sources

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In the past few years, significant advancements have been made in the development of Instrumental Odour Monitoring Systems, though very little data is available for IOMS measurement at emission sources and it is believed that the main cause is associated with issues affecting continuous sampling from streams with high humidity. In this paper we show an approach developed for continuous sampling from flow ducts aimed at feeding a trained IOMS with DO data collected from the same sampling system. The system was devised to sequentially sample from two duct flows, enabling the characterization of input and output odour flows through an odour abatement device while monitoring its efficiency in odour reduction. The primary design issues addressed include: 1) decreasing relative humidity through controlled dilution, 2) implementing hardware and software adjustments to account for temperature fluctuations during extended operation and 3) developing algorithms to establish correlations between odour concentrations obtained through sampling/measurement according to EN 13725:2022 and the instrumental odour concentration provided by IOMS. Here we present the field-calibrated results of the continuous sampling coupled with IOMS: the device was installed across the flow ducts both upstream and downstream of an odour abatement unit within a waste treatment plant. After the final training/calibration, the system operated for several weeks and the collected data of instrumental odour concentration are presented: the analysis covers both the odour fluctuations over the plant's daily working cycle and the efficiency of the installed abatement unit in reducing instrumental odour concentration.

1. Introduction

The adoption of more stringent regulatory measures, driven by an increased sensitivity of the population to odour emissions, has spurred research and development efforts aimed at monitoring and controlling odour emissions from industrial facilities. Over the past decade, Electronic Noses or Instrumental Odour monitoring systems (IOMS) have gained importance, due to the adoption of low-cost sensor arrays and the widespread capability of machine learning algorithms. This technology has been applied in several environmental case studies, especially in situation where detecting odour immissions, i.e. the odours of the ambient air along the fence line of the industrial plant, is a significant concern (Oliva et al., 2021, Cangialosi et al., 2021, MacDondald et al. 2022). On the other hand, while emissions are often well-defined in terms of sampling procedures for analysing odour concentration, especially for stationary emission sources (as outlined in EN 13725:2022), there is little emphasis on continuous monitoring specifically aimed at detecting odour compounds. Consequently, there is a notable scarcity of literature data concerning the measurement of Instrumental Odour Monitoring Systems (IOMS) at emission sources. In such scenarios, where DO samples are typically available for straightforward training and calibration tasks, challenges may arise due to issues associated with continuous sampling from streams with high humidity. One noteworthy case study, where IOMS was installed near to the emission source (Prudenza et al., 2023), involved the use of a dilution system. In this paper, a technology is described for continuous sampling and subsequent analysis of airflows within flow ducts for determining odour concentration. The system (OSMOTREFF®) was designed to sequentially sample from two distinct duct flows, allowing for characterization of both input (hereafter defined as "raw") and output (defined "clean") airflows passing through an odour abatement device. This assessment involves measuring the chemical concentration

of selected compounds and subsequently quantifying the Instrumental Odour Unit (IOU/m³) after a comprehensive training and calibration process. This calibration is conducted using samples collected from the same system and analysed using Dynamic Olfactometry (DO) according to EN 13725:2022.

2. Materials and methods

2.1 Odour emission continuous sampling: prototype development

In Figure 1 the schematic of OSMOTREFF® system is shown (within the dotted square), along with the sampling lines from an industrial odour abatement unit.

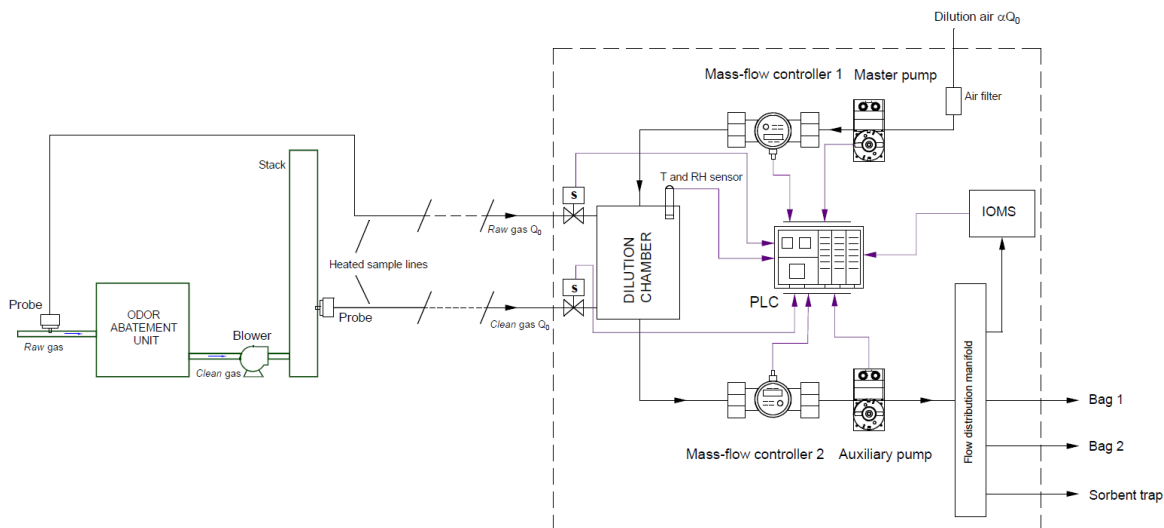


Figure 1: OSMOTREFF® schematic (within the dotted square), along with the sampling lines from an industrial odour abatement unit

The main design challenge tackled was reducing relative humidity through controlled dilution: in fact, finding stack emissions with humidity levels below 80% is highly unusual, particularly in emissions associated with waste or wastewater treatment plants. Under such conditions, sampling lines quickly become clogged with condensed water, while sensor corrosion or damage is likely to occur within a few weeks of continuous operation. To address this primary concern, a dynamic dilution system was devised by using two diaphragm pumps, operating in a master/slave configuration and digitally controlled by a PLC. Diaphragm pumps were selected because of their characteristics: high inertia, minimal overheating, and the absence of lubricated parts in contact with the sample. These features mitigate issues such as memory effect, contamination of the pumping line, or alterations in the odour profile of the gas flow. One of the two pumps (master pump) is connected to a treatment system capable of removing moisture and odour compounds from dilution ambient air. The fluidic design of the OSMOTREFF® system incorporates a dilution chamber constructed from inert material. Within this chamber, the dilution air flow is regulated based on user-defined settings. Subsequently, the auxiliary pump draws the mixed gas flow from the chamber, directing it to the sensor chamber. The flow rate of the auxiliary pump, is always equal to or greater than that of the master pump supplying dilution air. If Q_o is the flowrate drawn from the sampling line (whether "raw" or "clean") with a concentration C_o and αQ_o represents the dilution air flowrate, then the dilution rate Dil can be defined as follows:

$$Dil = \frac{\alpha Q_o}{Q_o + \alpha Q_o} = \frac{\alpha}{1 + \alpha} \quad (1)$$

where the denominator is the flow rate of the auxiliary pump extracting the mixed gas from the chamber. Given the critical role of the diaphragm pumps in the fluidic setup of the dynamic diluter, both pumps are precisely regulated by two mass flow controllers equipped with integrated solenoid valves to ensure optimal control. To monitor potential condensation within the diluted stream, temperature and humidity sensors within the dilution chamber continuously provide digital readings to the controller. Within the PLC, an operational routine has been implemented to oversee the different sampling phases from the "raw" and "clean" streams, with intermittent fluidic and sensor chamber rinsing cycles. As a result, the system operates in a continuous loop, executing a cyclical program. This program entails sampling from either the "raw" or "clean" stream at the designated dilution ratio, with each interval interposed by a rinsing phase. Consequently, a complete cycle

comprises the following sequence: raw-rinse-clean-rinse. During the rinsing phase, only filtered ambient air is introduced into the system to cleanse the lines and sensor chamber after each sampling step, thus preventing any potential cross-contamination between the two streams. The PLC is also programmed to control a group of actuated solenoid valves within the flow distribution manifold to distribute the mixed gas from the dilution chamber onto the following lines:

- a) IOMS: Dedicated line to sensors with a flow rate adjustable from 1 L/min up to a maximum of 3 L/min.
- b) Bag 1&2. Dedicated lines for filling bags for olfactometric analysis according to EN 13725:2022.
- c) Sorbent Trap. Dedicated line for sampling adsorbent supports for chemical analysis in the laboratory.

2.2 Integrating the diluter with IOMS: odour continuous sampling and measuring

The IOMS (NetPID Plus, Labservice Analytica, Anzola Dell'Emilia (BO), IT) sensor chamber, made of inert and odourless material, is fluidically interfaced onto the gas line downstream of the auxiliary pump of the dilution module through the flow distribution manifold. The sensors installed in the IOMS chamber include a photoionization detector (PID) calibrated in isobutylene for VOCs, and two electrochemical sensors for H₂S and NH₃. However, the model employed in this case study was equipped with only VOC and H₂S sensors. The chamber's sealing integrity ensures both measurement accuracy and the protection of electronic components, while also preventing potentially hazardous gas accumulations inside the box due to gas leaks. After measurement, the gas is exhausted from the system box through a forced air circulation system, which was designed also to mitigate the impact of temperature fluctuations on sensor response, thus enhancing overall performance and reliability. The data acquisition and processing system operates in two distinct logical phases:

- A. Initially, it computes incremental concentration values relative to background conditions for each sensor ($C(t) - C_{BI}$), using the raw data acquired, which contains aggregated information from processing cycles (dilution ratios for "raw" and "clean" stream, sampling and rinsing time).

With reference to the schematic in Figure 1 and bearing in mind the definition provided in Eq (1), assuming the dilution chamber is completely mixed, it is simple to establish that the concentration $C(t)$, for each chemical compound detected in the sensor chamber, follows a first-order ordinary differential equation (ODE), the solution of which is:

$$\frac{(C(t) - C_{BI})}{(C_{mix} - C_{BI})} = (1 - e^{-t/\tau}) \quad (2)$$

where:

C_{BI} is the concentration baseline, when only filtered dilution air is supplied to the system;

C_{mix} indicates the concentration achieved at equilibrium when the feed stream (either "raw" or "clean") with a concentration C_0 and dilution stream (flowrate αQ_0) are mixed, equal to $C_0/(1+\alpha)$;

τ is the time constant of the dilution process, given by the ratio between the volume of the dilution chamber (V_{mix}) and the total flowrate resulting from the dilution process: $Q_{mix} = Q_0(1+\alpha)$.

In the typical range of operation, Q_{mix} is around 2 l/min and τ is $V_{mix}/Q_{mix} = 4.8$ s. Hence, the time ($t_{90\ mix}$) one must wait to have 90% of the final mixed concentration C_{mix} is $2.3 \tau = 11$ s. A typical EC sensor (such as for H₂S) has a step response time ($t_{90\ sensor}$) of 40-50 seconds. This suggests that the mixing/diluting phase is not the rate-limiting step in the process of sampling-diluting-measuring, ensuring that the signal measured is not affected by the continuous sampling device.

- B. In the second phase, an algorithm, trained on DO samples collected by the sampling system itself, utilizes the incremental concentration data to calculate the instrumental odour units (IOU/m³) for both the "raw" and "clean" streams.

The instrumental odour units data for the two sampling streams and the efficiency of odour reduction are synchronized on a cloud platform, enabling real-time access to the data, trend analysis based on user defined time interval, and the setting of threshold values for automatic email notifications in case of exceeding the set conditions.

2.3 Plant installation and on-site training

The data presented in this present paper are derived from the first long-duration experimental campaign, which lasted several months. OSMOTREFF® was installed in a MSW treatment plant to evaluate the performance of a wet scrubber treating the exhausted air (25,000 Nm³/h) before a biofilter. The biofilter in the study is an active area source, so it was not possible to install OSMOTREFF® to sample the air after biofilter treatment and evaluate biofilter's efficiency, but this should be feasible in the case of a closed biofilter, where the treated air is emitted from a stack. Following several preliminary tests and system improvements, particularly addressing the temperature issue initially affecting sensor response, the system underwent optimization in terms of cycle duration (raw-rinse-clean-rinse) and dilution ratio Dil to achieve optimal sensor response. In fact, as mentioned

in the previous paragraph, the duration of the "raw" (or "clean") sampling phase and the subsequent rinsing phase is not constrained by the sampling/dilution phase, but rather determined by the shortest sensor response time. For the present case study, each cycle was configured to last 5 minutes, allowing for the measurement of three data points from the "raw" stream (untreated air sample) and three data points from the "clean" stream (air sample after wet scrubber treatment) within 1 hour. With this setup, it is feasible to collect up to six sample bags per hour for Dynamic Olfactometry (DO) analysis in accordance with EN 13725:2022 (three for the "raw" stream and three for the "clean" stream). For the development and training of the final algorithm used to derive instrumental odour unit from the sensors' response, a total of 42 samples were collected and analysed using Dynamic Olfactometry (DO) according to EN 13725:2022 by T&A laboratory. The algorithms used for instrumental odour calculation are described elsewhere (Cangialosi et al., 2021); here, it is sufficient to mention that fewer signals and features can be extracted, analysed, and utilized for machine learning algorithms due to the low number of sensors. However, this is compensated by the clearer sensors' response obtained from stationary source emissions, eliminating the need for specific signal pre-treatment or filtering.

3. Results and discussion

3.1 Data acquisition

In the following figure the raw data acquired by PID and electro chemical sensors are shown. The duty cycles are easily recognizable as the higher peaks (for VOC and H₂S) correspond to the analysis of the raw gas, the lower peaks correspond to the analysis of the clean gas, while the rinsing phases in between a "raw" and "clean" cycle correspond to the decreasing concentrations pieces of the signal.

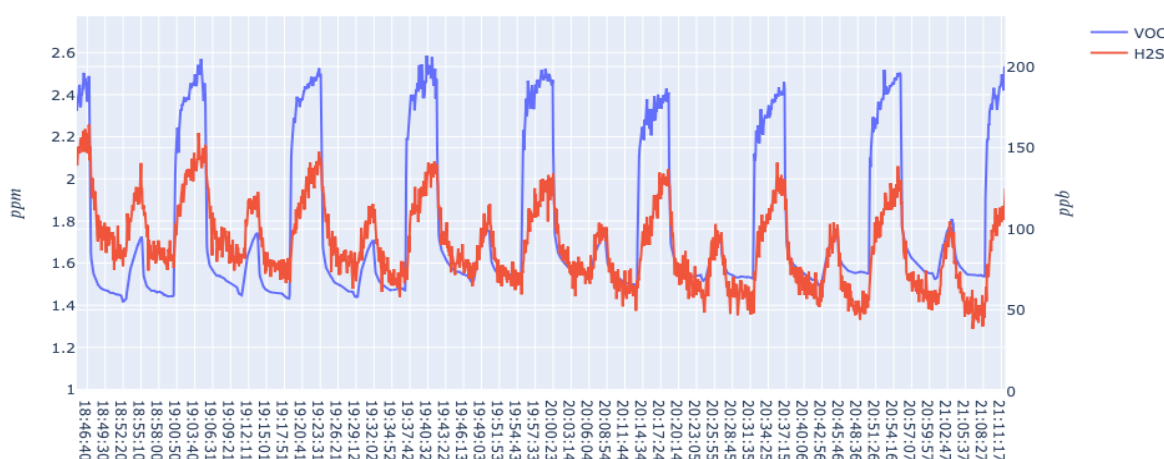


Figure 2: OSMOTREFF® raw data response: in blue (left axis) VOC concentration, in red (right axis) H₂S concentration

The plots in the first column (Figures 3a and 3b) display the data from the PID sensor (VOC) and the H₂S sensor, respectively, revealing a trend with periodic spikes representing the sensors' responses to the "raw" and "clean" streams. Once the durations of each phase of the duty cycle (raw-rinse-clean-rinse) are established, a data processing routine calculates the incremental concentration values relative to background conditions for each sensor ($C(t)-C_B$) and for each stream. These incremental concentration values are depicted in Figures 3c and 3d for VOC, where data collected from the untreated samples are plotted in continuous (red) lines. Figures 3e and 3f illustrate the H₂S data for both the "raw" and "clean" streams. By simply examining the scales of the plots, it can be pointed out that the scrubber can achieve approximately a 50% reduction in terms of VOC. However, H₂S does not appear to be affected by the wet scrubber treatment, as expected, given that the scrubber does not employ chemicals (like NaOH) to treat reduced sulphur compounds.

In Figure 3, the monitoring results of a 24-hour scrubber operation are presented.

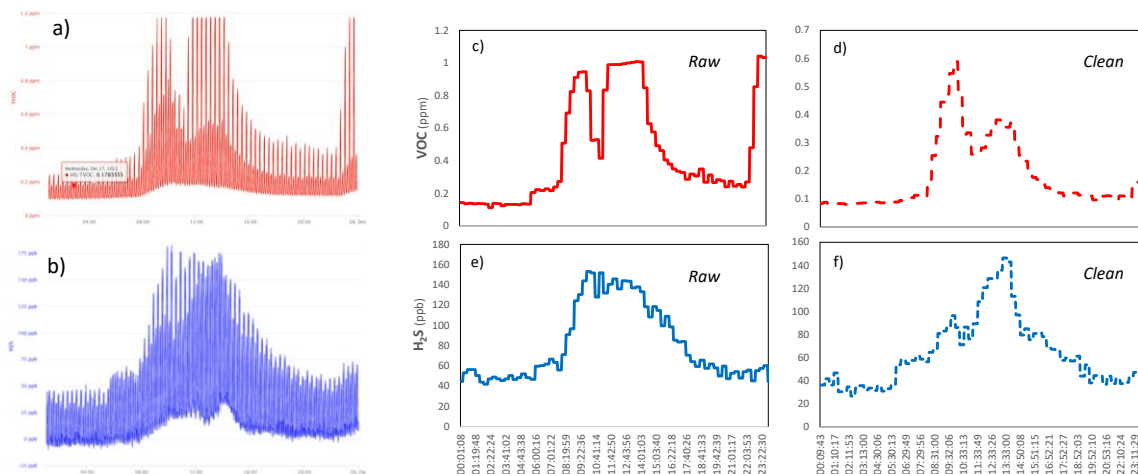


Figure 3a-f: OSMOTREFF® data: Figures a) and b): raw data responses for VOC and H₂S. Figures 3c and 3d: VOC incremental concentrations for the "raw" and "clean" streams. Figures 3e and 3f: H₂S incremental concentrations for the "raw" and "clean" streams

3.2 Instrumental Odour Unit from sensors data

In Figure 4, the Instrumental odour unit for the same 24-hour time interval as in Figures 3a-f is displayed.

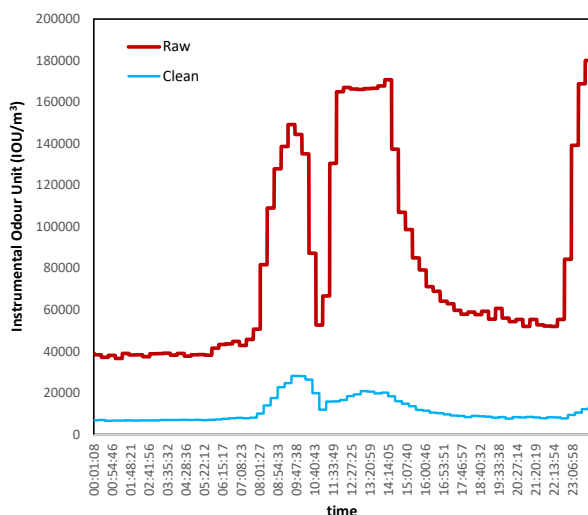


Figure 4: OSMOTREFF® data response in IOU/m³ (in blue clean concentration, in red raw concentration)

A detailed discussion regarding the correlation between DO analyses and IOMS data will be provided in a forthcoming paper. One conclusion worth emphasizing here is that simple single-sensor correlation is not sufficient for odour prediction as also recently highlighted by Prudenza et al. (2023). Indeed, it was discovered that within the same range of VOC concentrations detected by the PID, different values of odour concentrations are observed for the "raw" and "clean" streams, with this difference appearing to increase as the concentration rises. Evidently, the complex chemical composition of the "clean" gas differs from that of the "raw" gas, and even if the PID sensor, calibrated in isobutylene, yields similar responses for both streams, the corresponding odour concentrations can be, and indeed are, noticeably different due to the varying chemical compositions before and after treatment. These findings highlighted what follows: simpler and cost-effective multi-sensor systems, compared to more complex IOMS used for ambient air or fenceline analysis, can be utilized for high-concentration applications such as source emissions. However, there is a trade-off: multi-sensors trained as IOMS for stationary emission sources may lack generality, requiring training to be conducted considering "clean" data separate from "raw" data. Additionally, the training algorithm should be selected to account for all sensor responses, exploring nonlinear correlations with DO data. Chemical mixtures containing two or more chemicals,

each with an odour threshold and an Odour Activity Value, often exhibit an odour concentration that differs significantly from the linear combination of the activity values of individual chemicals, demonstrating a nonlinear and multicomponent behaviour (Szulczyński and Gębicki, 2019). Following an extensive experimental phase, a standardized procedure involving 40 to 50 DO samples and an appropriate ML algorithm was developed. The validity of the algorithm and the optimal number of training samples were tested by comparing the results of odour concentration in DO before and after the treatment with the instrumental odour concentration IOU/m³ (Cangialosi and Fornaro, 2023). In this case study, 42 samples were employed for ML training and testing. Once integrated into the OSMOTREFF® system, the algorithm computes Instrumental Odour Units (IOU/m³) in real-time based on the incremental concentrations derived from multi-sensor data acquisition.

It is important to highlight that: 1) "raw" odour concentrations exhibit a fourfold increase within the same day, the peaks coinciding with mechanical waste treatment activities in the buildings; 2) the scrubber odour abatement efficiency over the 24-hour period is approximately 85%, a remarkably high value, though caution is advised in its interpretation as long-term analyses of the system performance may offer more representative data. The odour treatment efficiency is significantly higher than that derived from the analysis of single sensor concentrations (50% for VOC and nearly zero for H₂S). This discrepancy arises because the odour concentrations associated with PID values obtained from the "raw" stream are much higher than those obtained from the "clean" stream. This highlights the importance of not exclusively using single sensors concentrations to evaluate odour reduction efficiency. Without utilizing a comprehensive dataset of DO samples alongside properly designed machine learning algorithms, such an approach can result in highly misleading outcomes.

4. Conclusions

In the paper, we have summarized the advancements made in the field of instrumental odour monitoring systems for stationary emissions. These advancements enable the characterization of input and output airflow odour concentrations through a wet scrubber while monitoring its efficiency in odour reduction. The schematic of the device (OSMOTREFF®), designed for continuous sampling with dynamic dilution, is presented alongside the integration with an IOMS consisting of one PID sensor and two electrochemical sensors for hydrogen sulphide and ammonia detection. Considering the typical response time of the sensors, which has been identified as the rate-limiting step in the sampling-diluting-analysing process, the system can measure up to 6 data points per hour, i.e. three data points from the untreated sample line ("raw"), and three from the sample line after the wet scrubber ("clean"). After training the IOMS with 42 samples analysed in dynamic olfactometry, instrumental Odour unit (IOU/m³) are calculated from the sensors response curves in real time. Field data collected over a 24-hour period from an industrial wet scrubber, which treated air from a municipal solid waste treatment plant, showed notable variations in odour concentrations on a daily basis, with fluctuations of up to 400% in terms of peak-to-baseline variation. The scrubber's treatment efficiency for odour abatement was approximately 85% during the monitoring period, while single sensor concentration reduction was 50% for VOC and negligible for hydrogen sulphide. This difference is explained by experimental evidence indicating that odour concentrations (determined according to EN 13725:2022) corresponding to the same PID values measured in the "raw" stream are significantly higher than those measured in the "clean" stream. This underlines the importance of calculating instrumental odour concentrations following an appropriate on-site training/calibration procedure, as single sensors measurements alone may be misleading when analysing odour concentration trends.

References

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