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Review

Measuring odours in the environment vs. dispersion modelling: A review☆

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HIGHLIGHTS

- Techniques for measuring odours in the field are reviewed.
- The possibility of relating results of field odour measurements and model outputs is investigated.
- Chemical analysis, though reliable and consolidated, is mostly unsuitable for odour assessment.
- Human panels (trained or untrained) are necessary for direct assessment of odour in the field.
- Electronic noses or sensors represent a promising technology for environmental odour monitoring.

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ABSTRACT

Source characterization alone is not sufficient to account for the effective impact of odours on citizens, which would require to quantify odours directly at receptors. However, despite a certain simplicity of odour measurement at the emission source, odour measurement in the field is a quite more complicated task. This is one of the main reasons for the spreading of odour impact assessment approaches based on odour dispersion modelling. Currently, just a very limited number of reports discussing the use of tracer gas dispersion experiments both in the field and in wind tunnels for model validation purposes can be found in literature. However, when dealing with odour emissions, it is not always possible to identify a limited number of tracer compounds, nor to relate analytical concentrations to odour properties, thus giving that considering single odorous compounds might be insufficient to account for effective odour perception. For these reasons, the possibility of measuring of odours in the field, both as a way for directly assessing odour annoyance or for verifying that modelled odour concentrations correspond to the effective odour perception by humans, is still an important objective. The present work has the aim to review the techniques that can be adopted for measuring odours in the field, particularly discussing how such techniques can be used in alternative or in combination with odour dispersion models for odour impact assessment purposes, and how the results of field odour measurements and model outputs can be related and compared to each other.

1. Introduction

Since several decades, it is known that the odours resulting directly or indirectly from human activities may cause adverse effects on citizens (Aatamila et al., 2011; Sucker et al., 2009; Witherspoon et al., 2004), and are recently being considered as atmospheric contaminants. It is important to highlight that odours are, among atmospheric pollutants, the major cause of population's complaints to local authorities (Henshaw et al., 2006). Indeed, several conventional pollutants are generally not perceived by population, even if they might be harmful for human health, especially if normal exposure limit concentrations are exceeded. On the contrary, some odours are perceived far below normal exposure limit concentrations, due to the presence of odorous compounds having extremely low odour detection threshold concentration (Nicell, 2003).

For these reasons, odours are nowadays subject to control and regulation in many countries (Nicell, 2009). The need to regulate

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odour impacts entails the requirement of specific methods for odour measurement.

Dynamic olfactometry (CEN, 2003) is now a widespread and common technique for the quantification of odour emissions in terms of odour concentration (Muñoz et al., 2010). Unfortunately, source characterization alone is not sufficient to account for the effective impact of odours on citizens. For the purpose of evaluating citizens' exposure to odours it would be useful to quantify odours directly at receptors. However, despite a certain simplicity of odour measurement at the emission source, odour measurement in the field is a quite more complicated task (Brandt et al., 2011a; Gostelow et al., 2001).

These difficulties are among the reasons for the spreading of odour impact assessment approaches based on odour dispersion modelling. Odour dispersion models allow to simulate how odour disperses into the atmosphere, and therefore to calculate ground odour concentration values in the simulation space-time domain (Capelli et al., 2011a; Sheridan et al., 2004; Sarkar et al., 2003a; Schauberger et al., 1999), thereby entailing the advantage of being not solely descriptive (as field measurements), but also predictive. Actually, nowadays, most odour regulations all over the world are defined based on the application of dispersion modelling.

In some cases, odour regulations fix acceptability standards in terms of the frequency with which a given odour concentration is exceeded (JORF, 2008; Regione Lombardia, 2012). One example of this approach is the "Integrated Pollution Prevention and Control (IPPC) – Horizontal Guidance for Odour Part 1 – Regulation and Permitting" published by the Environmental Agency of the United Kingdom (UK Environmental Agency, 2002). The approach it takes is to establish exposure criteria in terms of ground level odour concentration at the 98th percentile, i.e. the maximum odour concentration that may only be exceeded for 2% of the hours in a year. The limits set by the guidelines are expressed in terms of hourly average odour concentration values at the 98th percentile, and are differentiated on the basis of the level of potential olfactory annoyance ("low", "medium" or "high") associated with the industrial category under consideration (Table 1).

In other cases, odour regulations specify the minimum distance from the closest inhabited area where possible odour-producing industrial or agricultural facilities can be located. Historically, minimum distances were tabulated, by taking into account the use (e.g., residential or agricultural area) or the residential density of the area in which the facility is located (Melse et al., 2009; JORF, 2005; Piringer and Schauberger, 1999; VROM, 1996). More recently, minimum distances are not tabulated but calculated by directly applying dispersion models (Piringer et al., 2007; Schauberger et al., 2002) or by using simplified mathematical expressions containing specific coefficients derived from dispersion modelling (Schauberger et al., 2012).

In general, different types of models can be used to simulate the dispersion of pollutants into the atmosphere (Mazzoldi et al., 2008; Holmes and Morawska, 2006; Caputo et al., 2003). Independently from the model used, model validation is fundamental in order to evaluate model reliability. Currently, reports on studies for validation of odour dispersion models are limited in literature (Hayes et al., 2006), even though some studies discussing the use of tracer gas dispersion experiments both in the field and in wind tunnels for model validation purposes can be found in literature (Abdul-Wahab et al., 2011; Dresser and Huizer, 2011; Latos et al., 2011; O'Shaughnessy and Altmaier, 2011; Santos et al., 2005; Vieira de Melo et al., 2012).

In the case of odour dispersion simulation, especially in the case of complex sources, it is not always possible to identify a limited number of tracer compounds (Capelli et al., 2012a). Moreover, given the difficulty of relating analytical concentrations to odour properties, considering single odorous compounds might be insufficient to account for effective odour perception (Dincer et al., 2006; Dincer and Muezzinoglu, 2007; Sarkar and Hobbs, 2002).

For these reasons, the possibility of measuring odours in the field, both as a way for directly assessing odour annoyance or for verifying that modelled odour concentrations correspond to the effective odour perception by humans, is still an important objective.

Different approaches and techniques can be used for measuring odours in the environment.

Such techniques include physical and chemical measurements for either the quantification of the concentration of one sole compound or the evaluation of global pollution (i.e. concentration of odorous compounds and VOCs), by means of exhaustive chemical analysis (Saral et al., 2009; Kim and Park, 2008) or, recently, electronic noses (Romain et al., 2008; Littarru, 2007; Stuetz et al., 1999).

Other techniques are based on sensorial measurements, such as dynamic olfactometry. As already mentioned, dynamic olfactometry should in general be limited to source sampling, however, it has in some cases been applied for ambient air sampling and analysis (Capelli et al., 2008a).

As an alternative, instead collecting samples on field and then analysing them in laboratory, it is possible to use human "sensors" directly in the field (Nicell, 2009).

Human "sensors" may be the resident population, who may collect records of odour episodes over prolonged periods of time to be compared with model results (Sironi et al., 2010; Drew et al., 2007; Sarkar et al., 2003b).

Otherwise, it is possible to rely on trained assessors, for instance by using a field olfactometer to determine the presence and intensity of odour directly on field (Nicell, 2009; Schiffman et al., 2005), or by running field inspections such as grid or plume measurements to evaluate the extent of the area impacted (Guillot et al. 2012; Mussio et al., 2001; Nicolas et al., 2006).

This paper has the object of reviewing the techniques that can be adopted for measuring odours in the field (i.e., at receptors), with the particular aim of discussing how such techniques can be used as an alternative or in combination with odour dispersion models for odour impact assessment purposes, and how the results of field odour measurements and model outputs can be related and compared to each other.

Table 1
Exposure criteria in terms of ground level odour concentration as a 98th percentile, in the United Kingdom.

Relative "offensiveness" of odour	Indicative criterion
HIGH (e.g., activities involving putrescible waste, processes involving animal or fish remains, wastewater treatment, oil refining)	1.5 ou_E m^{-3} 98th percentile
MEDIUM (e.g., intensive livestock rearing, fat frying, sugar beet processing)	3.0 ou_E m^{-3} 98th percentile
LOW (e.g., chocolate manufacture, brewery, fragrance and flavourings, coffee roasting, bakery)	6.0 ou_E m^{-3} 98th percentile

2. Development and application of odour dispersion models

2.1. Models for pollutant dispersion simulation

In general, different types of models can be used to simulate the dispersion of pollutants into the atmosphere (Mazzoldi et al., 2008; Holmes and Morawska, 2006; Caputo et al., 2003).

The simplest models are analytical stationary plume models. Among them, Gaussian models, for which turbulent dispersion is parameterized with empirical coefficients derived from experimental campaigns, are the most traditional ones and very cheap for computation (Gifford, 1959; Pasquill, 1961; Smith, 1995). Critical